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Universal Principles of Professional Safety

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This guide has been prepared to harmonize occupational safety research methods across diverse fields of human activity. It integrates theoretical foundations, international standards, and practical applications to provide a comprehensive framework for risk identification, assessment, and management. By combining quantitative and qualitative approaches, the text ensures both academic rigor and practical utility.

The inclusion of ISO 31000 and ISO 45001 standards, along with references to ILO, WHO, IEC, NFPA, and other international organizations, underscores the universal relevance of the material. Each chapter is supported by explanatory tables and visual schemes, designed to help readers grasp complex concepts with clarity and precision.

This manual is intended for students, researchers, and professionals who seek to strengthen their knowledge of occupational safety and apply it in practice. It emphasizes that safety is not merely a technical requirement but a fundamental human value, essential for protecting life, health, and the environment.

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Introduction

Occupational safety is defined as a comprehensive system of measures designed to protect human life and health in the workplace. It integrates social, technical, hygienic, and organizational approaches, aiming to establish conditions where professional activity can be carried out safely and sustainably.

The concept of safety extends beyond individual protection, encompassing collective mechanisms that normalize the working environment itself. These mechanisms include air purification, lighting, noise and vibration reduction, and protective systems against electrical, mechanical, chemical, and biological hazards. Their effectiveness is independent of personal skills or qualifications, ensuring universal applicability.

Individual protective equipment complements collective measures by safeguarding workers against specific risks. Helmets, gloves, masks, protective clothing, and specialized devices provide targeted defense, though their reliability depends on proper use and adherence to safety protocols.

International standards, including ISO 45001 and ILO conventions, emphasize the principle of priority: collective protection must always precede individual measures. Collective systems eliminate hazards at the source, while individual equipment reduces exposure. Together, they form a coherent framework for occupational safety, ensuring resilience across industries and protecting both human health and organizational integrity.

1. Preliminary Remarks

1.1. Definitions

Theoretical Integration

This chapter establishes the methodological foundation of the guide. It defines the concept of risk, the formulation of its indices, and the methods of analysis. It provides the framework for *systematic analysis (SISAN)*, which will later be applied in practice in subsequent chapters.

The risk index presented in this chapter ($R = P \times S$) provides the foundation for single-factor analysis. In subsequent chapters, particularly Chapter 14, this model is expanded into a multi-factor and multi-component analysis, where technical, organizational, hygienic, and social factors are considered simultaneously. Thus, the methodological framework of Chapter 1 evolves into a comprehensive systemic model that enables more complete and realistic assessment.

Integration with Standards

- **ISO 31000 requirement:** risk identification, quantitative evaluation (R = P × S), and prioritization.
- **ISO 45001 emphasis:** preventive measures, employee involvement, and standardization of safety procedures.

Pedagogical Integration

- Provides readers with tools for the practical calculation of risk indices.
- Short notes within the chapter show how each topic connects to ISO standards.

- **Risk index formula (R = P × S):** represents ISO 31000's requirement for quantitative risk evaluation.
- **Prioritization:** ISO 31000 requires a risk matrix to ensure that high risks are controlled first.
- **Planning control measures:** ISO 45001 emphasizes preventive actions — technical, organizational, and individual.
- **Monitoring and improvement:** ISO 45001's PDCA cycle (*Plan–Do–Check–Act*) ensures continuous upward improvement of the safety system.
- This paragraph should be revisited after mastering the material of the chapter in full [13, 14, 43, 48].

1.2. Key Concepts and Documents

General Definition of Risk

Risk is defined as the effect of uncertainty on the achievement of objectives. It may be positive (opportunity) or negative (hazard) and requires systematic analysis and management. In high-risk sectors — such as mining, transport, chemical industry, healthcare, construction, and other similar fields — risk is often directly associated with threats to life, health, and safety, which increases the strategic importance of its management.

Hazard

A potential source of harm. Harm may affect people, infrastructure, or the environment. For humans: harm manifests as diseases, injuries, or other health impairments, either individually or collectively. For infrastructure: harm may result in partial or complete destruction of buildings and structures. For the environment: harm may arise from toxic, explosive, or other hazardous substances, or from fire, affecting flora and fauna.

Single Case – harm affecting only one person.

Group Case – harm affecting more than one person.

Dangerous Situations – conditions where there is a real probability of harm. Severity (Intensity) of Hazard – the degree or magnitude of a specific hazard. Hazards are particularly intensified during natural disasters and catastrophic events.

Risk

The probability of hazard realization combined with the magnitude of the resulting harm. When discussing risk, it is essential to distinguish between:

• Probability of occurrence (how often it may happen).

• Severity of consequences (how serious the outcome will be).

Safety

A condition in which hazards and risks are reduced to an acceptable level.

Occupational Safety

The creation of a safe environment in professional activity that excludes health damage or other harm.

Risk Assessment

The process of determining the level of risk, its sources, and the scale of its impact.

Risk Management

A set of measures aimed at reducing or eliminating identified risks.

Stages of Risk Management

Hazard identification, qualitative/quantitative risk assessment, prioritization, planning of control measures, monitoring, and evaluation of results. Observation of work processes and feedback. All of these contribute to improving the level of safety [1-3].

International Standards: ISO 31000:2018, ISO 45001:2018

ISO 31000 is an internationally recognized standard that provides general principles and recommendations for organizational risk management. Its key features include:

- Risk identification, analysis, and evaluation.
- Context-specific approaches tailored to organizational needs.
- Integration into organizational processes.
- Continuous review and improvement.

ISO 31000 enhances organizational resilience, supports the achievement of strategic objectives, and ensures ongoing improvement of processes. It does not establish certification requirements but serves as a framework applicable to organizations of any type and size.

ISO 45001 is the international standard for occupational health and safety management systems. It places particular emphasis on risk assessment and preventive measures. Its main principles are:

- A systematic approach to occupational safety risks.
- Employee participation and consultation.
- Monitoring and continuous improvement of processes.
- Employer responsibility and legal compliance.

ISO 45001 explicitly incorporates the concept of risk-based thinking, requiring organizations to identify not only existing but also potential risks and to develop preventive policies. It stresses that collective protective measures must be prioritized, while individual protective equipment serves as supplementary support.

Universality of ISO 31000 and ISO 45001. These standards are not sector-specific; they provide a universal framework adaptable to different contexts.

Other International Standards

- **ICNIRP (International Commission on Non-Ionizing Radiation Protection):** establishes threshold values for electromagnetic fields, defining safe exposure levels for human health.
- **IAEA (International Atomic Energy Agency):** sets safety standards for ionizing radiation, including dosimetric monitoring, waste management, and rules for individual protection of personnel.
- **WHO (World Health Organization):** emphasizes the importance of organizational and hygienic measures for protecting sensitive organs (eyes, brain, cardiovascular system).

Connection to the Guide

In this manual, short notes are provided to highlight the relationship between the discussed material and international standards. These notes ensure that readers maintain a clear overall picture and understand the place of each topic within the context of international standards.

1.3. Practical Application of ISO Standards (mining industry)

Objective

The aim is to apply ISO 31000 and ISO 45001 standards in a practical context, enabling the researcher to identify hazards, perform quantitative risk assessment, and plan control measures.

Steps:

1. Hazard Identification

• Identify potential sources of harm in mining operations (e.g., rock falls, toxic gases, machinery accidents).

• Document conditions that may lead to dangerous situations [11, 12, 14-17].

2. Risk Index Calculation ($R = P \times S$)

• Calculate the risk index (R) by multiplying the probability (P) of occurrence by the severity (S) of consequences.

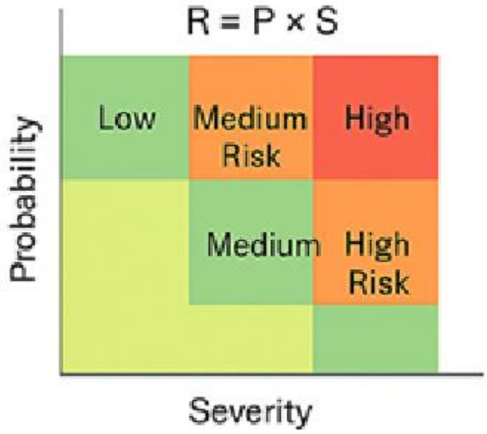
• For example: probability of explosion $P = 0.2$, severity of consequence $S = 5$.

• Calculation of risk index $R = 0.2 \times 5 = 1.0$.

• Index R indicates the average risk that requires control measures.

• Use numerical scales to ensure comparability across hazards.

• The index indicates an average risk that requires control measures. The sum of all weights must equal 1, ensuring systematic distribution of results.



Visual Scheme 1.1. Risk Matrix: Formula: $R = P \times S$
Axes: Vertical: Probability (P); Horizontal: Severity (S); Color-coded zones: Green - Low Risk; Yellow/Orange - Medium Risk; Red - High Risk. This matrix helps visualize the relative position of risks and supports prioritization decisions

3. Prioritization of Risks

• Apply a risk matrix to rank hazards according to their calculated risk index.

• High-risk hazards must be addressed first, ensuring that critical threats are controlled before lower-level risks.

• Prioritization must also be validated against expert judgment and statistical incident data.

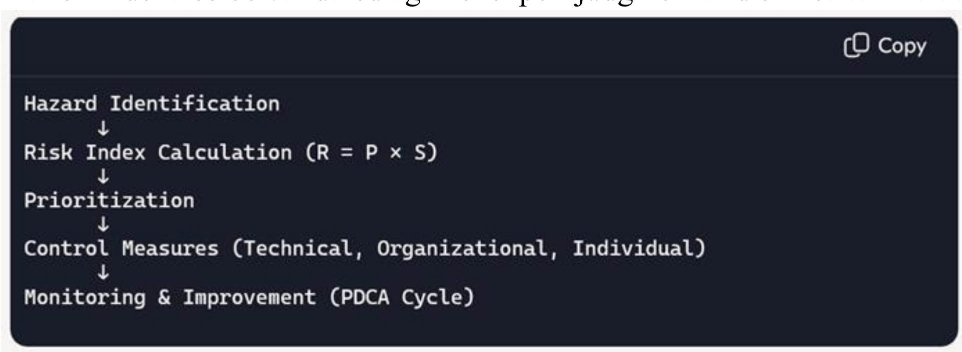


Fig. 1.2. Risk management stages in mining industry according to ISO standards

4. Planning Control Measures

• Develop preventive actions at technical, organizational, and individual levels.

• Examples: Technical - installation of ventilation systems, reinforcement of tunnels. Organizational - safety training, clear emergency procedures. Individual - provision of personal protective equipment (helmets, respirators).

5. Monitoring and Improvement

• Implement the **PDCA cycle (Plan–Do–Check–Act)** to ensure continuous improvement.

• Regularly review risk assessments, update control measures, and integrate feedback from workers.

1.4. Practical Application of ISO Standards (healthcare)

The objective is to use ISO 31000 and ISO 45001 standards in healthcare for systematic patient and staff safety management.

Steps:

1. Hazard Identification

• Spread of infection (hospital-acquired infections).

• Incorrect drug dosage.

• Malfunction of technical devices (e.g., respirator).

• Psychosocial risks (stress, fatigue).

2. Risk Index Calculation

• Use formula (1) $R = P \times S$.

• For example: - Probability of infection spread $P = 0.3$, severity of outcome $S = 4$.

• Risk Index Calculation: $R = 0.3 \times 4 = 1.2$.

• The index indicates a significant risk requiring immediate control.

• The sum of all weights must equal 1, ensuring systematic distribution of results.

3. Prioritization

• Hazards with a high index (infection, equipment failure) should be controlled first.

• Medium-risk hazards (stress, fatigue) require systematic monitoring.

• Prioritization should be cross-checked with hospital statistics and expert medical evaluation.

4. Control Planning

• Technical: Regular inspection and certification of equipment.

• Organizational: Double-check drug dosages.

• Individual: Staff training in infection prevention and stress management programs.

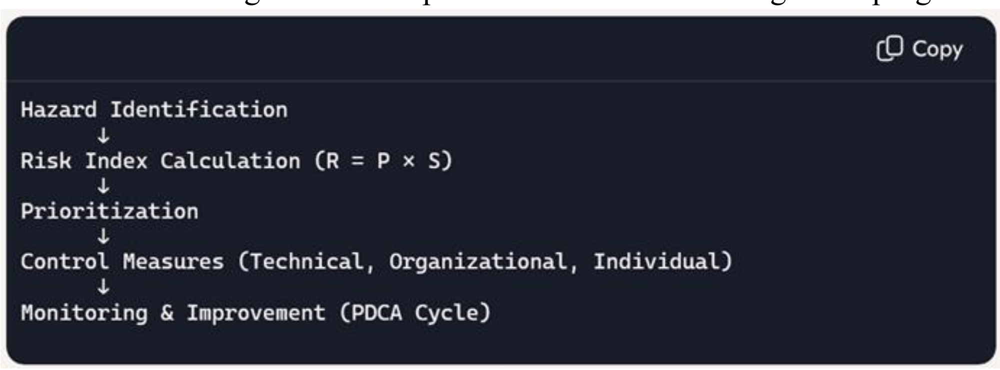


Fig. 1.3. Risk management stages in healthcare sector according to ISO standards

5. Monitoring and Improvement

• Regular audits of the safety system in accordance with ISO 45001 requirements.
• Receiving feedback from staff and patients.
• Periodic review and improvement of indicators.

Visual diagram of the practical application of ISO standards in healthcare: Hazard Identification → Indicator Calculation → Prioritization → Control Measures → Monitoring.

1.5. Practical Application of ISO Standards (digital technologies)

Objective – To apply ISO 31000 and ISO 45001 standards in the digital environment in order to ensure systematic management of data security, cybersecurity, and working conditions of personnel.

Steps:

1. Hazard Identification

• Cyberattacks (data leakage, system paralysis).
• Software malfunction.
• Staff fatigue due to constant online mode.
• Power supply or network interruptions.

2. **Risk Index Calculation**

• Use formula (1): $R = P \times S$.
• Example: Probability of data leakage $P = 0.25$, severity of consequence $S = 5$.
• Risk index calculation: $R = 0.25 \times 5 = 1.25$.
• The index indicates a significant risk requiring immediate control.
• The sum of all weights must equal 1, ensuring systematic distribution of results.

3. **Prioritization**

• High-index hazards (cyberattacks, power supply interruptions) must be controlled first.
• Medium risks (staff fatigue) require systematic monitoring and support.
• Prioritization must be supported by cybersecurity incident statistics and expert IT evaluation.

4. **Planning of Control Measures**

• Technical: Strengthening cybersecurity systems, data encryption.
• Organizational: Regular IT staff training, flexible distribution of working hours.
• Individual: Stress management programs, maintaining balance between work and rest.

5. **Monitoring and Improvement**

• Periodic review of risks in accordance with ISO 31000 requirements.
• Audit of working conditions in accordance with ISO 45001.
• Collecting feedback from users and employees.

In the practical application of ISO standards, the results are applied in:

- Risk prioritization
- Resource allocation
- Safety policy planning
- Educational practice through practical examples
- Verification of compliance with international standards.

Visual Scheme of Practical Application of ISO Standards in Digital Technologies:

Hazard Identification → Risk Index Calculation → Prioritization → Control Measures → Monitoring.

```
Hazard Identification
       ↓
Risk Index Calculation (R = P × S)
       ↓
Prioritization
       ↓
Control Measures (Technical, Organizational, Individual)
       ↓
Monitoring & Improvement (PDCA Cycle)
```

Fig. 1.4. Risk management stages in digital technologies according to ISO standards

1.6. Practical Application of ISO Standards (construction)

Objective – To apply ISO 31000 and ISO 45001 standards in the construction sector in order to ensure systematic management of workplace safety and operational processes.

Steps:

1. **Hazard Identification**

• Falling from heights.
• Malfunction of heavy machinery.
• Exposure to chemical substances.
• Electrical accidents during power use.

2. **Formulation of Risk Index**

• Use formula (1): $R = P \times S$.
• Example: Probability of falling from height P=0.15, severity of consequence S=5.
• Risk index calculation: $R = 0.15 \times 5 = 0.75$.
• The index indicates a significant risk that requires control measures.
• The sum of all weights must equal 1, ensuring systematic distribution of results.

3. Prioritization

- High-index hazards (falling from heights, heavy machinery malfunction) must be controlled first [4-9, 11, 12].
- Medium risks (chemical exposure, electrical accidents) require systematic monitoring.

4. Planning of Control Measures

- Technical - Safety nets, harnesses, regular inspection of machinery.
- Organizational - Safety briefings, marking of work zones.
- Individual - Use of protective helmets, gloves, and specialized footwear.

5. Monitoring and Improvement

- Regular safety audits in accordance with ISO 45001 requirements.
- Analysis of incident statistics.
- Periodic review and improvement of risk indices.

Visual Scheme of Practical Application of ISO Standards in Construction:
Hazard Identification → Risk Index Calculation → Prioritization → Control Measures → Monitoring.

Additional Note for the Researcher

Although the manual provides specific examples such as methane emission, infection spread, cyberattacks, and falls from height, the researcher must select additional risks based on personal experience and practical observation. This enables the researcher to adapt the risk index formula to the actual research environment. Individual experience ensures sector-specific relevance and enhances the credibility of the study. The manual offers only a framework, while the selection of concrete risks is determined by the researcher's professional competence.

```
Hazard Identification
       ↓
Risk Index Calculation (R = P × S)
       ↓
Prioritization
       ↓
Control Measures (Technical, Organizational, Individual)
       ↓
Monitoring & Improvement (PDCA Cycle)
```

Fig. 1.5. Risk management stages in construction sector according to ISO standards

As can be seen from Figures 1.2-1.5 of the Math lab matrices, the stages of risk management are identical to each other. This is true in all cases considered. This is very important in the interests of understanding the material.

1.7. Expert Evaluation

Objective

Expert evaluation is a research method that enables the investigator to assess a specific risk, identify its causal factors, and develop indices that reflect both the intensity of the risk and the possibilities for its management.

```
Selection of Risk
       ↓
Definition of Variables
       ↓
Formulation of Equation
       ↓
Data Collection
       ↓
Risk Index Calculation
       ↓
Evaluation of Results (Comparison, Trends, Recommendations)
```

Fig. 1.6. Expert evaluation stages in occupational safety research

Steps for the Researcher

1. **Selection of Risk** — for example, methane emission in mining operations.
2. **Definition of Variables** — data must be available or collected through inspection.
3. **Formulation of Equation** — the formula should reflect cause-and-effect relationships.
4. **Data Collection** — sensors, incident archives, technical documentation.
5. **Calculation of Risk Index** — apply the formula to different sites, time periods, or processes.

6. **Evaluation of Results** — comparison, identification of trends, and formulation of policy recommendations.
7. **Expert evaluation** must be validated with statistical data, and the sum of indices must equal 1 to ensure systematic distribution of results.

1.8. How the Researcher Should Act

Objective - The purpose is to design an instructional roadmap for research that integrates the definition of objectives, risk classification, methodological selection, application of indices, data collection, and interpretation of results.

Steps:

1. Formulating the Research Objective

Define the type of risks to be studied (clinical, chemical, physical, psychosocial, technical).

Objectives may include: assessing risks in a specific sector, comparing indices, or analyzing preventive mechanisms.

2. Applying Typological Classification

Develop a risk map based on functional categories.

For example: chemical risk → anesthesia in healthcare; use of paints in construction.

3. Selecting the Methodological Framework

Observation → behavioral and ergonomic risks.

Interview → psychosocial and organizational risks.

Statistical analysis → frequency and trends of incidents.

Modeling → forecasting technical and physical risks.

Triangulation → reinforcing the reliability of data.

4. Defining Indices as Research Tools

Security Integrated Index (SII): combines incident frequency, effectiveness of preventive mechanisms, and staff involvement.

Impact Index (II): reflects risk intensity and its potential for reduction.

The formula for indices must be tailored to the specific characteristics of the sector.

The sum of all index weights must equal 1, ensuring systematic distribution of results.

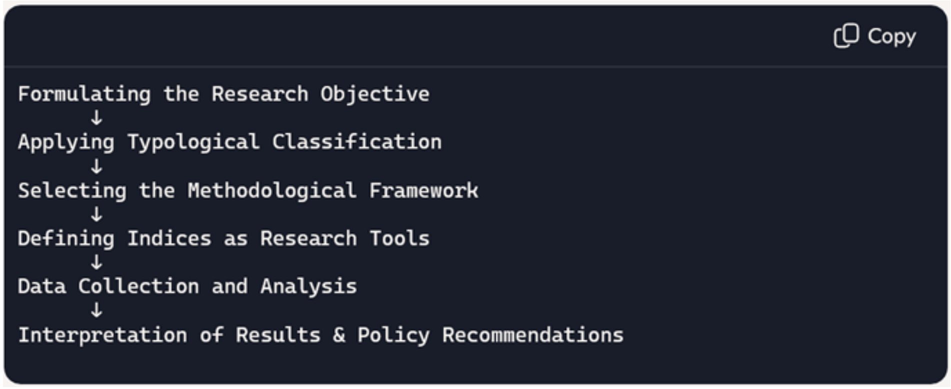


Fig. 1.7. Instructional roadmap for researchers in occupational safety

5. Data Collection and Analysis

Use questionnaires, inspection reports, and technical documentation.

Disaggregate data for analysis and reintegrate it during the synthesis stage.

6. Interpretation of Results and Policy Recommendations

Compare indices across different sectors.

Identify priorities (where is the highest Impact Index – II?).

Formulate recommendations such as training, inspection, and technological integration.

In the practical application of ISO standards, the results are applied in:

- Risk prioritization.
- Resource allocation.
- Safety policy planning.
- Educational practice through practical examples.
- Verification of compliance with international standards.

1.9. Safety of Production and Technological Processes

Concepts

The notions of production and technological processes are closely related but not identical. A technological process is typically part of the overall production process, since under production conditions several technological processes may be involved. Thus, the production process represents the totality of actions performed by workers and means of labor, required to produce goods, provide services, or carry out other tasks for third parties. A technological process, by contrast, is the specific action through which a given technology is implemented within the production process.

Measures to Ensure Safety of Production Processes. The requirements for the safety of production and technological processes are set forth in unified occupational safety rules, sectoral and cross-sectoral regulations, sanitary norms, technological regulations, occupational safety standards, and other similar documents.

Unified safety rules are mandatory for enterprises and organizations across all sectors, regardless of their administrative affiliation (for example, sanitary norms for design; rules for electrical supply, grounding, ventilation, heating, water supply, and other communications). Cross-sectoral safety rules ensure safe conditions for tasks common to multiple industries (for example, safety and industrial hygiene rules for locksmiths, carpenters, welders, etc.). Sector-specific safety rules are designed for a particular branch of industry and apply to all enterprises within that branch (for example, Safety Rules for Coal and Oil Shale Mines).

General Safety Requirements.

The safety of production processes throughout their entire cycle is achieved by maintaining the risk of hazardous situations at an acceptable level. This can be accomplished through the following means:

1. Use of technologies that:

a. eliminates direct worker contact with harmful and dangerous production factors;

b. minimizes accident risk to the lowest possible level, consistent with technological development and economic feasibility;

c. prevents harmful factors from reaching workers in the event of an accident;

d. increases the level of worker protection and ensure strict, consistent compliance with safety rules.

2. Use of production buildings, structures, and engineering systems that automatically maintain the required level of sanitary-hygienic and fire safety across all production areas and facilities.

3. Use of safe production equipment that guarantees worker safety during installation and dismantling operations.

4. Rational arrangement of production equipment and workplaces, as well as organization of the production process in accordance with ergonomic requirements.

5. Development and application of optimal work and rest regimes, supported by strict adherence to production and labor discipline.

6. Use of raw materials, preparations, semi-finished products, and other inputs specified in project and technological regulations, which do not generate unforeseen risks for workers and do not contribute to hazardous or harmful conditions.

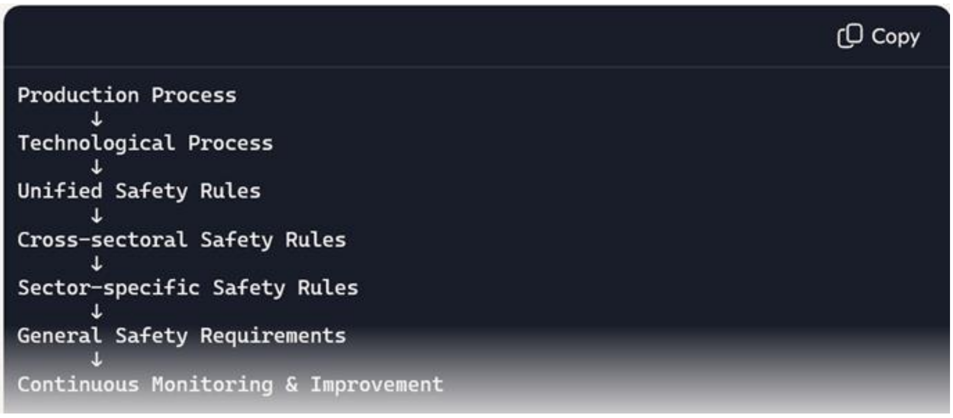


Fig. 1.8. Safety measures in production and technological processes according to occupational safety standards

7. Proper storage and warehousing of raw materials, preparations, semi-finished products, and finished goods in compliance with safety requirements, thereby eliminating risk.

8. Reasonable use of collective and individual protective equipment, aligned with the locations where harmful and hazardous factors may arise.

9. Identification, demarcation, and marking of hazardous zones within production.

10. Enhancement of workers' professional knowledge through instruction, training, internships, and selection of highly qualified personnel.

11. Application of effective monitoring methods and tools for the entire process or specific cycles.

12. Maintenance of buildings, structures, tools, and equipment in proper working condition throughout the production process.

In addition, the production process must not cause environmental pollution (air, soil, water), or must maintain it within permissible limits defined for such processes. Based on these principles, specific safety measures are developed for workplaces or professions within the given production process, taking into account the results of investigations into occupational injuries and diseases.

1.10. Research Methods in Occupational Safety

Research methods applied in occupational safety ensure a systematic approach to understanding and solving problems. They consist of various methods, techniques, and methodologies — that is, a research plan — which guarantee validity, accuracy, and reliability. The following methods are commonly used in occupational safety:

- **Observation** – direct collection of facts.
- **Comparison** – aligning data to identify differences and similarities. For example, comparing data from countries, regions, or individual facilities to highlight optimal outcomes, expand best practices, or avoid clearly negative approaches.
- **Experiment** – altering the conditions of ongoing processes to obtain or measure new results.

- **Statistical Analysis** – quantitative processing of data.
- **Modeling** – replacing a real process with a physical or mathematical model to enable preliminary risk assessment.
- **Scientific Analysis and Synthesis.**

Scientific Analysis involves breaking down a phenomenon or process into its constituent parts to better understand the properties, interconnections, and influences of each element. For instance, analyzing a specific incident allows identification of the factors that contributed to its occurrence.

Scientific Synthesis is the opposite process, in which collected data and observations are integrated into a comprehensive picture. Through synthesis, information from different sources is combined to support decision-making.

Scientific analysis is one of the most important research methods, providing in-depth evaluation of both theoretical and practical issues. It enables detailed structuring of complex processes and phenomena, identification of patterns, and formulation of conclusions based on clear logical and empirical foundations. This method is particularly significant in occupational safety, as it establishes the basis for identifying realistic risks and managing them effectively. It not only adds academic depth to research but also ensures the reliability and applicability of recommendations at the practical level.

Scientific analysis allows not only the systematization of factual data but also the identification of multifactorial risks, their quantitative and qualitative assessment, and forecasting. Accordingly, scientific analysis is not an auxiliary but a fundamental tool, without which the development and refinement of modern occupational safety standards would be impossible.

Research methods in occupational safety encompass both quantitative and qualitative approaches to evaluate risks, behaviors, and the effectiveness of safety policies. Let us examine in detail the scientific methods most frequently used in occupational safety and their objectives.

Quantitative Methods

These methods are based on statistical data and are used to assess risks, incident frequency, and the effectiveness of safety policies. Types of quantitative methods include:

- **Surveys and Questionnaires** – used to evaluate employees' knowledge, attitudes, and behaviors regarding safety issues.
- **Statistical Analysis** – analyzing data on incidents, accidents, and occupational diseases to identify trends and risk factors.
- **Monitoring and Measurements** – recording environmental conditions (e.g., temperature, noise, concentration of toxic substances) using specialized measuring instruments.

Qualitative Methods

Qualitative approaches focus on human factors, behaviors, and organizational culture.

- **Interviews and Focus Groups** – obtaining in-depth information about employees' experiences, perceptions, and safety culture.
- **Observation of Work Processes** – assessing behaviors and procedures in real work environments to identify potential hazards.
- **Case Analysis** – detailed study of a specific incident to determine causes and develop preventive measures.

Mixed Methods

When quantitative and qualitative approaches are combined, research becomes more complex and comprehensive.

- For example, after conducting statistical analysis of incidents, interviews may be carried out to uncover behavioral causes.

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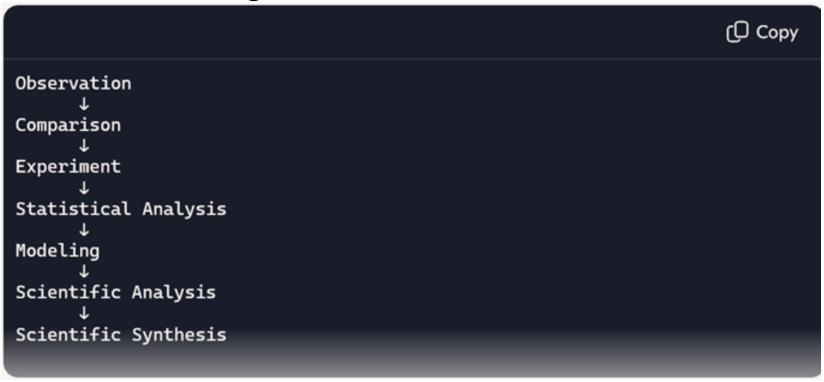


Fig. 1.9. Research methods applied in occupational safety

1.11. Methodological Map – Triangulation

The table below presents a methodological map indicating the priorities of research method application.

Table 1.1. Priorities of Research Method Application

Method	Application
Observation	Ergonomic, behavioral risks
Statistical Analysis	Incident frequency, trends
Modeling	Forecasting of physical and chemical risks
Interview	Psychosocial and organizational risks

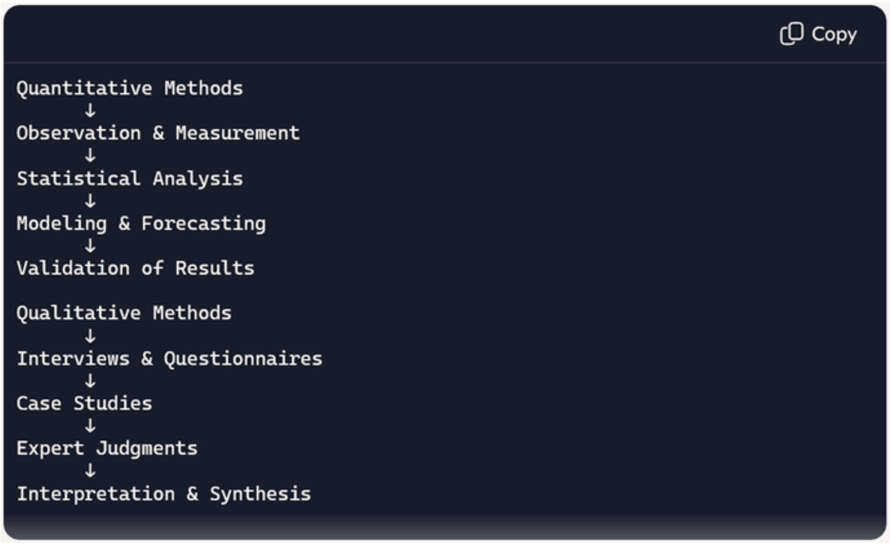


Fig. 1.10. Quantitative and qualitative methods applied in occupational safety research

To enhance the reliability of research, triangulation is often employed. Triangulation is defined as the combination of methods in the study of the same phenomenon, that is, the verification of data through different approaches (e.g., observation + interview + statistics). This provides a more objective and multifaceted picture.

Thus, triangulation involves studying the same phenomenon through multiple methods so that the results obtained are more objective, reliable, and comprehensive. Below is a specific example in the context of occupational safety.

Assessment of Chemical Risks in a Laboratory

- **Observation:** A safety specialist observes personnel behavior in real work processes — whether protective equipment is used and how chemical substances are stored.
- **Interviews:** Detailed interviews are conducted with staff to determine their perceptions and attitudes toward chemical risks.
- **Statistical Analysis:** Incident history is reviewed — how often chemical leaks, poisonings, or other cases have been recorded.

1.12. Detailed Modular Description of Research Methods

1. Observation

Used to assess behavioral and ergonomic risks. The researcher directly observes the work process, recording staff behaviors, postures, movement logic, and compliance with safety rules.

Application:

• Mining: identifying behavioral violations during wagon operation.
• Healthcare: evaluating staff behavior when moving patients.

2. Interviews

Focused on psychosocial and organizational risks. The researcher conducts in-depth interviews with employees to assess stress, fatigue, safety culture, and communication.

Application:

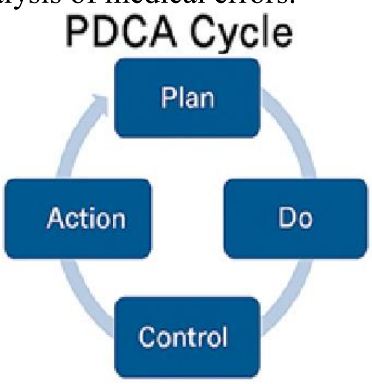
• Mining: evaluating perceptions of safety.
• Healthcare: analyzing the emotional burden of medical staff.

3. Statistical Analysis

Assesses incident frequency, trends, and risk factors. Used for quantitative processing of historical data.

Application:

• Mining: statistics on methane explosions.
• Healthcare: quantitative analysis of medical errors.



Visual Scheme 1.11. PDCA Cycle. Plan → Do → Control → Act
Used for continuous improvement in occupational safety systems, as emphasized in ISO 45001. Each stage supports feedback and refinement of safety measures

4. Modeling

Applied to forecast physical and technical risks. The researcher creates simulated scenarios to evaluate potential accidents or system failures.

Application:

• Mining: predicting tunnel collapses.
• Healthcare: modeling the spread of infection.

5. Triangulation

Combines multiple methods to increase data reliability — for example, observation + interview + statistics. This ensures objectivity and multidimensional analysis.

Application:

• Mining: assessment of chemical risks.
• Healthcare: multifaceted analysis of a clinical case.

6. Questionnaires and Surveys

Used to evaluate employees' knowledge, attitudes, and behaviors.

Application:

• Mining: assessing knowledge of personal protective equipment use.
• Healthcare: determining the level of knowledge of hygiene protocols.

7. Case Analysis

The researcher investigates a specific incident in detail to identify causes, procedural failures, and preventive measures.

Application:

• Mining: analysis of an explosion or collapse case.
• Healthcare: detailed analysis of a medical error.

8. Measurement Monitoring

Involves quantitative assessment of environmental conditions using specialized instruments.

Application:

• Mining: monitoring gas concentrations, temperature, vibration.
• Healthcare: measuring radiation levels, air sterility.

9. Experiment

The researcher alters the work environment or procedure to evaluate the effectiveness of new preventive measures.

Application:

• Mining: testing a new ventilation system.
• Healthcare: assessing the impact of a new disinfection protocol on infections.

1.13. Risk Typology:
Cross-Sectoral Parallels

In occupational safety research, risk typology makes it possible to identify both sector-specific and universal features. Despite the functional differences between healthcare and construction, risks in both sectors can be classified according to common categories, enabling cross-sectoral analysis. Similar opportunities exist in other industries as well, which can be practically useful. In our view, safety is such a fundamental value that its comprehensive and detailed discussion and analysis is never superfluous.

Hazardous and Harmful Production Factors

Production processes are accompanied by hazardous and harmful factors that cause or contribute to worker injuries and diseases.

- **A hazardous factor** is one that, when acting upon personnel, causes injury or a sharp deterioration in health.
- **A harmful factor** may be either a production factor or an environmental condition. In both cases, human work capacity is significantly reduced and health is damaged.

Prolonged exposure to harmful factors leads to irreversible processes and occupational disease.

Thus, hazardous production factors or processes cause injuries, while harmful production factors lead to occupational diseases. A harmful factor may, depending on its manifestation, be assessed as hazardous — in cases where it is characterized by high intensity or strength. Often, harmful factors contribute to injuries in the workplace.

Types of Hazardous and Harmful Factors (by cause or process): Physical; Chemical; Biological; Psychophysical.

- **Physical factors:** vibration; noise; high levels of ionizing radiation; abnormally high thermal radiation; high levels of electromagnetic radiation; high electrical field intensity; high magnetic field intensity; increased energy of light rays; high levels of ultraviolet or infrared radiation, etc.
- **Chemical factors:** dissemination of toxic, explosive, flammable, and poisonous substances used in technological processes into the production environment. These substances may also be intermediate or final products of the process.
- **Biological factors:** spread of microbes, phages, strains, and other biological agents in the production environment.
- **Psychophysical factors:** poor health, inadequate rest, violations of labor discipline, etc.

Methods of eliminating or mitigating the effects of harmful and hazardous factors vary according to type. Examples include ventilation, shielding, isolation, conditioning, filtration, deactivation, and others. Their essence, application areas, and operating principles will be discussed only fragmentarily, as they fall outside the scope of this manual.

The typology presented corresponds to the functional classification we proposed, according to which risks should be assessed by type and mechanism of action. Such a typological structure not only simplifies risk identification but also creates prerequisites for quantitative evaluation and the formulation of comparable indices.

Table 1.2. Risk Typology in Healthcare and Construction Sectors

Type	**Healthcare**	**Construction**
Clinical	Diagnostic error, medication risk	Technical defect, structural failure
Chemical	Anesthesia, disinfectants	Paints, concrete composition
Physical	Radiation, electromagnetic exposure	Working at height, heavy machinery
Psychological	Stress, fatigue	Workload, fear of safety risks
Financial	Budget overruns, funding risk	Project delays, cost escalation
Organizational	Lack of coordination, HR problems	Inconsistent work of contractors
Legal/Ethical	Patient rights, consent procedures	Violation of labor safety, absence of permits
Informational	Data protection, cybersecurity	BIM system security, project data leakage
Social/Cultural	Ethnic barriers, communication	Multilingual team, cultural disagreements

Cross-Sectoral Methodology of Risk Management. This methodology is based on systems analysis, which integrates quantitative and qualitative approaches. The aim of research is to establish a methodological framework that enables effective identification and management of both universal and sector-specific risks. Triangulation — the combination of different methods to study the same phenomenon — plays a particularly important role in this process, as it increases data reliability and depth of interpretation.

Circumstances Where Standardized Approaches Are Effective in Both Healthcare and Construction:

- Standardized processes: use of personal protective equipment, safety training, inspection protocols.

- Quantitative risk assessment: statistical analysis of incident frequency, accident rates, and financial losses.

- Integration of international standards: frameworks such as ISO 31000 and ISO 45001 ensure harmonization and structured monitoring.

In these conditions, universal indices such as the Security Integrated Index (SII) and the Impact Index (II) can be applied, enhancing the predictability and strategic dimension of risk management.

Cases Requiring Sector-Specific Approaches:

- Clinical decisions and technical construction: in healthcare, decisions are based on bioethical principles and patient conditions, while in construction they rely on engineering calculations and technical regulations.
- Ethical frameworks: patient consent procedures, confidentiality, and medical ethics differ from construction permits and labor regulations.
- Nature of risk sources: biological, chemical, and psychosocial risks in healthcare require different approaches compared to physical and technical risks dominant in construction.

Thus, sector-specific approaches are necessary where universal frameworks cannot provide sufficient accuracy, adequacy, or ethical compliance.

1.14. Formulas for Calculating Integrated Indices

Methane Release Index (MRI)

$$MRI = \frac{C_m \cdot F_e}{T_s \cdot R_p} \quad (1.2)$$

Purpose: To evaluate the intensity of methane release and the effectiveness of preventive mechanisms.

Where: C_m - methane concentration (%); F_e - monthly frequency of release (cases/month); T_s - response time of sensor systems (seconds); R_p - number of preventive measures (standard procedures).

Interpretation: The higher the MRI, the greater the risk. The index should be assessed dynamically, across different sites.

Pressure Stability Index (PSI)

$$PSI = \frac{S_r}{P_z \cdot D_f} \quad (1.3)$$

Purpose: To evaluate the structural stability of mines or shafts in high-pressure zones.

Where: S_r - stability rating (expert evaluation, scale 1–10; discussed in a separate paragraph below); P_z - pressure level (MPa); D_f - frequency of deformation per week (cases/week).

Interpretation: A high PSI indicates a stable zone. A low PSI requires additional reinforcement measures.

Transport Safety Index (TSI)

$$TSI = \frac{N_i}{V_t \cdot E_s} \quad (1.4)$$

Purpose: To evaluate the safety of transportation by wagons and conveyors.

Where: N_i - number of incidents during transportation; V_t - volume of transported load (tons/day); E_s - number of safety systems (protective mechanisms).

Interpretation: A low TSI indicates efficient transportation. A high TSI requires systemic review.

Enrichment Risk Index (ERI)

$$ERI = \frac{C_r \cdot T_p}{M_s \cdot Q_c} \quad (1.5)$$

Purpose: To evaluate technological and chemical risks in wet and dry enrichment processes.

Where: C_r - number of chemical reagents; T_p - process duration (minutes); M_s - number of safety monitoring systems; Q_c - frequency of product quality control.

Interpretation: A high ERI indicates increased technological risks. The index should be assessed separately for wet and dry enrichment processes.

1.15. Integrated Safety Index (SII)

Concept and Purpose

This section continues the previous discussion on the practical application of ISO standards. It introduces the Integrated Safety Index (SII), which consolidates different types of risks into a single cumulative figure. The index can be used for comparison, forecasting, and evaluation across various sectors.

Table 1.3. Integrated Safety Index for Healthcare

Risk Category	Frequency (0–10 scale), R_i	Weight (0–1 scale), w_i	$R_i \cdot w_i$
Physical Risks	7	0.25	1.75
Chemical Risks	5	0.20	1.00
Biological Risks	9	0.30	2.70
Psychosocial Risks	6	0.15	0.90
Ergonomic Risks	4	0.05	0.20
Technical/Mechanical Risks	3	0.05	0.15

Explanation of Columns:

***Column 1*:** Risks are classified and grouped according to their mechanism of action.

Column 2: Incident frequency is presented on a 0–10 scale. This scale is conditional and context-dependent.

- *Absolute scale:* 10 represents the maximum possible risk (e.g., mortality, systemic collapse).
- *Relative scale:* 10 represents the highest risk within a given environment (e.g., a specific clinic or mine).

- Frequencies are based on statistical or other objective data, such as annual averages, maxima, or multi-year datasets.

Column 3: Weights are determined by experts. Alternatively, weights can be calculated from frequency data using the formula:

$$w_i = \frac{R_i}{\sum_{j=1}^{n} R_j} \quad (1.6)$$

Where R_i is the frequency of incidents for a specific risk type, and $\sum_{j=1}^{n} R_j$ - the total frequency of all incidents.

7-step explanation regarding column 3:

Step 1 – How to determine weights.

- Weights are set on a 0–1 scale: Low (0.1–0.3), Medium (0.4–0.6), High (0.7–1.0). The sum of the assigned weights for all three categories must be equal to 1.
- Guiding questions: Does it affect life/health? → High; Process safety? → Medium; Efficiency/comfort only? → Low.

Step 2 – How to refine weights.

- If too many factors fall into one category, split Medium into Medium-Low (0.3–0.4) and Medium-High (0.6–0.7).
- Sector parallels: Mining → methane (Very High), dust (Medium), lighting (Low).

Step 3 – How to validate.

- Compare chosen weights with:
- Expert assessments → e.g., professional risk priority lists.
- Statistical data → frequency of accidents, incidents, or failures.
- If discrepancies are large, adjust. This ensures the index reflects actual risk severity.

Step 4 – When to stop.

- Practical limit: 5–7 categories.
- Fewer categories produce overly general results with low sensitivity.
- Too many categories make the process complex without a proportional gain in accuracy.
- Beginners: 3 categories are enough; advanced: up to 5. Beyond 7 loses practical value.

Step 5 – Practical usefulness.

- Categories build the floors, weights are the stairs leading upward.
- The student sees the whole structure and learns to distinguish details step by step.
- This process ensures clear prioritization and correct construction of Table 1.3.

Step 6 – Total weight limit.

- The sum of all weights $w_i = 1$.
- This is not an absolute truth, but a practical tool that helps in analysis and decision-making.
- It is easier to start with simple initial evaluations, and then their combination leads to a more balanced outcome, rather than relying solely on intuition without coefficients.

Step 7 – Resource for refinement.

- The result always has a resource for refinement.
- The first approximation provides an initial map, but the second or third may prove more accurate and better.
- Refinement is a natural part of the process, ensuring more reliable, pattern-based outcomes.

Final emphasis – Use of coefficients and application of results:

- Using coefficients based on individual indicators is more reliable than visual judgment alone.
- An inexperienced researcher will make fewer mistakes if each factor is assigned a numerical coefficient.

• Coefficients increase accuracy, provide better analytical opportunities, and preserve a resource for refinement.

Applications of results:

- Risk prioritization.
- Resource allocation.
- Safety policy planning.
- Creation of practical examples in education.
- Verification of compliance with international standards.

Column 4: The Integrated Safety Index is calculated as

$$SII = \sum_{i=1}^{n} R_i \cdot W_i \tag{1.7}$$

Where SII is the integrated security index; R_i — risk frequency (0–10); W_i— risk weight (0–1).

Interpretation: The cumulative value $SII = 6.70$ indicates that the overall risk level in healthcare is above average.

Applications of SII:

- Comparing different clinics.
- Analyzing the effectiveness of preventive policies.
- Cross-sectoral comparison (e.g., with mining operations).
- Forecasting risk trends (increase or decrease).
- Identifying priorities (which category requires more active management).

Table 1.4. Integrated Safety Index for Mining

Risk Category	**Frequency (0–10 scale),** R_i	**Weight (0–1 scale),** w_i	$\boldsymbol{R_i \cdot w_i}$
Physical Risks	8	0.30	2.40
Chemical Risks	6	0.20	1.20
Biological Risks	3	0.10	0.30
Psychosocial Risks	5	0.15	0.75
Ergonomic Risks	7	0.15	1.05
Technical/Mechanical Risks	6	0.10	0.60

Comparative Analysis:

• The cumulative SII for mining, based on Table 1.4, can be directly compared with the healthcare SII (Table 1.3).

• Mining shows higher contributions from physical and ergonomic risks, reflecting the demanding and hazardous nature of underground operations.

• Healthcare, by contrast, demonstrates greater influence from biological risks, consistent with exposure to pathogens and clinical environments.

• Both sectors share psychosocial risks, though their manifestations differ (stress and fatigue in healthcare vs. workload and safety concerns in mining).

• Technical/mechanical risks are present in both, but their weight and frequency vary according to sector-specific processes.

Interpretation: The comparison of Tables 1.3 and 1.4 illustrates how the Integrated Safety Index (SII) enables:

• Cross-sectoral evaluation of cumulative risk levels.

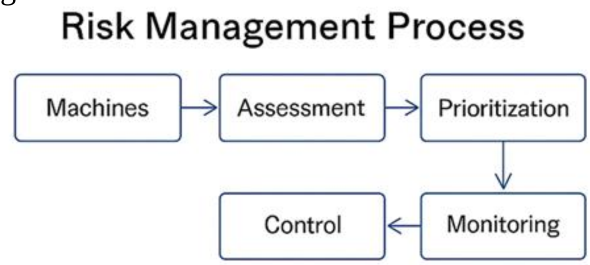
• Identification of dominant risk categories in each sector.

• Strategic prioritization of preventive measures tailored to sector-specific conditions.

Additional Considerations on Weights

Although objective statistical data can be used to calculate weights, expert-based weights are equally important. The rationale for introducing expert weights is as follows:

1. **Data are not the full reality.** Historical data reflect what has already occurred, but not what may occur. For example, if no technical accident has been recorded in a clinic, its statistical weight would be zero — yet the risk still exists. Experts can anticipate potential hazards that have not yet materialized.
2. **Data may be incomplete or distorted.** In small clinics, the number of incidents may be low, but the risk remains high. Some risks (e.g., psychosocial pressure) are often under-reported or not systematically recorded. Expert judgment fills these gaps.
3. **Strategic priorities.** An organization may decide to prioritize ergonomic risks, even if statistically fewer incidents are recorded. Expert weights reflect policy, prevention focus, and strategic vision.



Visual Scheme 1.12. Risk Management Process
Flowchart: Machines → Risk Assessment → Prioritization → Monitoring → Control. This process illustrates how hazards are systematically managed from identification to mitigation

4. **Multi-criteria evaluation.** Statistical data often capture only frequency. Experts, however, assess multiple dimensions: frequency, severity, detectability, and prevention potential. This holistic perspective cannot be derived from raw data alone.

Conclusion. Expert-based and data-based weights do not compete; rather, they complement each other.

- **Data-based weights** ensure objectivity and quantitative rigor.
- **Expert-based weights** incorporate foresight, policy priorities, and contextual depth.

Together, they provide a balanced foundation for calculating the Integrated Safety Index (SII).

Influence Index (II)

Alongside the cumulative Integrated Safety Index (SII), the Influence Index (II) is used in scientific practice to evaluate the impact of individual risk categories.

$$II_i = R_i \cdot W_i \quad (1.8)$$

Where: II_i - Influence Index for a specific risk category; R_i - frequency of incidents (0–10 scale); W_i - weight (0–1 scale).

Table 1.5. Difference Between Influence Index (II) and Cumulative Index (SII)

Characteristic	Influence Index (II_i)	Cumulative Index (SII)
Content	Combines frequency and weight for each category	Sum of all $R_i \cdot W_i$ across categories

Formula	$II_i = R_i \cdot W_i$	$SII = \sum_{i=1}^{n} R_i \cdot W_i$
Purpose	Evaluates the impact of each risk category	Provides the overall systemic risk level
Application	Comparison of categories, prioritization	Cross-sectoral comparison, forecasting, strategic analysis
Application	Biological risk: $II = 9 \cdot 0.3 = 2.7$	Sum of all II values: $SII = 6.70$

Interpretation

- The **Influence Index (II)** highlights the relative importance of each risk category.
- The **Integrated Safety Index (SII)** aggregates all categories into a single systemic measure.
- Together, they provide both **granular insights** (II) and **holistic evaluation** (SII).

The interpretation of the range of change of the integrated (total) security index SII by sector is given in Table 1.6, which should be considered as a table of actions.

Table 1.6. Indicative Numerical Ranges of the Integrated Safety Index (SII)

Risk Level	Mining	Construction	Healthcare	Digital Technologies
Low	R < 1.0	R < 0.8	R < 0.5	R < 0.3
Medium	1.0 ≤ R < 2.0	0.8 ≤ R < 1.5	0.5 ≤ R < 1.0	0.3 ≤ R < 0.7
High	2.0 ≤ R < 3.5	1.5 ≤ R < 2.5	1.0 ≤ R < 2.0	0.7 ≤ R < 1.5
Critical	R ≥ 3.5	R ≥ 2.5	R ≥ 2.0	R ≥ 1.5

Interpretation of Frequency and Scaling:

- When quantitative data are available, the maximum number of incidents is set as the benchmark. For example, if five toxic leaks represent the maximum, this is rated as 10 points on the 0–10 scale. Other risks are proportionally converted.
- When quantitative data are not available, expert evaluation is used to estimate the maximum. Several experts may provide ratings, and averages can be used.

Table 1.7. Comparative Analysis of Risk Frequency Sources

Method	Description	Advantage	Limitation
Statistical	Historical data	Objectivity	Sometimes insufficient
Predictive	Modeling, simulation	Scenario-specific	Dependent on assumptions
Expert	Interviews, focus groups	Contextual depth	Subjectivity

Practical Management of Approximation:

- Transparency — always indicate whether data are modeled or expert-based.
- Sensitivity Analysis — test different scales (0–10, 0–8, etc.) to refine accuracy.
- Interval Approach — use ranges (average, minimum, maximum, or mean ± standard deviation).
- Documentation — record how maxima were defined and which sources were used.

Table 1.8. Illustration of Expert-Defined Weights

Category	Weight in Mining	Weight in Healthcare
Physical Risks	0.30	0.15

Chemical Risks	0.20	0.25
Biological Risks	0.10	0.30
Psychosocial Risks	0.10	0.15
Ergonomic Risks	0.10	0.05
Technical/Mechanical Risks	0.20	0.10
Total	**1.0**	**1.0**

Interpretation:

- Expert weights highlight sector-specific priorities: biological risks dominate in healthcare, while physical and technical risks dominate in mining.
- This methodology supports systemic analysis (SISAN), enabling both cross-sectoral comparison and prioritization of specific risks.

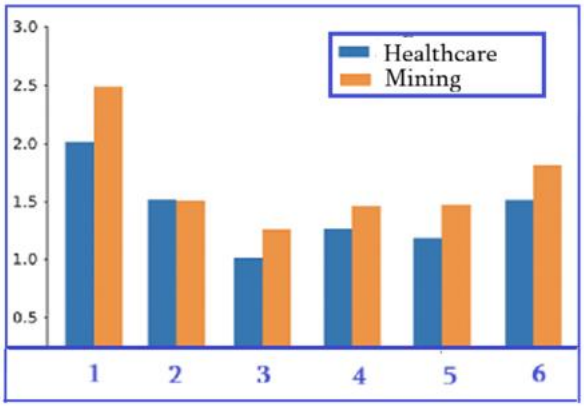


Fig. 1.13. Variation of the Integrated Safety Index (*SII*) in healthcare and mining by risk category: 1 – Physical; 2 – Chemical; 3 – Biological; 4 – Psychosocial; 5 – Ergonomic; 6 – Technical/Mechanical.

Final Remarks on 1.15:

- Indices differ significantly across sectors, reflecting unique risk profiles and data structures.
- Cross-sectoral approaches are effective for standardized, quantifiable hazards, especially under ISO frameworks (ISO 31000, ISO 45001).
- Sector-specific approaches are essential for ethical, clinical, and technical details where universal models lack precision.
- The Integrated Safety Index (*SII*) and Influence Index (*II*) are strategic tools that enhance predictability, prioritization, and resilience in risk management.

1.16. Collective and Individual Means of Protection

General Distinction:

According to their mode of application, protective means are divided into collective and individual.

- Collective means protect two or more persons simultaneously.
- Individual means protect a single worker.

ISO 45001 explicitly emphasizes the priority of collective protective measures, while individual protective equipment serves only as supplementary support.

Collective Protective Means are classified into two main categories: objective and subjective.

Objective Means of Protection:

- Operate independently of personnel and create a safe working environment.
- Examples include: air quality regulation, workplace lighting, noise and vibration control, protection against electric shock, mechanical, chemical, and biological hazards, establishment of restricted zones, green buffer areas separating industrial and residential zones.
- Their effectiveness must not depend on human experience or qualifications.
- Typical objective means: enclosures, barriers, isolation, ventilation, conditioning, heating, protective grounding, noise suppression, vibration damping.

Reliability Requirements. Design, manufacture, and operation of objective means must account for possible failures that could initiate accidents. Reliability is characterized by:

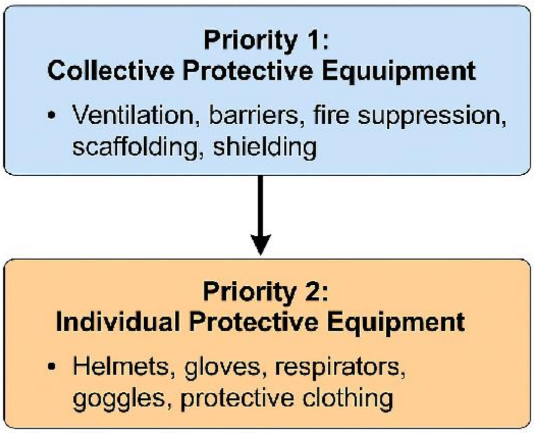
- Durability — ability to maintain functionality throughout its service life.
- Maintainability — ability to restore protective function after maintenance or repair.
- Low Failure Rate — minimizing dangerous malfunctions.

Critical elements may require duplication or automatic shutdown systems to prevent unsafe operation.

Subjective Means of Protection.

Their effectiveness depends on personnel's perception and behavior.

- Examples: warning signs, posters, sound and light signals, control and monitoring devices.
- Automatic control and signaling systems assist personnel in monitoring pressure, temperature, voltage, fluid levels, etc. Hazardous levels are marked in red; alarms are triggered when thresholds are exceeded.



1.14. Collective and Individual Means of Protection

- Posters are categorized as:

1. Prohibitive (Do not work without grounding, do not smoke).
2. Warning (Caution: oversized load, Avoid trains).
3. Indicative (Fire exit, medical station).

Color Coding

Conditional coloring ensures consistent human reaction:

- Red — prohibitive signals, emergency indicators.
- Electrical phases: A – yellow, B – green, C – red.
- Pipelines: water – green, steam – red, air – blue, natural gas – red.
- Cylinders: oxygen – blue with black inscription; CO_2 – black with yellow inscription.

Correct and timely reaction to subjective means (signals, posters, instruments, color coding) prevents accidents and injuries. However, factors such as fatigue, noise, poor health, inadequate lighting, or information overload may reduce effectiveness [6, 13, 15-19].

Individual Protective Means.

Special clothing, footwear, and equipment (e.g., protective suits, goggles, earplugs, masks) are considered property of the organization.

- Must be returned upon termination of employment.
- If worn out before the prescribed period without worker fault, they must be replaced or renewed.
- Reusable items must undergo sanitary treatment before re-issue.
- If the organization fails to provide equipment, workers may purchase it themselves and claim reimbursement under labor law.
- The administration is responsible for storage, cleaning, drying, disinfection, deactivation, and repair of protective equipment.

Protective clothing and footwear vary by sector, designed to shield the body from harmful natural or artificial environmental factors.

Conclusion

This paragraph, together with Sections 1.2–1.6 and related notes, forms a global framework for the manual. After studying hazards and risks, subsequent chapters will discuss effective methods of mitigation through the use of collective and individual protective means.

Collective Protective Equipment (CPE):

Collective protective equipment refers to technical and organizational measures designed to protect groups of workers simultaneously. These measures are prioritized in occupational safety standards because they provide systemic protection and reduce risks at the source. Examples include:

- Ventilation and air purification systems.
- Noise reduction barriers and acoustic insulation.
- Safety nets, guardrails, and scaffolding in construction.
- Automatic fire suppression systems.
- Radiation shielding and protective enclosures.

Individual Protective Equipment (IPE):

Individual protective equipment refers to personal devices and tools used by workers to protect themselves from specific hazards. These are supplementary measures, applied when collective protection is insufficient or cannot fully eliminate risks. Examples include:

- Helmets, gloves, and protective footwear.
- Respirators and gas masks.
- Earplugs and earmuffs.
- Safety goggles and face shields.
- Specialized clothing (chemical-resistant suits, reflective vests).

Principle of Priority:

Occupational safety standards (ISO 45001, ILO conventions) emphasize that collective protective equipment must always be prioritized over individual protective equipment. Collective measures eliminate hazards at the source, while individual measures only reduce exposure. Therefore, organizations must first implement collective solutions and then provide personal equipment as complementary protection.

1.17. Application of Risk Index

Healthcare — Infection spread.

Problem statement:

In a clinic, 12 cases of infection spread were recorded. Calculate the risk index. The results of solving the task are given in Table 1.9.

Table 1.9

Incident	Cases	Severity, *S*	Probability, *P*	Weight, *W*	Risk Index, *R*
Infection spread	12	4	0.30	1.00	1.20

How we got here:

- Severity=4 (serious, not catastrophic; scale 1–5).
- Probability=0.30 (0–1 scale; frequent but not constant; 12 cases suggest mid-level occurrence. 0.50 would imply every second case, which is not supported here).
- Weight=1.00 (single category).
- Risk Index = 0.30 × 4 = 1.20.

Application:

Prevention, monitoring, standards, training.

Construction — Falls, equipment failure, chemical exposure.

Problem statement:

7 falls from height, 5 equipment failures, 3 chemical exposures. The results of solving the task are given in Table 1.10.

Table 1.10

Incident	Cases	Severity, *S*	Probability, *P*	Weight, *W*	Risk Index, *R*
Fall from height	7	5	0.15	0.47	0.75
Equipment failure	5	4	0.10	0.33	0.40
Chemical exposure	3	3	0.05	0.20	0.15

How we got here:

- Severity: 5, 4, 3 based on impact.
- Probability: 0.15, 0.10, 0.05 — oriented by frequency (rare to more frequent).
- Weight: normalized by cases (7/15, 5/15, 3/15).
- Risk Index: R = P × S.

Application:

PPE, protocols, inspections, on-site response.

Transport — Tunnel fire.

Problem statement:

4 tunnel fire incidents. The results of solving the task are given in Table 1.11.

Table 1.11

Incident	Cases	Severity, *S*	Probability, *P*	Weight, *W*	Risk Index, *R*
Tunnel fire	4	5	0.20	1.00	1.00

How we got here:

Severity=5 (catastrophic potential), Probability=0.20 (rare but real), Weight=1.00, Risk Index=1.00.

Application:

Pre-entry checks, sensors, CCTV, mandatory checklists.

Energy — Power plant fire.

Problem statement:

6 fire incidents at a power plant. The results of solving the task are given in Table 1.12.

Table 1.12

Incident	**Cases**	**Severity,** S	**Probability,** P	**Weight,** W	**Risk Index,** R
Power plant fire	6	5	0.25	1.00	1.25

How we got here:

Severity=5, Probability=0.25 (selected within 0.20–0.30 band as reasonable), Weight=1.00, R=1.25.

Application:

Fire systems, inspections, response teams.

Digital technologies — Cyberattack, software fault, network outage.

Problem statement:

8 cyberattacks, 4 software faults, 3 network outages. The results of solving the task are given in Table 1.13.

Table 1.13

Incident	**Cases**	**Severity,** S	**Probability,** P	**Weight,** W	**Risk Index,** R
Cyberattack	8	5	0.27	0.53	1.35
Software fault	3	3	0.10	0.20	0.30
Network outage	4	4	0.13	0.27	0.52

How we got here (no secrets):

- Severity: 5/3/4 on a 1–5 scale based on impact.
- Probability: oriented estimates reflecting frequency, not direct proportions. Totals (8/15, 4/15, 3/15) were used for weights; probabilities (0.27, 0.13, 0.10) are reasonable, interpretable values indicating often, less often, rare. A global orientation level ≈ 0.30 can be communicated to students as a non-exact, guiding benchmark since none of the individual probabilities are catastrophic.
- Weight: normalized by case counts; sum = 1.
- Risk Index: $R = P \times S$.

ISO 31000 Risk Management Framework requires that risk evaluation combine both probability (P) and severity (S). Probability alone is insufficient, because even rare events may have catastrophic consequences. Severity alone is incomplete, because frequent minor events may accumulate into systemic risk. Therefore, ISO 31000 emphasizes the integrated formula $R = P \times S$, which ensures that organizations prioritize risks not only by likelihood but also by potential impact.

1.18. Checklist for selecting indices

1. Severity, S:
Always selected from the range 1–5.
1 → insignificant outcome, 5 → catastrophic outcome.
The selection is made according to the severity of the outcome (for example, loss of life = 5).
2. Probability, P:
Range 0–1.
The selection is made according to the frequency of occurrence.
The value is indicative, reflecting the levels of rare, medium, frequent.
For example: 0.05 → rare, 0.30 → frequent, 0.50 → every other, 0.70–1.00 → constant.
3. Weight, W:
Taken from the number of occurrences.
Normalized so that the sum of the weights of all categories is always 1.
If there is only one category, the weight automatically = 1.
4. Risk index, R:
Calculated by the formula: $R = P \times S$
The product shows the level of risk.

ISO 45001 requires that indices be selected according to the specific characteristics of the workplace. Indices must not only reflect statistical data but also capture real operational risks. For example, ISO 45001 emphasizes that indices should cover technical, organizational, and psychosocial hazards, ensuring that preventive policies are comprehensive. This aligns with **ISO 31000's** principle that risk management must be tailored to context and objectives.

2. Occupational Injuries and Occupational Diseases

2.1. Guide to Chapter II

Theoretical Integration:
• The material presented in Chapter II demonstrates, through practical examples, how risks are realized in the production process.
• Occupational injuries and occupational diseases represent the outcomes of risks, requiring both analysis and management.
Integration with Standards:
• ISO 45001 requirement: identification of workplace risks and implementation of preventive policies.
• ISO 31000 framework: methods of analyzing injuries (statistical, monographic, topographic) as instruments of risk analysis.
General Integration:

• This section provides readers with the opportunity to apply analytical methods to real cases.

• The following short notes highlight the correspondence of specific points with ISO standards:

• Hazardous and harmful factors → Note: ISO 45001 requires identification and classification of workplace risks.

• Methods of injury analysis (statistical, monographic, topographic) → Note: These methods correspond to ISO 31000's framework for risk analysis and evaluation.

• Rules for providing first aid → Note: ISO 45001 emphasizes employee involvement and the standardization of safety procedures.

• Work capacity and fatigue → Note: ISO 45001 includes management of psychosocial risks such as fatigue and stress.

```
Production Process Risks
      ↓
Occupational Injuries & Diseases
      ↓
Analysis & Management
      ↓
Integration with ISO 45001 (Risk Identification, Preventive Policy)
      ↓
Integration with ISO 31000 (Statistical, Monographic, Topographic Methods)
      ↓
Pedagogical Application (Real Cases, Practical Use)
```

Fig. 2.1. Integration of occupational risks with ISO standards and pedagogical application

2.2. Definition of Concepts

In the production process, workers may suffer two types of harm: a. Occupational injury; b. Occupational disease.

An occupational injury occurs suddenly as a result of hazardous production conditions. By contrast, an occupational disease develops gradually over time, caused by harmful factors of production, technology, or the environment.

Occupational injury is defined as an accident occurring in the workplace during the performance of official duties. It also includes injuries sustained during overtime work, while eliminating the consequences of natural disasters, during business trips, or while commuting to and from work using enterprise transport.

The causes of occupational injuries may be classified as:

1. Technical violations – malfunctioning machinery, design defects, imperfect technological processes, insufficient mechanization or automation, and other technical deficiencies.

2. Sanitary-hygienic shortcomings – deviations in air parameters (temperature, humidity, composition, velocity), insufficient lighting, lack of sanitary facilities, etc.

3. Organizational faults – overtime work, improper organization of loading/unloading operations, inadequate instruction, violation of safety rules, insufficient provision of protective clothing and equipment, absence of warning signs and posters.

4. Psychophysical factors – violation of labor discipline, fatigue, poor health, impaired vision or hearing, alcohol consumption in the workplace, intentional self-injury, and similar issues.

Occupational injuries may be classified by severity:

- Minor – the worker retains work capacity (e.g., scratches, bruises).
- Moderate – temporary loss of work capacity for 1–3 days.
- Severe – partial or complete disability.
- Fatal – death of the worker.

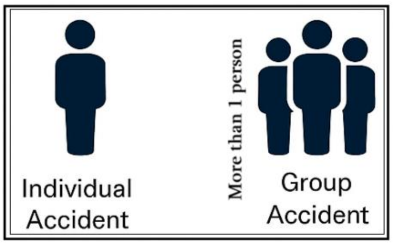


Fig. 2.2. Classification of cases of traumatism and occupational disease

Occupational disease is the result of prolonged exposure to harmful production or environmental conditions. Such exposure may include vibration, noise, toxic gases, dust, radiation, and other factors. Occupational diseases are usually chronic. Examples include vibration disease, pneumoconiosis, joint disorders, dermatitis, bursitis, and others.

In practice, acute occupational diseases also occur. These resemble injuries in nature and manifestation, developing suddenly (within a single shift) due to high doses of harmful substances or radiation. Exposure may occur through the respiratory tract, vision, skin, or gastrointestinal system. Examples include poisoning by chlorine, carbon monoxide, or nitrogen oxides, and eye damage from ultraviolet radiation during welding.

When more than one person is affected, the case is classified as a group occupational disease. Similarly, accidents involving multiple individuals are considered group injuries.

2.3. Hazardous and Harmful Production Factors

Production processes are accompanied by hazardous and harmful factors that cause injuries and diseases among workers or contribute to their occurrence.

A hazardous production factor is one that, when acting upon personnel, results in injury or a sharp deterioration of health. A harmful factor may originate either from the production process or from the environment. In both cases, human work capacity is significantly reduced and health is damaged. Prolonged exposure to harmful production factors leads to irreversible processes and the development of occupational diseases.

Thus, hazardous production factors or processes cause injuries, while harmful production factors cause occupational diseases.

A harmful factor may, depending on its manifestation, be assessed as hazardous. In such cases, the harmful factor is characterized by high intensity or strength. Frequently, harmful factors contribute to injuries in the workplace.

According to their origin or nature, hazardous and harmful production factors are classified into the following categories:

Physical, Chemical, Biological, Psychophysical.

Physical factors include vibration; noise; high levels of ionizing radiation; abnormally high levels of thermal radiation; high levels of electromagnetic radiation; high voltage of electric fields; high intensity of magnetic fields; increased energy of light rays; high levels of ultraviolet or infrared radiation, and others.

Chemical factors arise from the spread of various toxic, explosive, flammable, and poisonous substances in the production environment. These substances may also be the final or intermediate products of technological processes.

Biological factors include the spread of various microbes, phages, strains, and similar agents in the production environment.

Psychophysical factors include poor health, inadequate rest, violation of labor discipline, and similar conditions.

The methods of eliminating or reducing the impact of hazardous and harmful production factors differ according to their type.

Among these methods are ventilation, shielding, isolation, air conditioning, filtration, deactivation, and others. Their essence, scope of application, and principles of operation will be discussed within the framework of this manual.

2.4. Methods of Analyzing Occupational Injuries

The following methods are used to analyze cases of occupational injuries: 1. Statistical; 2. Monographic; 3. Topographic; 4. Technical; 5. Economic.

1. Statistical Method

This method involves processing injury data to determine various indicators (coefficients).

- **Frequency coefficient of injuries** for a given calendar period (e.g., one year), calculated per 1000 workers, is defined by the formula

$$K_1 = \frac{1000N}{n} \quad (2.1)$$

where K_1 is the injury frequency coefficient for the enterprise during the specified period; N is the total number of accidents in that period; n is the number of employees in the enterprise. The minimum value of the coefficient is 0 ($K_1^{min} = 0$.). This coefficient allows assessment of the dynamics of occupational injuries within the enterprise and comparison of similar indicators across different enterprises.

For smaller enterprises, the frequency coefficient is calculated per 100 workers, replacing 1000 with 100 in the formula. This practice is common and should not cause confusion when comparing data in the literature.

- **Severity coefficient of injuries** is defined by the formula

$$K_2 = \frac{D}{N} \quad (2.2)$$

where K_2 is the severity coefficient; D is the total number of lost workdays due to injuries. The minimum value is 1 ($K_2^{min} = 1$).

- **General injury coefficient** is calculated by multiplying the frequency and severity coefficients

$$K_3 = K_1 K_2 \tag{2.3}$$

Its minimum value is 0 ($K_3^{min} = 0$).

- **Coefficient of disability or fatality percentage** is defined by the formula

$$K_4 = \frac{T}{N} 100 \tag{2.4}$$

where K_4 represents the percentage of disabled or deceased workers; T is the total number of disabled and deceased individuals. The minimum value is 0 ($K_4^{min} = 0$).

- **Average number of injured workers per 1000 employees** is calculated by the formula

$$K_5 = 1000 \frac{P}{N} \tag{2.5}$$

where K_5 is the average number of injured workers per 1000 employees; P is the number of injured workers resulting from N accidents.

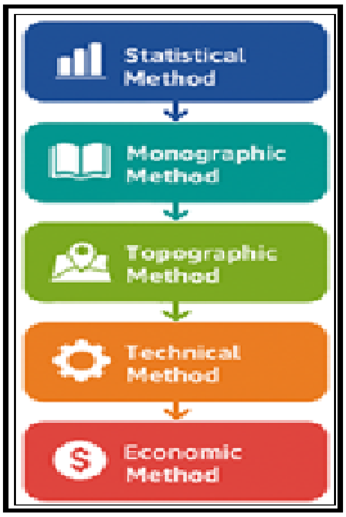


Fig. 2.3. Methods of analyzing occupational injuries according to ISO standards

A special form of the statistical method is the **group method**, in which cases are ranked (grouped) according to characteristic features. This highlights significant factors or their combinations, making it possible to select preventive measures more purposefully.

2. Monographic Method

Derived from the Greek words monos (one) and grapho (to write), this method involves a comprehensive study of a single indicator related to labor. Monographic analysis is usually carried out by specialists of different profiles working together. For example, it may examine work techniques for a specific operation or the use of a particular tool, assessing the safety of applied methods.

Based on results, recommendations can be made — for instance, that electrical tools equipped with protective grounding are safer to use. The purpose of monographic analysis is to evaluate the causes of accidents and develop measures to prevent them.

3. Topographic Method

Derived from the Greek words topos (place) and grapho (to write), this method involves marking accident locations on a graphical representation of the enterprise's territory (scheme, drawing, or map). When sufficient data are available, the most hazardous areas of the enterprise become evident.

The topographic method can be applied both to the enterprise plan (horizontal section) and to vertical sections.

4. Technical Method

This method involves the calculation and testing of technical means, the results of which determine the most reliable equipment and tools. The technical means to be tested may include passive and active fire protection systems, machines, mechanisms, tools, and both individual and collective protective equipment.

5. Economic Method

This method evaluates the economic consequences of occupational injuries, demonstrating to employers the economic attractiveness of safe working conditions through the use of new technologies, equipment, and safety measures. Conversely, if analysis shows that injuries are not economically disadvantageous for the employer, it may indirectly indicate that national legislation is not sufficiently oriented toward ensuring safe working conditions for employees.

Connection to ISO Standards

The methods discussed are directly linked to the requirements of ISO 31000 and ISO 45001:

- **Statistical Method** → Provides quantitative risk assessment (ISO 31000).
- **Monographic Method** → Reflects context-specific approaches (ISO 31000).
- **Topographic Method** → Relates to hazard identification in the workplace (ISO 45001).
- **Technical Method** → Corresponds to verification of control measures (ISO 45001).
- **Economic Method** → Demonstrates the value of safe working conditions (ISO 31000).

When mastering this material, it is important to follow the methodological line connecting the analysis methods with ISO 31000 and ISO 45001:

- Statistical method corresponds to ISO 31000's requirement for risk identification and evaluation. Statistical coefficients (K_1–K_5) create a quantitative basis used within ISO 45001 for monitoring workplace safety.
- Monographic method corresponds to ISO 31000's context-specific approach. Detailed study of a process or tool supports ISO 45001's preventive measures.
- Topographic method corresponds to ISO 45001's requirement for hazard identification in the workplace. Marking accident locations provides visual data integrated into ISO 31000's systematic analysis.
- Technical method corresponds to ISO 45001's technical control measures. Testing technical means ensures the effectiveness of ISO 31000's risk management measures.
- Economic method corresponds to ISO 31000's achievement of strategic objectives. Economic analysis demonstrates the value of safe working conditions and ISO 45001's employer responsibility.

Table 2.1. Summary of Analysis Methods, Their Application, and Research Value

Method	Application Area	Research Value
Statistical	Quantitative analysis of injury data	Creates a quantitative basis for risk indices
Monographic	Detailed study of a specific process/tool	Provides context-specific recommendations

Topographic	Identification of hot spots in the workplace	Graphical marking of accident locations
Technical	Testing of technical means	Verifies reliability of control measures
Economic	Economic evaluation of injury	Demonstrates economic effectiveness of safety

ISO 31000 requires quantitative bases for risk management. Statistical coefficients (K1–K5) provide measurable indicators of frequency, severity, and overall injury rates. This aligns with ISO 31000's principle that risk analysis must be systematic, comparable, and predictive, enabling organizations to monitor trends and implement preventive measures.

2.5. Investigation and Reduction of Injury Cases

The risk index model $R = PxS$ discussed in Chapter I is applied in practice to the results of Chapter II. For example, statistical coefficients (K_1–K_5) can be integrated into the calculation of the index: K_1 reflects the probability of occurrence (P), while K_2–K_4 represent the severity of consequences (S). Thus, injury analysis creates a data base that is transformed into risk indices in accordance with ISO standards.

The investigation of injury causes is carried out both to provide assistance to victims and to analyze contributing factors, with the aim of eliminating causes and preventing future injuries.

Investigation begins with employee notification. According to the Law of Georgia on Occupational Safety, employees are obliged to inform the employer of any accident occurring in the workplace, whether involving themselves or others, provided their health condition allows them to do so.

Fig. 2.4. Investigation process and reduction measures for occupational injuries

Employer obligations include:

- Taking immediate measures to preserve the life and health of the injured person.
- Preserving the accident site unchanged until investigative authorities arrive, except when necessary to protect the victim's health. In such cases, the employer must accurately describe the situation to facilitate investigation.
- Notifying within 24 hours:

- Employee unions and occupational safety representatives;
- Law enforcement authorities if criminal activity is suspected;
- Supervisory authorities in cases of severe, fatal, or mass accidents.
- Recording the incident and establishing an investigative commission composed of: the injured employee or their representative; an occupational safety representative; a trade union representative; an occupational safety specialist; and, if necessary, the employer who assigned the worker [20, 21].
- Informing the employer of an external person if the accident involves them.
- Preserving evidence for the following periods: medium severity (5 years); severe (7 years); fatal (10 years); mass accidents (15 years).

The employer must ensure that all relevant individuals are interviewed as deemed necessary by the commission. Instructions issued by supervisory authorities based on the investigation report are mandatory for the employer.

ISO 45001 requires that investigation processes actively involve workers and their representatives, ensuring transparency and collective responsibility. ISO 31000 complements this by requiring continuous monitoring and improvement, meaning that every investigation must feed back into the risk management cycle.

Investigation deadlines:

- Medium severity – within 10 calendar days.
- Severe – within 15 calendar days.
- Fatal – within 7 calendar days.
- Mass accidents – within 30 calendar days.

These deadlines may be doubled if all commission members sign and justify the decision.

In cases of medium severity, severe, fatal, and mass accidents, the commission may request:

- Involvement of experienced specialists as experts.
- Special laboratory studies.
- Drawings, diagrams, plans, or photographs of the accident site.
- Provision of protective clothing and equipment for commission members and experts.

Medical institutions issue health certificates for victims according to schemes developed by the Ministry.

At the conclusion of the investigation, a formal report must be prepared and signed by all commission members, who may also record dissenting opinions. The report must include:

- Drawings, diagrams, plans, photographs, and other documentation of the accident site.
- Certificates of occupational safety training or other relevant knowledge of the victim.
- Statements from witnesses and the victim.
- Expert conclusions, if applicable.
- Laboratory analyses and research results, if applicable.
- Medical conclusions regarding the victim’s health condition.
- Documentation of personal protective equipment provided to the victim.
- Supervisory authority instructions, if applicable.
- Any other documents deemed necessary by the commission.

The commission must submit the report and attached documents to the supervisory authority, the victim, and commission members within 5 working days of completing the investigation.

Reduction of Occupational Injuries

Reduction of occupational injuries can be achieved through:

- Organizational and technical measures;
- Sanitary and hygienic measures;
- Medical and preventive measures;
- Strict compliance with occupational safety norms;
- Improvement of production technology;
- Automation of production processes and compliance monitoring;
- Use of personal protective equipment, special clothing, and footwear;
- Compliance with standards for noise, lighting, and microclimate parameters;
- Training in occupational safety and development of appropriate skills among personnel;
- Certification of production facilities to verify compliance with occupational safety requirements.

2.6. Investigation of occupational disease cases

General approach to investigation

Occupational disease cases can be investigated using the same methods employed for accident analysis. Therefore, the methods discussed in Section 2.3 apply here: 1) statistical, 2) monographic, 3) topographic, 4) technical, 5) economic — and we will not dwell on them further. It must be remembered that injuries and occupational diseases manifest differently. The Law of Georgia On Occupational Safety defines the procedures for registration, investigation, and reporting of occupational diseases.

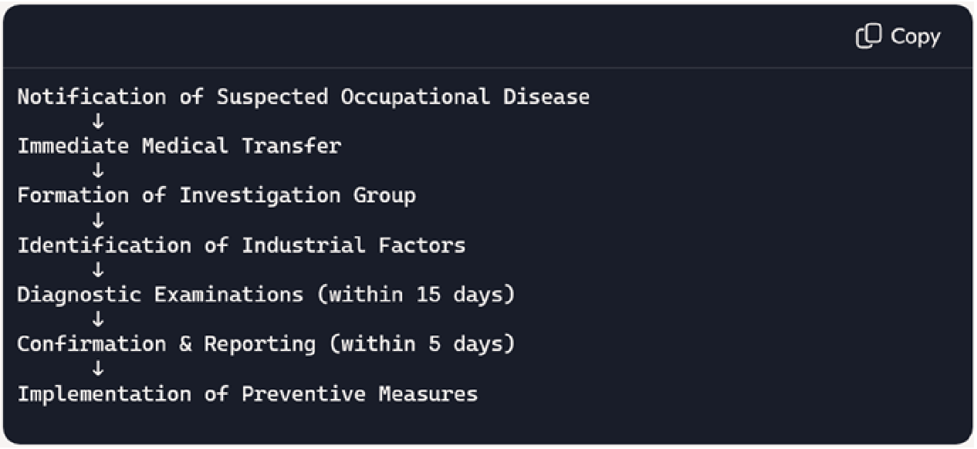


Fig. 2.5. Investigation process of occupational disease cases

All cases of acute or chronic disease (hereinafter occupational diseases) that develop as a result of work processes in workplaces with increased hazard, hard, harmful, and dangerous conditions, or analogous industrial environments, are subject to registration, investigation, and reporting.

Employer obligations:

- **Continuous preventive measures:** To preserve the life and health of employees by preventing occupational diseases, the employer must ensure ongoing measures to reduce hazardous industrial environments and other harmful conditions noted above.

- **Immediate medical transfer:** In case of suspected acute occupational disease, promptly transfer the affected person to a medical institution for further treatment and notify the supervisory authority.
- **Investigation team formation:** To determine the possible cause of an occupational disease, create an appropriate investigation team. If necessary, at the employer's expense, invite relevant specialists: physician, public health specialist, chemist, toxicologist, and other needed experts.
- **Implementation of measures:** Carry out the measures determined by the investigation team or invited specialists.
- **Diagnostic initiation:** Within 15 working days after identifying the possible cause of an occupational disease, initiate appropriate examinations for the affected person at a relevant institution with the aim of diagnosing the occupational disease.
- **Reporting:** Within 5 working days after confirming the occupational disease, send the completed special registration form (record sheet) to the supervisory authority.
- **Accountability:** The employer is responsible for the timely investigation, registration, and reporting of occupational diseases, as well as for developing and implementing measures to eliminate possible causes of the disease.

Investigation groups

- **Composition:** The investigation group includes:

1. **Employer or authorized representative** as group leader;
2. **Employees' representative for occupational safety** (where such exists);
3. **Trade union representative** (where such exists);
4. **Occupational safety specialist** (where such exists).

- **External specialists:** If items 2–4 above cannot be fulfilled, the employer is obliged to invite appropriate specialists from outside.
- **Supervisory participation:** A staff member of the supervisory authority may join the investigation group.
- **Public notice:** Information about the composition of the investigation group must be announced in writing at a clearly visible location.
- **Purpose:** The investigation group's goal is to determine the industrial factors that may cause acute or chronic occupational disease.
- **Decision-making:** The investigation group makes decisions by majority vote.
- **Timeline:** The group must determine the industrial factors that may cause acute or chronic occupational disease within 60 calendar days from its formation. This period may be extended only once—for the same duration.

Supervisory authority: rights and responsibilities

- **Responsive action:** Upon receiving notification of an employee's acute or chronic occupational disease, take appropriate action and require the employer to form an investigation group. A notification includes substantiated information submitted in writing by the employer, the employee, or another person, or received through the hotline.
- **Sanitary-hygienic characterization:** On its own initiative, compile a sanitary-hygienic characterization of working conditions and submit it to the investigation group or the employer.
- **Independent commission:** If necessary, form an independent commission to determine a possible acute or chronic occupational disease.
- **Information gathering:** Obtain all information related to the matter.

• **Interviews:** Conduct interviews with eyewitnesses, other employees, the employer, and other relevant persons for the purpose of investigating the possible acute or chronic occupational disease.

Parallel measures and training

Alongside organizational, technical, and economic measures, a proven way to reduce industrial accidents and occupational diseases is education, instruction, and training.

ISO 45001 requires that occupational disease investigations be integrated into the organization's health and safety management system. This means that every case must be documented, analyzed, and used to improve preventive measures. Worker participation is essential, as ISO 45001 emphasizes consultation and involvement of employees in safety processes. ISO 31000 complements this by requiring systematic analysis of causes, probability, and severity, ensuring that occupational disease investigations are not isolated events but part of a continuous improvement cycle. Together, these standards transform investigation into a proactive tool for prevention, aligning organizational practices with international requirements.

2.7. Worker Training and Instruction

Training of engineering-technical personnel and workers in occupational safety must be conducted according to a special program that reflects the specific characteristics of the enterprise. When preparing the program, existing occupational safety rules, instructions, and standards must be taken into account. The training program for workers should cover issues directly related to their working conditions.

```
Introductory Instruction
       ↓
Primary Instruction at Workplace
       ↓
Repeated Instruction (every 6 months)
       ↓
Unscheduled Instruction (new process, accident, violation)
       ↓
Reinforcement of Safety Requirements
```

Fig. 2.6. Types of occupational safety training and instruction

The instruction must include study of the following topics:

- Industrial sanitation and occupational hygiene
- Methods for eliminating harmful working conditions (noise, vibration, etc.)
- Prevention of causes of occupational injuries
- Organization of medical and sanitary services
- Electrical safety
- Actions of workers and engineering-technical personnel in factories, enterprises, and technological lines
- Fire prevention measures
- Review of occupational injury cases and investigation of accident causes

No worker may be admitted to work without undergoing introductory instruction. Introductory instruction must be provided to all personnel, regardless of education or work experience, whether permanent or temporary. Its purpose is to familiarize personnel with safety measures, safe work practices, and issues of industrial sanitation.

Within the framework of instruction, workers are informed about internal labor regulations (working hours, rest, leave), their duties during working time, rules for using protective clothing, procedures for providing first aid, basics of personal hygiene, conditions for compensation of damages, and other issues depending on the specifics of production and the position to be held. Introductory instruction is conducted by the occupational safety engineer.

Following introductory instruction, **primary instruction** is carried out directly at the workplace by the immediate supervisor. The new employee is carefully introduced to the workplace and safety rules specific to that location. Such instruction is also required when personnel are transferred from one unit to another.

Repeated instruction is conducted by the work supervisor (foreman, production manager, senior production manager) at least once every six months, or according to a schedule approved by the enterprise management. Repeated instruction is also carried out when personnel are transferred from one type of work or equipment to another. Its purpose is to reinforce safety requirements in the memory of personnel.

Unscheduled instruction is conducted when a new technological process is introduced, when an accident occurs, or when a violation is detected that could lead to an accident.

Conclusion: Introductory instruction must be conducted by the occupational safety engineer, while all other types of instruction are conducted by the immediate supervisor.

ISO 45001 requires that organizations ensure competence and awareness among all employees. Training and instruction are not optional but mandatory elements of the occupational health and safety management system. Introductory and primary training correspond to ISO 45001's requirement for initial competence, while periodic and unscheduled training reflect the standard's emphasis on continuous improvement and adaptation to change. **ISO 31000** complements this by requiring communication and consultation throughout the risk management process, meaning that training must also serve as a channel for feedback and dialogue. Together, these standards ensure that training programs are systematic, context-specific, and directly linked to risk reduction.

2.8. Rules for Providing First Aid

In cases of acute poisoning by toxic substances, electrical injury, or other traumatic incidents, four possible conditions may be encountered:

1. The victim is conscious, breathing, and has a heartbeat.
2. The victim is unconscious, but pulse and breathing are present.
3. The victim is breathing poorly, but pulse is detectable.
4. No pulse or heartbeat is present; pupils are dilated and unresponsive to light or painful stimuli.

Checking vital signs

Heart contractions indicate cardiac activity. This can be detected by listening with the ear placed on the left side of the chest or by checking the pulse at the carotid artery, where even the weakest pulse can be felt. If no pulse is detected, the heart has stopped. Pupils will be dilated. Breathing and heartbeat must be checked quickly, within 15–20 seconds.

Case 1: Conscious victim

The person must not move. Lay them on a dry surface, cover with clothing, and wait for medical assistance. Monitor breathing and heartbeat. In cases of poisoning, gastric lavage should be performed. If medical assistance cannot be summoned, transport the victim to hospital on a stretcher.

Case 2: Unconscious but breathing and pulse present

Lay the victim comfortably, loosen belts and clothing, provide fresh air, place ammonia-soaked cotton near the nose, sprinkle water on the face, massage and warm the body. Keep them in a calm environment until medical help arrives.

Case 3: Poor breathing but pulse present

Artificial respiration must be performed immediately. This can be done manually or with a special device. Devices deliver 0.25–1.5 liters of air per compression and may be connected to an oxygen cylinder. Manual methods are less effective; the most common is the mouth-to-mouth technique, using gauze, a handkerchief, or a special tube.

Fig. 2.7. First aid procedures for occupational accidents

The victim should be laid on the floor or table, clothing loosened, head tilted back so chin and neck align, mouth cleared of blood, saliva, or dentures. The rescuer breathes deeply and exhales into the victim's mouth, covering the nose with cheek or hand. For infants, air is blown into both mouth and nose simultaneously.

Adults require 10–12 breaths per minute; children 15–18 breaths per minute. Continue until independent rhythmic breathing resumes.

Case 4: No vital signs (clinical death)

Immediate artificial respiration and cardiac massage are required. Clinical death precedes biological death by 4–5 minutes, sometimes longer. First aid must continue until medical assistance arrives.

Cardiac massage procedure

Lay the victim supine on a firm surface, expose the chest. The rescuer places one hand on the lower third of the sternum, the other hand on top, pressing vertically with straight arms. The sternum should depress 3–4 cm (5–6 cm in obese individuals). Compression rate is about once per second. For children, use one hand, at a rate of twice per second.

If two rescuers are present, one performs cardiac massage, the other artificial respiration, alternating every 5–10 minutes. Standard ratio: one deep breath followed by five compressions; if ineffective, two breaths followed by fifteen compressions.

Signs of effectiveness include pulse at the carotid artery, pupil constriction, return of breathing, and reduction of cyanosis. Pulse should be checked every 2 minutes. If absent, continue massage. If other functions return but pulse does not, this indicates fibrillation, requiring defibrillation.

Defibrillation

Defibrillation restores normal cardiac rhythm by applying short, high-voltage electrical impulses to the heart. This excites all myocardial cells simultaneously, producing a coordinated contraction. Defibrillation is performed with a defibrillator, which discharges a capacitor through the heart. Electrodes are placed on the chest (one to the right, one directly over the heart). During preparation, cardiac massage and artificial respiration must continue. Successful defibrillation restores pulse immediately or within 2–4 minutes, after which artificial respiration and massage may be continued until stable rhythm is achieved.

ISO 45001 requires organizations to establish emergency preparedness and response procedures, which explicitly include first aid. This means that first aid rules must be standardized, documented, and practiced regularly. The standard emphasizes that employees should be trained not only to recognize the four conditions (conscious, unconscious with pulse, poor breathing, clinical death) but also to respond consistently according to established protocols. **ISO 31000** complements this by requiring systematic planning for emergencies, ensuring that first aid is integrated into the broader risk management framework. Together, these standards transform first aid from an individual skill into an organizational responsibility, guaranteeing that immediate response reduces the severity of accidents and improves survival outcomes.

2.9. Work Permits

Permit for conducting work

Earthworks or other activities in areas with communications that may pose hazards (electric shock, explosion, fire, release of toxic or harmful substances, etc.) are permitted only for authorized organizations or individuals.

The permit must specify:

1. Scope of work and completion deadline.
2. Anticipated hazards and possible risks.
3. List of control measures to minimize hazards.
4. Conditions for coordination with all participants and with adjacent work performers.
5. Evacuation plan for people in case of accidents and measures to reduce negative environmental impact.
6. Responsible person and participants.
7. Documents confirming participants’ qualifications.

Work without a permit is prohibited and entails liability for violators.

Permit for de-energizing energy systems

De-energizing electrical, mechanical, hydraulic, pneumatic, and other energy systems requires compliance with the same seven points listed above. Additionally:

1. Specification of means for utilizing accumulated energy (or justification of impossibility of accumulation), agreed with a qualified specialist, and execution by a qualified specialist.
2. Installation of fencing and warning signs at de-energizing locations.
3. Periodic verification of reliability of de-energizing using approved methods.

Work without a permit is prohibited and entails liability for violators.

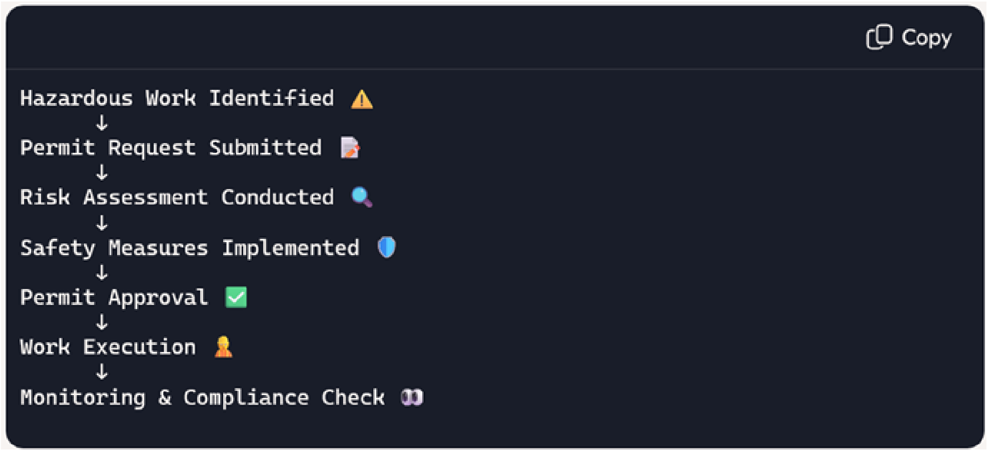


Fig. 2.8. Permit process for hazardous work activities

Permit for work under unusual conditions

Work in confined spaces (underground, underwater, on bridges, dams, overpasses, etc.), or in environments with toxic, radioactive, vibrational, or abnormal temperature conditions requires compliance with the same seven points listed above. Additionally:

1. Justification that the work cannot be performed by other means.
2. Confirmation that personnel involved have appropriate qualifications for working under unusual conditions.
3. De-energizing of all energy systems affecting safety, periodic verification of reliability using approved methods, assessment of harmful effects of accumulated energy, and specification of technical means used to minimize them.
4. Installation of fencing and warning signs at the workplace.
5. Prevention of unauthorized access to workplaces by assigning guards.
6. Verification of air quality in the environment, conducted in the manner, frequency, and with equipment defined by normative acts.

Work without a permit is prohibited and entails liability for violators.

ISO 45001 requires organizations to establish control procedures for hazardous work, and the work permit system directly fulfills this requirement. Permits ensure that dangerous tasks are performed only under controlled conditions, with clear responsibilities and documented safety measures. **ISO 31000** complements this by framing permits as part of risk treatment, ensuring that risks are not only identified but actively managed through procedural safeguards. Together, these standards emphasize that work permits are not bureaucratic formalities but essential tools for preventing accidents and ensuring accountability.

2.10. Scientific Organization of Work

Technical progress significantly expands production capabilities, alters working conditions, means, and methods, increases labor productivity, and transforms the nature of human work activity.

A person can work productively only if they have the ability and opportunity to optimally use available technical means, which assist in revealing their functional capacities.

In the interaction between humans and machines, it is often observed that even when a machine is well-designed from an engineering perspective, human errors occur during operation, sometimes leading to accidents or disasters.

Compared to machines, humans tire more quickly, are more easily distracted by external stimuli, perform calculations more slowly and often inaccurately, process smaller amounts of information within a given time, and have limited throughput. Under such conditions, machines are far stronger than humans.

With the development of technology, it has often been suggested that humans would be replaced by machines, which are seemingly more reliable, faster, and precise. Proponents of this view argue that if humans cannot be completely excluded from production processes, their role should be reduced as much as possible.

It is generally accepted that problems in human-machine interaction arise due to the limitations of human capabilities. Equally, problems arise from the limitations of machines. Indeed, machines cannot operate effectively in unexpected situations, correct all errors, or work with incomplete information.

Because of the limitations of both humans and machines, the issue of proper distribution of functions between them is critical. In production, the role and place of humans change with the introduction of new technology. Tasks previously performed by humans are gradually transferred to machines. Human functions in production increasingly involve programming, management, and control.

Humans must manage multiple objects simultaneously. Direct control loses its contact-based nature and becomes remote. Modern technology forces humans to work much faster.

With changing working conditions, new questions arise: how many signals can a person perceive simultaneously; what is the optimal speed of response; which colors and light intensities are optimal under specific conditions, and so forth. Addressing these questions requires in-depth study of human psychological processes. For system reliability, it is important not only to determine the operator’s individual perceptual, cognitive, and functional abilities, but also to study their activity as a whole. All factors influencing operator performance must be considered. In this respect, the distribution of functions between humans and machines, the organization of the work field, the working environment, interpersonal relations, and management are of particular importance.

ISO 45001 requires organizations to implement organizational controls that reduce risks at their source. The scientific organization of work directly corresponds to this requirement, because rational task distribution and ergonomic workplace design minimize exposure to harmful factors. Automation and optimized human–machine interaction reflect ISO 45001’s emphasis on preventive measures and worker well-being. **ISO 31000** complements this by requiring a systematic framework for risk management, meaning that organizational design must be integrated into the overall risk management cycle. Together, these standards ensure that scientific organization of work is not only a productivity tool but also a cornerstone of occupational safety.

2.11. Engineering Psychology

Engineering Psychology and Ergonomics. Psychology is needed practically everywhere that involves the effective use of human intellectual and emotional resources.

The peculiarities of human activity in the labor process are studied by *work psychology*, which began to take shape at the beginning of the 20th century. Initially, the central focus of work psychology was the problem of professional selection. At that time, researchers attempted to determine a person's ability to master a particular profession through special questionnaires. Counseling bureaus were opened to assist young people in choosing their careers. During the same period, great importance was attached to studying the causes of fatigue and the decline in labor productivity. In exploring these issues, work psychology became closely connected with *work physiology*.

Later, a new stage in the development of work psychology began. It became necessary to clarify how the environment, the workplace, the design of tools, their arrangement, and other factors influence mental activity. The first studies in this field were conducted in the 1920s, laying the foundation for an independent branch of work psychology known as *engineering psychology*.

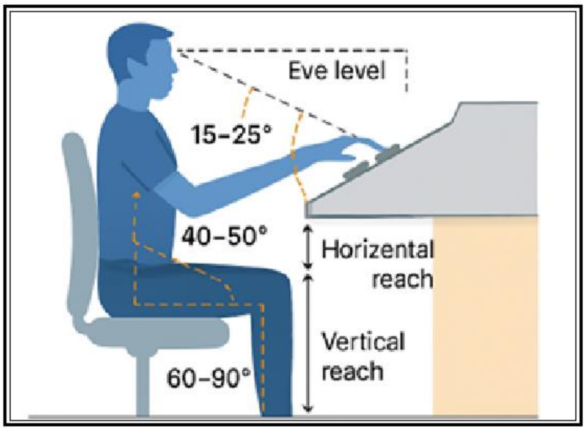


Fig. 2.9. Ergonomic arrangement of controls in a workplace. Seated posture

Engineering psychology examines the actions of the human operator within automated control systems. It was established as an independent science in the 1940s and today occupies one of the central places in psychology. It is a discipline that developed at the intersection of psychology and technology.

Engineering psychology is essentially knowledge about human behavior within any system. Its aim is to design the system's components in such a way that human capabilities are maximally revealed — achieving the greatest efficiency with minimal expenditure of energy.

Organization of the Workplace

In ergonomics, workplace organization is understood as the optimal alignment of two main elements: the working zone and the operator's posture.

The working zone is the area where the worker is systematically or periodically located to carry out observation, experimentation, or production processes.

Selection of the working zone can be achieved in two ways:

- Experimental determination (through modeling, mock-ups, etc.).
- Indirect determination (through anthropometric measurements of the human body, i.e., average dimensions such as height, arm length, and reach radius). For example, in Georgia, the average height for men aged 20–50 is taken as 170 cm, and for women 160 cm.

Optimal working zones at a desk (Figure 2.9).

For standing work, zones are defined similarly. The operator's optimal position should provide a wide field of vision and bodily comfort. Research shows:

- If small muscle groups are engaged, seated posture is preferable.
- If large muscle groups are engaged, standing posture is recommended.
- Provide appropriate inclination of the backrest.

Workers adopt various postures, some maintained for long periods. Not all are equally comfortable; some are harmful, causing abnormal breathing, fatigue, or even pathological outcomes. Poor workplace organization, especially incorrect chair and table heights, leads to strained or bent sitting positions, which are detrimental.

Based on extensive research, the following guidelines ensure optimal adaptation of chairs to human needs:

1. **Seat height** should be less than leg length, allowing feet to rest on the floor. Unsupported feet hinder blood circulation.
2. **Seat depth** should not exceed the distance from knees to back.
3. **Seat surface** should slope 3–5 degrees backward to prevent sliding when leaning on the backrest.
4. **Backrest inclination** should be 105–115 degrees.

Although proper work performance places additional strain on the operator, seated posture itself develops static fatigue. Therefore, the workplace must be arranged so that the operator can work equally well in both standing and seated positions. The best solution is the sit–stand type of workplace, with the work front arranged at standing height and a high chair that allows comfortable work in both positions.

The sit–stand posture enables the operator to choose the desired working position at any moment. This is rational not only psychologically but also physiologically. Changing posture allows different muscle groups to be engaged, resting fatigued muscles and restoring normal blood circulation in body parts affected by prolonged static positions. For certain types of monotonous work, the **sit–stand posture** is not only desirable but essential, as it introduces variety and combats monotony and related states such as drowsiness.

In this posture, the work table (machine or other equipment) must be higher than for seated work. Chair and footrest dimensions also increase, while other table dimensions and viewing angles remain the same as recommended for seated posture.

The key principle is to avoid static tension, unnecessary movements, and excessive body displacement. Rational posture minimizes active muscular strain. Researchers note that normal posture is when the body remains vertical with forward bending limited to 150 degrees.

Anthropometric considerations. Workplace organization must take into consideration anthropometric data to define the operator's working zones. The maximum zones of the upper limbs approximate a hemisphere with a radius equal to arm length. Within this hemisphere, fingers should reach all points. However, such movements are inefficient, requiring excessive time and energy. This maximum zone is limited to 50 cm; the normal zone is defined as 40 cm, while the optimal zone depends on specific work conditions. The most rational movements occur within normal and optimal zones, where manipulation can be performed with forearm movement alone, without full arm displacement. Tools, controls, materials, and documents should be placed in these zones, while rarely used items may be placed in the maximum zone.

Movements reaching extreme positions (maximum flexion or extension) are energetically inefficient, as they require significantly greater muscular effort to overcome resistance.

Ergonomic design of indicators and controls. Ergonomics also addresses the design of indicators. Optimal characteristics of visual and auditory indicators are specified. Research shows that humans receive about 80% of necessary information visually and 20% through auditory channels. To reduce visual overload, information should be distributed rationally among different indicators.

Indicators should be simple and uncluttered. Scales should increase numerically from bottom to top or left to right. Signals must not contain redundant information requiring extra time to interpret. For easier control, ranges of normal operation and overload should be marked in different colors. Scales should use light backgrounds to maximize contrast with markings.

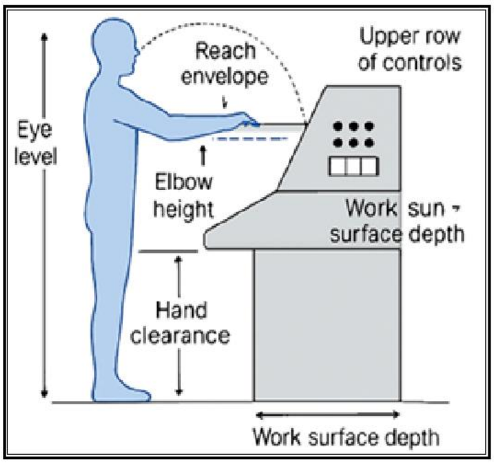


Fig. 2.10. Ergonomic arrangement of controls in a workplace. Standing posture

Principles of rational arrangement of controls. To increase operator speed and accuracy while reducing fatigue, ergonomic principles guide the arrangement of signaling devices and controls:

1. **Functional organization principle** – grouping tools and controls by function.
2. **Importance principle** – frequently used tools placed in convenient zones, others in secondary zones.
3. **Sequential principle** – arrangement according to the order of operations.
4. **Frequency principle** – most frequently used tools placed in the most accessible locations.
5. **Optimal arrangement principle** – considering the specific characteristics and precision requirements of each tool or control.

For effective operation, the choice of control system (manual or foot-operated) must be defined. Manual control is used for precise tasks requiring little force, while foot control is suitable for tasks requiring greater force but less precision.

Since manual control is most common, ergonomics pays special attention to **psychotechnics**, which studies the correspondence between the shape of controls and the anatomical and physiological characteristics of the human hand. Buttons and keys that fit the hand's anatomy are considered most convenient.

It is a misconception that the best controls are those requiring no effort to operate. In reality, such controls reduce tactile feedback, leading to inaccurate actions. Moreover, humans themselves are flexible, intelligent generators of small amounts of energy, and a minimal expenditure of muscular effort is necessary for effective work.

ISO 31000 requires context-specific analysis of risks, and engineering psychology directly supports this requirement by examining how human factors influence safety outcomes. Reaction times, perception limits, and ergonomic design are not abstract concepts but measurable variables that determine accident probability. **ISO 45001** emphasizes consideration of human factors in workplace safety, requiring organizations to adapt machines, tools, and processes to human capabilities. Together, these standards ensure that engineering psychology is integrated into risk management, transforming human–machine interaction into a structured element of occupational safety.

2.12. Work Capacity and Fatigue

One of the fundamental conditions for ensuring occupational safety is maintaining a high level of work capacity among employees.

Work capacity refers to the potential ability of a person to perform labor activities with a defined level of effectiveness over a given period of time.

The inverse of work capacity is **fatigue**, which represents physiological changes in the worker's body caused by energy expenditure during labor activities.

Work capacity is not constant; it changes over time, a phenomenon known as the **dynamics of work capacity**.

- In the initial stage of work, capacity increases and reaches its maximum after 0.5–1.5 hours. This is called the **stage of entering work**.
- The second stage is **stable work capacity**, lasting about three hours.
- The third stage is the **development of fatigue**, lasting 0.25–0.5 hours, during which a break is recommended.

After rest, all stages repeat, though the stage of entering work is shorter and productivity is lower than in the first half of the day.

Methods of Increasing Work Capacity. Work capacity can be increased through **active** and **passive** methods:

- **Active methods:**
- Division and cooperation of labor;
- Optimization of work rhythm;
- Rational organization of the workplace;
- Improvement of work-rest schedules;
- Rational use of physical culture and sports.
- **Passive methods:**
- Improvement of meteorological conditions and lighting;
- Reduction of noise and vibration;
- Reduction of air dustiness and pollution.

Active methods directly influence the work process, its organization, and the worker's body. Passive methods create the best environment for optimal work capacity.

Work capacity refers to the ability of a worker to perform tasks effectively over a given period of time. It is influenced by physical, psychological, and environmental factors. High work capacity ensures productivity, while its decline leads to errors, accidents, and occupational diseases.

Fatigue is a natural consequence of prolonged work and manifests as reduced efficiency, slower reaction times, and diminished concentration. It may be physical, mental, or emotional, and is often exacerbated by poor workplace organization, inadequate rest, or harmful production factors such as noise, vibration, or toxic substances.

The study of fatigue is essential for occupational safety. Preventive measures include:

- Rational organization of work and rest periods.
- Improvement of workplace ergonomics.
- Reduction of harmful production factors.
- Medical monitoring and preventive healthcare.
- Training workers in self-regulation and stress management.

ISO 45001 emphasizes the management of psychosocial risks such as fatigue and stress, recognizing their impact on safety and productivity. By integrating ergonomic design, organizational measures, and preventive healthcare, enterprises can maintain high work capacity and reduce risks associated with fatigue.

ISO 45001 requires effective hazard communication, which includes the use of standardized safety signs and markings. This ensures that all employees, regardless of language or background, can recognize hazards and follow safe practices. ISO 31000 complements this by emphasizing information sharing as part of the risk management process. Safety signs are not only visual aids but integral elements of systematic risk communication, ensuring that preventive measures are clearly conveyed and consistently applied. Together, these standards guarantee that safety signs and markings are reliable tools for reducing accidents and strengthening workplace safety culture.

2.13. Control of Objects

Information display devices. These provide the operator with complete information about the state of the controlled object. The ultimate goal of designing information displays is to ensure timely delivery of necessary information to the operator, enabling analysis, logical processing, and decision-making. To enhance efficiency and reduce operator strain, information must meet the following requirements:

1. Adequately reflect the state of the controlled object and surrounding conditions.
2. Present only the data essential for decision-making and execution of defined actions.
3. Be formatted in accordance with the operator’s tasks and psychophysiological capabilities for receiving and processing information.

Control devices. Their purpose is to transmit control actions from the operator. Through them, the operator implements decisions. Control devices must be reliable in operation, convenient to use, and designed to prevent accidents or injuries caused by overloads or operator errors.

Control devices can be classified into four groups:

1. Devices for switching equipment on, off, or between modes.
2. Devices for repetitive actions.
3. Devices for continuous regulation and adjustment of equipment.
4. Emergency control devices.

When designing control devices, rational work movements must be considered. Inefficient, redundant, or fatiguing movements must be eliminated. To prevent accidental activation, devices should be arranged to exclude unintended engagement during normal operations. Reliable blocking and mechanical resistance must be incorporated to ensure activation or deactivation requires deliberate effort.

Control panels. In workplace organization, beyond anthropometric factors (height, reach radius for hands and feet, line of sight, etc.), the following must be considered:

1. Operator's working posture.
2. Configuration and arrangement of indicator panels and control devices.
3. Visibility of the workplace.
4. Use of the work surface for writing, telephone placement, storage of instructions and materials.

The workplace element containing information displays and control devices is called the **control panel**. Its design is determined by purpose, operator tasks, and anthropometric factors. The shape and dimensions depend on the number of displays and controls, as well as the operator's working posture.

Optimal arrangement of controls and zones for manual operations are shown in Figure 2.2. The most frequently used and critical controls must be placed in the first zone.

The relative arrangement of displays and controls is crucial. Elements must be positioned so the operator can use both hands rationally and economically. When numerous controls are present, switches of different shapes are recommended to allow operation without visual monitoring.

Operator's chair. To facilitate work and reduce fatigue, proper selection of the operator's chair is essential. Its design must support maintenance of the primary working posture for long periods, not hinder work movements or changes of position, and provide opportunities for rest.

ISO 45001 requires documented information as part of the occupational health and safety management system. Safety instructions and regulations are a direct expression of this requirement, ensuring that procedures are written, communicated, and maintained. The standard emphasizes that instructions must be accessible to all employees and regularly reviewed for relevance. **ISO 31000** complements this by requiring integration of safety policies into the overall risk management framework, meaning that instructions are not isolated documents but part of a systematic approach to hazard control. Together, these standards guarantee that safety instructions and regulations are reliable, enforceable, and aligned with international best practices.

2.14. Consolidated Data, Objectives, and Integration with Standards

The first paragraph of this chapter provided theoretical and pedagogical integration, showing the general connection of the discussed issues with ISO standards. The purpose of the final paragraph is to consolidate the data covered, highlight interconnections, and align them with technical regulatory norms. As a result, the student must be able to distinguish between occupational injury and occupational disease, individual and group cases, and their causes: physical, chemical, biological, and psychophysical factors (ISO 31000 requirement). The student must also understand methods for reducing their impact.

The primary objective of instruction is the classification of factors, comprehension of their effects, and harmonization with standard requirements.

Through training, the student should acquire knowledge of various analytical methods—statistical methods and corresponding coefficients, group, monographic, topographic, technical, and economic methods—and develop the ability to apply them. After instruction, the student should be able to identify types and causes of minor, moderate, severe, and fatal injuries. They should also know the types of chronic and acute diseases, their causes, mechanisms of development, and methods of reduction. The student must understand ways to reduce concentrations of toxic and harmful substances in the workplace, strengthen safety culture, appreciate the importance of instruction, and be able to provide first aid when necessary, developing the ability to respond quickly [22-26].

As a result of training, the student should comprehend safety control mechanisms, be able to assess their own physical and psychological condition as well as that of others (ISO 45001 requirement), and be capable of monitoring and optimizing production processes, thereby reducing risks and ensuring safety (ISO 31000 requirement).

ISO 45001 requires performance evaluation as part of the occupational health and safety management system. Consolidated data provide the evidence base for assessing whether preventive measures are effective and whether objectives are being met. **ISO 31000** complements this by requiring continuous improvement, meaning that data analysis is not a one-time activity but an ongoing cycle of monitoring, evaluation, and adjustment. Together, these standards ensure that consolidated data are transformed into actionable objectives, aligning enterprise policies with international best practices and creating a feedback loop that strengthens safety culture.

3. Air Composition and Standardization

3.1. Guide for Chapter 3

Theoretical Integration:

Concerns environmental parameters: air composition, pressure, humidity, density.

Shows how physical-chemical data of the environment affect safety.

Integration with Standards:

ISO 45001 requirement: air quality control and compliance with sanitary-hygienic norms.

ISO 31000 framework: use of quantitative data in determining the risk index.

General Integration:

Exercise examples provide the reader with practical skills for calculating data and comparing them with standards.

The following short notes show the connection with ISO standards.

- Atmospheric air composition: ***short note***: ISO 45001 requires air quality control in the workplace.
- Partial pressures (Dalton's law): ***short note***: according to ISO 31000, these data are used in determining the risk index.
- Relative humidity: ***short note***: ISO 45001 sanitary-hygienic norms require humidity control in the workspace.
- Case study (e.g., mine, hospital): ***short note***: ISO 45001 requires monitoring in real environments and a feedback system.

ISO 31000 requires effective risk communication as a central element of the risk management process. This means that safety principles must be communicated clearly across all organizational levels, ensuring that information flows both top-down and bottom-up. **ISO 45001** emphasizes worker participation, requiring that employees be actively involved in identifying hazards, proposing solutions, and monitoring safety performance. Together, these standards ensure that the introduction to Chapter 3 is not only a theoretical overview but also a practical framework for building a participatory safety culture. By aligning communication and participation with international standards, organizations create the foundation for systematic risk prevention and continuous improvement.

ISO 31000 also requires organizations to apply risk treatment options systematically, beginning with elimination and substitution before relying on protective equipment. This hierarchy ensures that risks are managed at their source rather than transferred to workers. **ISO 45001** emphasizes preventive and protective measures, requiring employers to integrate engineering controls, administrative procedures, and PPE into a coherent safety management system. Together, these standards guarantee that risk prevention strategies are not isolated actions but part of a structured, continuous process that prioritizes hazard elimination and worker protection.

3.2. Atmospheric Air Composition

Atmospheric air is a gaseous envelope surrounding the Earth, moving together with it, and consisting of a mixture of gases and various vapors. The physical state and chemical composition of atmospheric air change over time and space. With increasing altitude, its temperature, humidity, density, and pressure decrease, while ozone content increases.

Atmospheric air is characterized by **pressure**, which is the force exerted by the mass of air on the Earth's surface and other objects due to gravity. In the case of building ventilation, the airflow is always influenced by atmospheric pressure, i.e., the force exerted by the mass of air above a given level.

From the equator toward the poles, atmospheric pressure increases and temperature decreases. Air has maximum temperature and humidity at sea level near the tropics.

With increasing altitude, air becomes more rarefied, but its **percentage composition** remains practically unchanged due to high turbulence within the range of 75–85 km above the Earth's surface. Deviations are mainly observed above large industrial centers, forest masses, and similar areas — i.e., depending on industrial or recreational zones located on the Earth's surface. Variability occurs primarily due to carbon dioxide, which is associated with the so-called greenhouse effect. Historically, the composition of atmospheric air has continuously changed toward deterioration of quality due to human technogenic activity, reduction of forest areas, and desert formation.

Atmospheric air, like any local volume of air (in a vessel, room, tunnel, etc.), satisfies **Amag's law**:

$$V = \sum V_i \tag{3.1}$$

where V is the total volume of air, m³; V_i – the volume of an individual component of air (e.g., nitrogen, oxygen, etc.), m³; the index i may denote nitrogen, oxygen, or other constituents.

Amag's law is, at first glance, very simple — the total volume of air equals the sum of the volumes of its individual components. The volume of each constituent is called partial volume, i.e., the volume occupied by a given gas from the total mixture under specific temperature and pressure conditions.

Alongside partial volume, each component has its corresponding partial pressure, which is the pressure that the component would exert if it alone occupied the entire volume of the mixture. The law of partial pressures is called Dalton's law, and its formula is:

$$P = \sum P_i \tag{3.2}$$

where P is the total pressure of the air mixture, Pa; P_i – the pressure of an individual component of air, Pa.

Each component of air can be characterized by its concentration, both for the entire atmosphere and for a local volume of air in a confined space. The volumetric concentration of any constituent is calculated by the formula:

$$c_i = \frac{V_i}{V} \times 100\% \tag{3.3}$$

where c_i is the concentration of an individual component of the gas mixture, %. Without multiplying by 100%, the obtained value is called **dimensionless concentration**, which is relatively rarely used in the post-Soviet space. In other countries, dimensionless concentration is widely used and is called part per million – ppm.

At sea level, the percentage composition of atmospheric air by volume, i.e., the concentration of individual components, is presented in Table 3.1.

Table 3.1. Atmospheric Air Composition and Volumetric Concentration at Sea Level

N	Atmospheric Air Components	c_i, %
1	Nitrogen	78,0840
2	Oxygen	20,9476
3	Argon	0,9340
4	Carbon dioxide	0,0314
5	Helium, neon, krypton, xenon, ozone, radon, hydrogen, hydrogen peroxide, ammonia, iodine, and other trace impurities	0,0030
6	**Total**	**100**

Note: Percentage composition is shown for absolutely dry air. The percentage of water vapor varies within the range of 0.2–2.6%. The carbon dioxide concentration given in the table can be considered historical. The current value is approximately 0.04% (400 ppm).

At sea level and 0 ℃ temperature, the partial pressure of oxygen, according to Table 3.1, is approximately 1/5 of atmospheric pressure, i.e., 20.95 kPa. Under this partial pressure, human blood achieves maximum oxygen saturation.

It is convenient to use kilopascals (kPa) as units, since the numerical value of partial pressure corresponds directly to the volumetric concentration (%) of the component.

Thus, in atmospheric air:

- Nitrogen partial pressure: 78.08 kPa;
- Argon partial pressure: 0.93 kPa;
- Carbon dioxide partial pressure: 0.03 kPa.

Exercise Example

Given:

- Air mixture: 78% nitrogen, 21% oxygen, 1% other gases
- Total pressure: 100 kPa

Tasks:

1. Calculate partial pressure of each component.
2. Compare results with sea-level data.
3. Identify which component's change most affects human health.

Solution:

$P_N = 100x0.78 = 78\ kPa$

$P_O = 100x0.21 = 21\ kPa$

$P_{other} = 100x0.01 = 1\ kPa$

Result matches sea-level data. The most critical component is oxygen, since its reduction directly impacts human health.

Note

Studying air components requires not only physical–chemical data but also understanding of application contexts. The same method solves different problems in various fields:

- **Mining industry:** Oxygen reduction in mines increases risk of asphyxiation. Methods (gas chromatography, underground gas analysis) are used for safety monitoring.
- **Healthcare:** Oxygen and CO^2 levels are critical in hospital environments, especially for respiratory equipment.
- **IT and digital technologies:** Air composition in data centers affects equipment durability.

Case Study

In a mining enterprise, measurements showed oxygen reduction to 19%. Workers experienced fatigue and breathing difficulty. Gas chromatography confirmed the issue, and additional ventilation was implemented.

ISO Connection:

- **ISO 45001:** Requires monitoring oxygen and harmful gases in workplaces.
- **ISO 31000:** Frames oxygen deficiency as a critical occupational risk.
- **ISO 10012:** Ensures accuracy of gas measurement instruments.
- **ISO 14001:** Links air composition monitoring to environmental management.

ISO 45001 requires leadership and worker participation as fundamental elements of occupational health and safety management. This means that top management must not only define policies but also demonstrate visible commitment by allocating resources and integrating safety into strategic decisions. Worker participation is equally emphasized, ensuring that employees are actively involved in hazard identification, decision-making, and monitoring. **ISO 31000** complements this by requiring accountability in risk management, meaning that responsibilities must be clearly assigned, documented, and evaluated. Together, these standards ensure that organizational responsibilities are not abstract principles but enforceable practices that align leadership, workers, and risk management into a unified system

3.3. Air Pressure and Relative Humidity

The outdated unit of pressure, **1 physical atmosphere**, is the pressure exerted on a unit area by a mercury column 760 mm high at sea level at 0 °C. The relationship between old units and international system units (Pascal, kilopascal, hectopascal, megapascal) is as follows:

- 1 phys. atm. = 760 mm Hg = 1.0332 kg/cm²
- 1 bar = 1.02 phys. atm. = 1000 hPa = 100 kPa
- 1 MPa = 10^6 N/m² = 10.2 phys. atm.
- 1 phys. atm. ≈ 1 bar = 1000 hPa

Since 1982, in the field of chemistry, the standard atmospheric pressure has been defined as 1 bar = 100 kPa. The variation of atmospheric pressure and oxygen partial pressure with altitude is shown in Fig. 3.1.

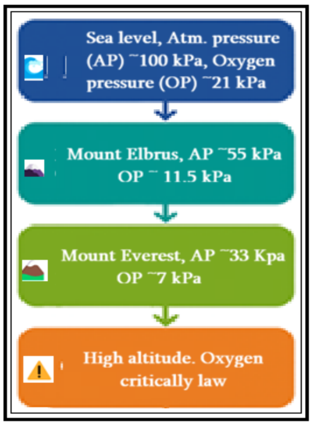


Fig. 3.1. Variation of atmospheric pressure and oxygen partial pressure: 1 – Air pressure; 2 – Oxygen partial pressure. Average values corresponding to the altitudes of Elbrus and Everest are indicated

In the atmosphere, there are always mechanical impurities: dust, smoke particles, tiny water droplets, and ice-like crystals. Air contains large amounts of dust over continents, while it is cleaner over oceans. An exception is the central Atlantic Ocean, where strong winds carry pollutants from industrial regions. Dustiness over continents is not constant either, but is most pronounced above large industrial centers.

It is noteworthy that these mechanical impurities also obey **Amag's law** and **Dalton's law**, and formula (3.3) can be applied to them as well. Thus, under constant total pressure, dust and smoke, by developing their own partial pressures in air, proportionally reduce the partial pressures of all other components, including oxygen. In this way, these components occupy oxygen's place, effectively displacing it from the gas mixture.

Using formula (3.3) for water vapor gives us **relative humidity**. For water vapor, the following formula is more commonly used

$$\varphi = \frac{\rho}{\rho_h} \times 100\% \quad (3.4)$$

where φ is the relative humidity of air, %; ρ – partial pressure of water vapor; ρ_h– partial pressure of saturated water vapor at the same temperature, Pa. Without multiplying by 100%, the value is called relative humidity in fractions.

Exercise Example

- Measured partial pressure of water vapor in a workspace: 2 kPa
- Saturated vapor pressure at the same temperature: 2.5 kPa

1. Calculate relative humidity (φ).
2. Assess how close the result is to the normative range (40–60%).
3. Determine what impact this humidity may have on the work environment.

Fig. 3.2. The influence of mechanical impurities on the partial pressure of oxygen

Solution:

Relative humidity in the workspace:

$$\varphi = \frac{2}{2.5} \times 100\ \% = 80\ \%$$

The result exceeds the normative range (40–60%). High humidity increases the risk of mold and bacterial spread in the work environment.

Note

It is evident that the study of humidity and pressure is a **universal method**, applicable in different fields:

- **Agriculture** – Humidity control in greenhouses determines crop quality.
- **Construction** – High humidity increases the risk of structural corrosion.
- **Healthcare** – Excess humidity in operating rooms promotes infection spread.

Thus, the same formula for calculating relative humidity,

$$\varphi = {}^{P}/_{P_h}\, x100\ \%$$

can be applied in both industrial and social contexts.

Case Study

In a hospital, humidity levels reached **75%**. As a result, infection spread increased. Based on the study, an automatic humidity control system was implemented.

3.4. Air Density

Density. The density of air, like that of any other substance, is the mass per unit volume, with dimensions in kg/m³. In general, the density of all substances is denoted by the letter ρ, while for ventilation purposes, the density of air is denoted by the symbol γ. Since the symbol ρ has already been used to denote the partial pressure of water vapor, we will use γ to denote density. Thus, for all substances, density is defined by the formula

$$\gamma = \frac{m}{V} \qquad (3.5)$$

where m is the mass of the substance, kg; V – the volume of the substance, m³.

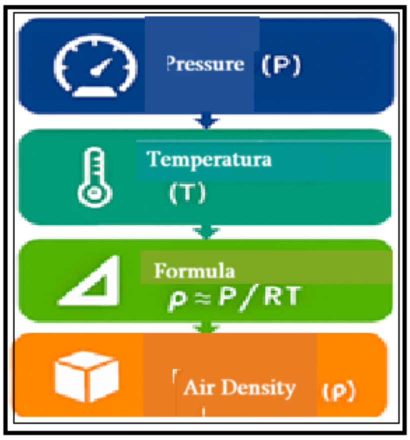


Fig. 3.3. Calculating air density

Density characterizes the average mass of any quantity of air in such a way that its numerical value does not depend on the total amount of air at a given location. It is clear that when using only mass as a unit, the numerical value depends on the amount of substance at a given location (or volume).

To characterize volume on average, the reciprocal of density is used, called specific volume. This quantity is used in thermodynamics, where the main working body is air or a gas mixture.

Another related concept is specific weight, which is the ratio of the weight of a substance (expressed in Newtons) to its volume.

Bulk Density. In technology and in general human practical activity, we often deal with heterogeneous bodies, materials, or products. For example: sand, coal, firewood, grain, etc.

To evaluate such materials or products, the concept of **bulk density** is used, which is the mass per unit volume, with dimensions in kg/m³. It is clear that the mineral part of a porous body made from the same material, such as a construction block, has constant density, while its bulk density varies depending on the degree of compaction. The higher the pressure used in manufacturing the block, the fewer voids it contains, and consequently, the greater its bulk density.

It should be noted that the non-system unit t/m³ for bulk density is widely used in engineering to evaluate solid and liquid materials. It is often incorrectly referred to as bulk weight.

Relative Density. For air components, the concept of relative density is used. The relative density of a given component of air is a dimensionless quantity that compares the numerical values of the density of that component with the average density of the air mixture. Relative density is defined by the formula

$$\zeta_i = \frac{\gamma_i}{\gamma} \tag{3.6}$$

where ζ_i is the relative density of the i-th component of air; γ_i – density of the i-th component of air, kg/m³; γ – average density of multicomponent air, kg/m³.

The relative density of a component with respect to air can be approximately calculated using the formula:

$$\zeta_i \approx \frac{M_i}{29} \tag{3.7}$$

where, in addition to the defined quantities, M_i is the molecular weight of the i-th component of air, taken from Table 3.2; 29 – the rounded molecular weight of air.

Table 3.2. Molecular Weights of Substances

Chemical Formula	Molecular Weight	Chemical Formula	Molecular Weight	Chemical Formula	Molecular Weight
NH_3	17.031	H_2COCH_2	44.053	NO_2	46.006
AsH_3	77.945	$HCHO$	30.026	N_2O_4	92.011
C_6H_6	78.114	H_2NNH_2	32.045	O_3	47.998
Br_2	159.808	H_2	2.016	PH_3	33.998
CS_2	76.143	HBr	80.912	CH_3CHOCH_2	58.080
CO	28.010	HCl	36.461	SiH_4	32.117
CCI_4	153.822	HCN	27.026	SO_2	64.065
Cl_2	70.905	H_2S	34.082	SO_2F_2	102.062
ClO_2	67.452	CH_3SH	48.109	$(CH_3)_2NNH_2$	60.0984
$(CH_3)S$	62.136	CH_3NHNH_2	46.072	Air	29
C_2H_4	28.054	NO	30.006		

Based on the data in Table 3.2, for hydrogen, formula (3.7) takes the form:

$$\zeta_{H_2} \approx \frac{2{,}16}{29} \approx 0{,}074 \tag{3.8}$$

Accordingly, the relative density of hydrogen with respect to air is 0.074, meaning hydrogen is lighter than air. Without sufficient turbulence, hydrogen can accumulate in the upper parts of buildings (arches) and cannot settle near the floor.

Using the data from Table 3.2 and formula (3.7), it is possible to determine the relative density of the listed substances and predict the preferential accumulation sites of harmful, hazardous, and toxic impurities in technological processes.

Exercise Example

- Average air density: 1.2 kg/m³
- Hydrogen molecular weight: M = 2, average air molecular weight: M = 29

1. Calculate the relative density of hydrogen with respect to air.

2. Explain why hydrogen is lighter.
3. Determine where hydrogen may accumulate in an industrial environment and what risks it creates.

Solution:

Relative density of hydrogen with respect to air:

- $\zeta_{H2} \approx \frac{2}{29} = 0.074$

Hydrogen is much lighter than air, therefore it accumulates in the upper parts of buildings (near arches). This creates an explosion risk if ventilation is insufficient.

Note

The study of density is important in practically all fields:

- **Transport** – In aviation, air density determines engine performance and fuel consumption.
- **Energy** – Variations in gas density in pipelines affect pressure and safety.
- **Mining** – Accumulation of light gases (e.g., hydrogen, methane) in vaults creates explosion risks.

These examples show that density research is not only of theoretical importance but can serve as the basis for real safety indices.

Case Study

In a chemical plant, hydrogen accumulation created an explosion hazard. As a result of the study, gas detectors were installed and the ventilation system was upgraded.

3.5. Concentration of Air Impurities

Air impurities. Atmospheric air contains various substances. Substances naturally present in air are called **air components**, while substances introduced into the air through human activity are called **air impurities**. Impurities introduced by human activity may be identical to those found in nature or may be exclusively of technogenic origin. According to their aggregate state, impurities can be solid, liquid, or gaseous.

A **harmful impurity** is one that, when safety requirements are violated, causes occupational injury, professional disease, or other deterioration of health upon contact with the human body (through skin, lungs, stomach, or blood), detectable by modern methods.

Permissible limits for harmful impurities vary according to their class (see Table 3.3). There are four classes:

- **Class I** – Extremely hazardous substances, permissible concentration in workplace air < 0.1 mg/m³.
- **Class II** – Hazardous substances, permissible concentration 0.1–1.0 mg/m³.
- **Class III** – Moderately hazardous substances, permissible concentration 1.1–10.0 mg/m³.
- **Class IV** – Less hazardous substances, permissible concentration > 10.0 mg/m³.

Table 3.3. Classification of Harmful Substances According to Their Effect on the Human Body

Indicator	Class I	Class II	Class III	Class IV
MAC in workplace air, mg/m^3	< 0,1	0,1-1,0	1,1-10,0	> 10,0
Average lethal concentration in air, mg/m^3	< 500	500-5000	5001-50000	> 50000
Lethal dose via ingestion, mg/kg	< 15	15-150	151-5000	> 5000
Lethal dose via skin contact, mg/kg	< 100	100-500	501-2500	> 2500

Notes:

1. The unit mg/kg means the amount of harmful substance per kilogram of human body weight.
2. Classes: I – Extremely hazardous substances; II – Hazardous substances; III – Moderately hazardous substances; IV – Less hazardous substances.
3. The data in the table do not apply to harmful substances containing radioactive or biological materials (complex biological structures, bacteria, phages, etc.).

Particularly hazardous are impurities that burn or explode when combined with air components (oxygen, carbon dioxide, or nitrogen). Harmful impurities are those that, under certain conditions, cause damage to humans. For example, neutral ash may become harmful if it enters the eyes or respiratory tract.

Fig. 3.4. Influence of Mechanical Impurities on Oxygen Partial Pressure

ISO connection:

- **ISO 45001** requires continuous monitoring of workplace air quality and compliance with permissible exposure limits (PEL).
- **ISO 31000** frames impurity concentration as a quantifiable risk factor in occupational safety risk assessments.
- **ISO 14001** emphasizes environmental management, linking workplace emissions to broader ecological impact.

Impurity concentration. The concentration of impurities can be expressed in terms of their volume or mass in air. If expressed by volume, the concentration indicator is volumetric; if expressed by mass, it must be reduced to unit volume of air.

The concentration of impurities reduced to unit volume is a dimensionless quantity, since the numerator represents the volume of impurities and the denominator represents the total volume of air. To convert this value into percentages, it must be multiplied by 100. The formula for calculating such a value was previously given (3.3) when discussing air components. The same formula can be used to determine the volumetric concentration of impurities. Therefore, we repeat the formula here, with slight modification:

$$c_1 = \frac{V_i}{V} \times 100\%.$$

Thus, impurity concentration by volume is expressed as a percentage (volume in volume), denoted by the symbol c_1.

Maximum Allowable Concentration (MAC).

The concept of **MAC** (Maximum Allowable Concentration) defines impurity levels that are not dangerous. Expressed in mg/m³ or ppm. For example, for CO, MAC is 200 mg/m³ if exposure does not exceed 15 minutes. In ppm, this equals 160, calculated by dividing 200 by 1.25 (standard air density in kg/m³).

Exercise Example

- Measured dust concentration: **5 mg/m³**
- Normative MAC: **3 mg/m³**

1. Determine how many times the actual value exceeds the norm.
2. Suggest two control measures (technical or organizational).
3. Assess the health impact of exceeding the norm.

Solution:

Exceedance: $\frac{5}{3} \approx 1.67 \rightarrow 67\%$ Above the norm.

Control measures:

- **Technical:** Strengthen ventilation, introduce filtration.
- **Organizational:** Reduce working time in high-dust areas.

Exceedance increases risk of respiratory diseases.

ISO connection:

- **ISO 45001:** Dust and gas monitoring is mandatory for worker safety.
- **ISO 14001:** Dust emissions are linked to environmental compliance.
- **ISO 31000:** Exceedance of MAC is a quantifiable risk indicator in safety audits

Case Study

At a construction site, dust concentration was twice the permissible norm. Workers developed respiratory problems. As a result, dust filtration systems were installed.

3.6. Main Components of Air

The main components of air are **oxygen, carbon dioxide, and nitrogen**. In addition, explosive, toxic, or radioactive substances may mix with air in gaseous, dust, or vapor form.

Oxygen (O^2)

Oxygen has no smell, color, or taste. Its relative density at sea level and 0 ℃ is **1.103**, i.e., higher than average air density. Molecular weight: **32**. Under normal conditions (air density 1.2 g/L), 1 L of oxygen has a mass of 1.323 g. Solubility in water at 0 ℃ is **5%** by volume.

Humans inhale air containing ~20% oxygen, exhaling ~17% O_2 and ~4% CO_2. Nitrogen concentration slightly increases in exhaled air. The amount of oxygen absorbed exceeds the amount of CO_2 released.

Maximum blood saturation occurs when oxygen partial pressure is 20.95 kPa (~1/5 of atmospheric pressure). This is called the Law of Fifths:

- ~1/5 of atmospheric air is oxygen.
- Humans absorb ~1/5 of inhaled oxygen.

Exhaled air with 17% O_2 corresponds to partial pressure of 17.0 kPa, causing discomfort (shortness of breath, rapid heartbeat). At 12.0 kPa, oxygen becomes lethal. Thus, the vital range for humans is 17.0–20.95 kPa.

Sudden addition of neutral gases in confined spaces reduces oxygen concentration sharply. At 3% O_2 (3 kPa), loss of consciousness occurs within 1–2 minutes; at 5–10 minutes, clinical death. Example: underground mining with sudden release of neutral gases.

In deep mining tunnels below sea level, permissible oxygen concentration may be lower (19.0–19.5%) than at sea level, because increased total pressure maintains oxygen partial pressure within the vital range.Exhaled air with 17% O_2 corresponds to partial pressure of 17.0 kPa, causing discomfort (shortness of breath, rapid heartbeat). At 12.0 kPa, oxygen becomes lethal. Thus, the vital range for humans is **17.0–20.95 kPa**.

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In deep mining tunnels below sea level, permissible oxygen concentration may be lower (19.0–19.5%) than at sea level, because increased total pressure maintains oxygen partial pressure within the vital range.

ISO connection:

- **ISO 45001** requires monitoring oxygen levels in confined spaces.
- **ISO 31000** treats oxygen deficiency as a critical risk factor.
- **ISO 7396-1** (medical gas pipeline systems) ensures oxygen supply in healthcare facilities.

Carbon Dioxide (CO^2)

CO^2 is a colorless gas with a slightly acidic odor. Relative density: **1.52.** Molecular weight: 44. Under normal conditions, 1 L CO^2 weighs 1.96 g. Solubility in water at 0 °C: 179.7% by volume.

CO^2 is chemically inert, does not burn, and does not support combustion. Physiologically, it is mildly toxic. At **3%** concentration, it stimulates breathing via excitation of the respiratory center. At **6%**, causes weakness and difficulty breathing. At **10%**, loss of consciousness. At **20–25%**, lethal poisoning.

Sudden natural release of CO^2 occurs in coal mines. Documented cases include sudden emissions of 700,000 m³ CO^2 with accompanying rock mass of 65,000 tons.

ISO connection:

- **ISO 45001** requires monitoring CO^2 in workplaces.
- **ISO 14001** links CO^2 emissions to environmental sustainability.
- **ISO 31000** frames CO^2 accumulation as a risk scenario in mining and industrial safety.

Nitrogen (N^2)

Nitrogen has no smell, color, or taste. Relative density: 0.97. Molecular weight: 28.016. Under normal conditions, 1 L nitrogen weighs 1.25 g. Solubility in water at 0 °C: 2%. Nitrogen is chemically highly inert. Increased nitrogen concentration affects humans only by reducing oxygen partial pressure.

ISO connection:

- **ISO 45001** requires monitoring inert gases in confined spaces.
- **ISO 31000** treats nitrogen accumulation as a risk factor due to oxygen displacement.
- **ISO 14001** links nitrogen oxides to environmental compliance.

3.7. Normalization of Air Concentration

Air concentration normalization is a sanitary task aimed at maintaining an environment with air suitable for human respiration. In Georgia, the protection of atmospheric air from harmful anthropogenic impacts is regulated by the Law of Georgia on Atmospheric Air Protection.

In addition, human technogenic activity may introduce toxic, radioactive, flammable, explosive, and other harmful impurities into the air. Their **Maximum Allowable Concentration (MAC)** is regulated according to sectoral norms. The purpose of normalization is to significantly reduce or prevent the entry of toxic and harmful substances into the human body through breathing, contact, or other pathways.

Compliance with these norms improves working conditions, prevents poisoning in workplaces, and in the long term reduces the risk of occupational diseases.

For obvious reasons, it is impossible to present all sectoral norms within this manual. This is especially difficult in Georgia, where diverse technical regulations are in force (e.g., Government Decree No. 45 of February 24, 2006). Therefore, when discussing toxic and harmful air impurities, the MAC values provided here correspond to the strictest norms — those for underground working conditions. For other types of work, the norms are less stringent [27-30].

ISO Connection:

- **ISO 45001:** Requires continuous monitoring of workplace air quality and compliance with occupational exposure limits.
- **ISO 31000:** Frames air impurity concentration as a quantifiable risk factor in safety management systems.
- **ISO 14001:** Links air quality normalization to environmental management and sustainability.
- **ISO 10012:** Ensures measurement management systems are reliable when monitoring air concentration.

3.8. Toxic and Explosive Air Impurities

Carbon Monoxide (CO)

Carbon monoxide has no smell, color, or taste. Relative density: 0.97. Molecular weight: 28. Mass of 1 L at normal conditions: 1.25 g. Solubility in water at 0 °C: 3.3%. CO burns and explodes in air within the concentration range of 12.5–75.0%. Maximum explosion energy occurs at 30% mixture, with ignition temperature 630–810 °C.

Reaction:

$$2CO + O_2 = 2CO_2.$$

CO is highly toxic because it binds to hemoglobin 250–300 times more strongly than oxygen, displacing O^2. Full blood saturation requires only 300 cm³ CO.

Symptoms of poisoning:

1. **Mild poisoning** – 0.048% CO for 1 hour: headache, tinnitus, dizziness, rapid heartbeat.
2. **Severe poisoning** – 0.128% CO for 0.5–1 hour: loss of motor ability, impaired thinking.
3. Lethal dose – 0.4% CO: unconsciousness and convulsions; at 1% CO, death after a few breaths.

Severity depends on body type (obese, thin) and condition (rested, fatigued). First aid: **artificial respiration in fresh air**.

CO is released during incomplete combustion, including in internal combustion engines. It may also form in compressors if lubricating oil decomposes at high temperature.

Permissible concentration:

- In coal mines: 0.0024% (20 mg/m³).

ISO connection:

- **ISO 45001:** Requires monitoring CO in workplaces.
- **ISO 31000:** Frames CO exposure as a critical risk scenario.
- **ISO 14001:** Links CO emissions to environmental compliance.

Nitrogen Oxides (NO, NO^2, N^2O^4, N^2O^5). Nitrogen oxides are characterized by brown color and pungent odor. Stable forms in air: NO^2 and N^2O^4. At higher temperatures, N^2O^4 decomposes into NO^2. Both dissolve well in water.

- NO^2 relative density: 0.97; molecular weight: 46.01; mass of 1 L: 2.05 g.
- N^2O^4 relative density: 3.18; molecular weight: 92.02; mass of 1 L: 4.11 g.

Nitrogen oxides are highly toxic, causing respiratory and eye irritation, and in severe cases pulmonary edema. Effects may be delayed (4–6 hours, sometimes 20–30 hours). Symptoms: nausea, coughing, headache, fever, cardiac disturbance, cyanosis.

Lethal dose: short-term inhalation at 0.025% concentration.

Danger: humans cannot immediately sense NO_x. A lethal dose may be inhaled without awareness for hours. Therefore, dosimetric monitoring is essential in workplaces where NO_x emissions are possible [31-34].

NO_x are released during explosive work and diesel engine exhausts (high NO_x, lower CO). Gasoline engines release more CO, less NO_x.

Permissible concentration in coal mines:

- For NO^2: ≤ 0.0002%.

ISO connection:

- **ISO 45001:** Requires monitoring NO_x in industrial and mining environments.
- **ISO 31000:** Frames NO_x exposure as a delayed but critical risk.
- **ISO 14001:** Links NO_x emissions to environmental sustainability.
- **ISO 10012:** Ensures measurement accuracy in dosimetric monitoring.

Sulfur Dioxide (SO^2). Sulfur dioxide is a colorless gas with a strong suffocating odor and acidic taste. Relative density: 2.22, molecular weight: 64.07, mass of 1 L at normal conditions: 2.86 g, solubility in water at 20 °C: 40 volumes per 1 volume of water.

SO^2 is highly toxic, causing respiratory and eye irritation. Severe cases lead to bronchitis, throat and lung edema [35].

- 0.05% concentration – lethal after a few breaths.
- 0.0005% concentration – detectable by humans, allowing basic control without instruments.

Permissible concentration in coal mines: 0.00035%.

ISO connection:

- **ISO 45001** requires monitoring SO^2 in workplaces.
- **ISO 14001** links SO^2 emissions to environmental compliance.
- **ISO 31000** frames SO^2 exposure as a critical risk factor.

Hydrogen Sulfide (H^2S)

Hydrogen sulfide is a colorless gas with a rotten egg odor and sweetish taste. Relative density: 1.19, molecular weight: 34.09, mass of 1 L at normal conditions: 1.52 g, solubility in water at 0 °C: 4.4 volumes per 1 volume of water. H^2S burns and explodes at 6% concentration in air. Detectable at 0.0001% concentration [36].

Highly toxic, irritating eyes and respiratory tract. Symptoms: irritation, fatigue, nausea, loss of consciousness.

Lethal dose: 0.1% concentration for a short time.

First aid: artificial respiration in fresh air; inhalation of chlorine; covering respiratory organs with a cloth soaked in chlorine solution.

Permissible concentration in coal mines: 0.00066%.

ISO connection:

- **ISO 45001** requires monitoring H^2S in confined spaces.
- **ISO 31000** frames H^2S accumulation as a high-risk scenario.
- **ISO 10012** ensures measurement accuracy in gas detection systems.

Ammonia (NH^3)

Ammonia is a colorless gas with a sharp odor. Relative density: 0.596, molecular weight: 17.03, mass of 1 L at normal conditions: 0.77 g, solubility: highly soluble in water.

Explodes in air at 30% concentration. Toxic, irritating skin, eyes, and respiratory tract. High concentrations cause throat swelling.

Maximum permissible concentration in air: 0.0025%.

ISO connection:

- **ISO 45001** requires ammonia monitoring in industrial workplaces.
- **ISO 14001** links ammonia emissions to environmental management.
- **ISO 31000** frames ammonia exposure as a quantifiable risk.

Acrolein ($CH^2CHCHOH$)

Acrolein is a colorless, volatile liquid. Produced at high temperatures during decomposition of diesel fuel and lubricants. Relative density: 1.9, solubility: dissolves well in water.

Highly toxic, irritating eyes and respiratory tract, causing dizziness, nausea, abdominal pain.

- 0.014% concentration for 10 minutes – lethal.

Maximum permissible concentration in air: 0.00008%.

ISO connection:

- **ISO 45001** requires monitoring acrolein in industrial environments.
- **ISO 14001** links acrolein emissions to environmental compliance.
- **ISO 31000** frames acrolein exposure as a critical risk.

Heavy Hydrocarbons and Acetylene

Heavy hydrocarbons such as **ethane** (C^2H^6), **propane** (C^3H^8), and **butane** (C^4H^{10}) may enter air during explosive work or processing of low-grade coal deposits. All are explosive and impart narcotic properties to air [37].

Acetylene (C^2H^2) is also a dangerous explosive substance, released during explosive work.

ISO connection:

- **ISO 45001** requires monitoring hydrocarbons in mining and industrial processes.
- **ISO 31000** frames hydrocarbon accumulation as a risk scenario.
- **ISO 14001** links hydrocarbon emissions to environmental sustainability.

Methane (CH^4)

Methane is considered one of the most dangerous gases due to its wide occurrence. Found in coal mining operations, landfill decomposition, and as the main component of natural gas. Also called swamp gas because swamps emit large amounts of it. No smell, color, or taste, relative density: 0.5539, molecular weight: 16.03, mass of 1 L at normal conditions: 0.716 g, solubility in water at 0 ℃: 3.5%.

Under normal conditions, methane is chemically inert, reacting only with halogens.

Small amounts of methane are not physiologically harmful. Danger arises when its concentration increases, reducing oxygen levels. At 50–80% concentration, with normal oxygen content, methane causes severe headaches and drowsiness. Mixtures with ethane and propane give air mild narcotic properties.

Combustion

Methane burns with a pale blue flame

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

In underground coal mines, methane combustion occurs under oxygen deficiency, producing carbon monoxide

$$CH_4 + O_2 = CO + H_2 + H_2O$$

Most of the water vapor condenses quickly, creating rarefaction in the area and facilitating inflow of fresh air.

- Ignition temperature: 650–750 ℃
- Depends on methane concentration, mixture composition, pressure, and ignition source.
- Heat of combustion: 54,425 kJ/kg (13,000 kcal/kg).

Methane forms flammable and explosive mixtures with air: at 5–6% concentration, burns only near a heat source, at 5–6% to 14–16%, the air–methane mixture explodes, above 14–16%, does not burn or explode, but can burn near a heat source if oxygen is supplied.

Maximum explosion strength occurs at 9.5% methane concentration. At higher concentrations, part of methane remains unburned due to oxygen deficiency. Methane's high calorific value lowers flame temperature of the explosion. Above 14–16%, self-extinguishing occurs and no explosion develops.

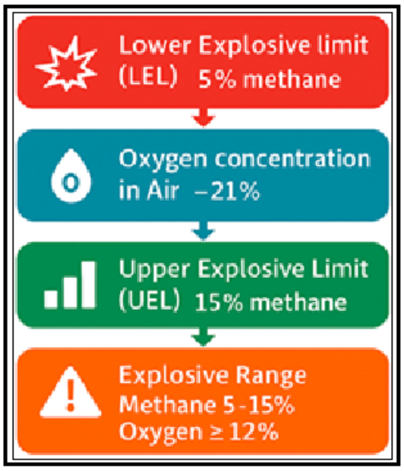

Fig. 3.5. Limits of methane explosiveness in air with oxygen

Methane Explosiveness

The mixture most easily ignited is that with methane concentration not exceeding 7–8%.

The lower explosive limit of mixtures of hydrocarbons (methane, ethane, etc.) and hydrogen with air is determined by Le Chatelier's formula

$$X = \frac{100}{\frac{K_1}{N_1}+\frac{K_2}{N_2}+\ldots+\frac{K_m}{N_m}} \tag{3.9}$$

where K^1, K^2, …, K_m are the concentrations (%) of each flammable or explosive component, under the condition that $\sum_{i=1}^{m} K_i = 100\%$; N is the lower explosive limit of each component in normal air composition (%).

Methane–air explosive limits expand with increased initial temperature or pressure. For example, at 10 atm pressure, the explosive range is 5.9–17.2%.

Methane exhibits ignition delay after contact with a heat source, called the induction period. Duration decreases sharply with rising temperature and increases slightly with higher methane concentration. Data are shown in Table 3.4.

Table 3.4. Induction Period Duration by Temperature and Methane Concentration

	Duration of the induction period (s) depending on the ignition temperature, ℃

Methane concentration, %	775	875	975	1075
6	1.08	0.35	0.12	0.039
7	1.15	0.36	0.13	0.041
8	1.25	0.37	0.14	0.042
9	1.30	0.39	0.14	0.044
10	1.40	0.41	0.15	0.049
12	1.64	0.44	0.16	0.055

Induction period is critical in **explosive operations in methane-containing coal mines**. Protected explosives are used, whose cooling time to safe temperature is shorter than the induction period [38-40].

In open space, methane explosion products reach **1875 °C**; in confined space, **2150–2650 °C**. Gas pressure is ~9 times higher than initial mixture pressure. With pre-compression by explosion waves, pressures may exceed **30 MPa (≈30 atm)**. Explosion wave velocity ranges from tens of meters per second up to **1000 m/s**.

Permissible methane concentration in coal mines: 1.0%.

Fatalities from methane explosions:

- In the USA, ~100 times fewer than in Ukraine. In Ukraine (2005), 4 deaths per million tons of coal mined.
- In Georgia (Tkibuli, 2010), fatalities per million tons mined were ~1000 times higher than in the USA.

ISO Connection:

- **ISO 45001:** Requires monitoring methane levels in mines and confined spaces.
- **ISO 31000:** Frames methane explosiveness as a critical risk scenario in occupational safety.
- **ISO 14001:** Links methane emissions to environmental sustainability and greenhouse gas management.
- **ISO 10012:** Ensures measurement accuracy in methane detection systems.

Hydrogen (H^2)

Hydrogen is a colorless gas. Relative density: 0.07, molecular weight: 1.0, mass of 1 L at normal conditions: 0.09 g, solubility in water at 0 °C: 2.1%. Hydrogen burns and explodes in air at concentrations **4–74%**. **Ignition temperature:** 450–550 °C. Released during battery charging, in coal mines, and from certain rock masses.

Maximum permissible concentration in air: 0.5%.

ISO Connection

- **ISO 45001**: Requires monitoring methane and hydrogen in mining and industrial workplaces.
- **ISO 31000**: Frames methane/hydrogen explosiveness as high-risk scenarios in occupational safety.

- **ISO 14001**: Links methane and hydrogen emissions to environmental sustainability.
- **ISO 10012**: Ensures measurement accuracy in explosive gas detection systems.

3.9. Industrial Dust in Air and Its Effects

During various technological processes, industrial dust is generated — small particles suspended in air that gradually settle. Suspended dust is called the dispersed phase, while air is the dispersed medium. The dust–air mixture is called an aerosol.

Dust is produced in technological processes such as crushing, grinding, sieving, transporting, loading/unloading, and processing of materials. It also arises during earthworks, electric welding, and other operations.

By origin, dust may be organic, inorganic, or mixed:

- Organic dust: animal or plant origin (fur, wood, coal, peat, etc.).
- Inorganic dust: metallic or mineral origin (aluminum, cement, building stone, etc.).

Effects on the Human Body

The harmful impact of dust depends on its physical–chemical properties, size, shape, concentration, duration of exposure, and other factors.

Dust's chemical composition significantly affects the body. Since dust enters mainly through the respiratory system, it primarily damages the lungs. It causes bronchitis, pneumoconiosis, and sometimes allergies. Non-specific diseases include upper respiratory tract damage, skin redness, and impaired vision. Inhaled dust may lead to tuberculosis or mild forms of oncological diseases [41-43].

The most harmful and aggressive dusts are those of silica, silicates, coal, and certain metals/minerals, which cause fibrosis in the lungs, impairing function and leading to severe occupational disease — pneumoconiosis.

Pneumoconiosis

Pneumoconiosis is a general term for occupational diseases caused by long-term inhalation of harmful aerosols. Specific forms include:

- **Silicosis** – caused by free silica dust (sand, quartz).
- **Asbestosis** – caused by asbestos dust.
- **Talcosis** – caused by talc dust.
- **Cementosis** – caused by cement dust.
- **Anthracosis** – caused by coal dust.
- **Aluminosis** – caused by aluminum dust.

The most widespread and dangerous form is silicosis, common among mining workers and those handling cement, sand, and gravel.

Free silica also negatively affects the skin. Prolonged exposure to dusty environments causes skin diseases, weakens vision and hearing, and damages the heart, lungs, and nervous system.

Dust Particle Size (Dispersion)

Dust harmfulness depends on dispersion (particle size). Dust is classified into three groups:

- Visible dust: ≥10 μm
- Microscopic dust: 0.25–10 μm
- Ultramicroscopic dust: <0.25 μm (visible only under electron microscope)

Smaller particles remain suspended longer, making their effects more harmful.

Industrial Dust Concentration and Control

Dust hardness has little practical effect on harmfulness. For example, quartz dust is more dangerous than harder mineral dusts (carborundum, corundum).

The harmfulness of dust is evaluated by its concentration and toxicity. Concentration is determined by passing a certain volume of dusty air through a filter, then calculating the mass of collected dust relative to air volume. Dust mass is measured by weighing the filter before and after sampling. The volume of air passed through the filter is measured using electrical or ejector aspirators.

Formula for Dust Concentration

$$c_2 = \frac{p_2 - p_1}{V_0} \tag{3.10}$$

where: p^1 – initial filter mass before sampling, mg; p_2 – filter mass after sampling, mg; V_0 – volume of air passed through the filter, m³.

3.6. Industrial Dust in Air

Measurement Methods

For relatively low dust levels, special instruments such as **OYEUC-1** konimeter are used, consisting of a cylindrical pump, receiving chamber, humidifying chamber, and control glass. Dust mass deposited on the glass is recalculated per unit air volume.

Other instruments for determining particle number and dispersion include:

- BDK-4 flow ultramicroscope;
- F-1, F-2, FEP-6 photodust meters;
- EKTM, EK-4 electrical konimeters;
- PRP-3 electrical dust meters.

Preventive Measures

To prevent harmful effects of dust, collective protective equipment, biological methods, and anti-dust technologies are essential. These include:

- Material moistening;
- Process hermetization;
- Pneumatic transport of dust-producing materials;
- Modern packaging and sealing machines;
- Hermetization of loading/unloading equipment.

The most important collective measure is effective local ventilation. Workers undergo medical examinations before employment and periodically thereafter to prevent disease.

Technological Measures

Dust prevention is more effective through technological improvements:

- Hermetization and mechanization of dust-producing processes;
- Installation of special herm.

ISO Connection:

- **ISO 45001:** Requires monitoring dust levels in workplaces and implementing protective measures.
- **ISO 31000:** Frames dust exposure as a quantifiable occupational risk.
- **ISO 14001:** Links dust emissions to environmental management and sustainability.
- **ISO 10012:** Ensures measurement accuracy in dust monitoring systems.

3.10. Normalization of Microclimatic Parameters in Industrial Spaces

The warm season is characterized by outdoor air temperatures of +10 ℃ or higher, while the cold season is defined by temperatures below +10 ℃.

In the workplace zone, both high and low air temperatures, as well as relative humidity and air velocity, are regulated.

Humans release different amounts of heat depending on whether they are working or resting. During work, excess heat is transferred to the environment through evaporation of fluids (sweating), which helps maintain thermal balance. Under equal conditions, the level and nature of human thermoregulation depend on air temperature, relative humidity, and velocity.

- Increased relative humidity reduces sweat evaporation, intensifying the impact of high temperatures.
- At low temperatures, high humidity increases air’s thermal conductivity, enhancing heat loss from the body.
- Thus, high humidity makes both high and low temperatures feel more extreme.

Air velocity has a similar effect: higher velocity increases the heat transfer coefficient, raising convective heat loss. The convective heat flux from the human body can be calculated by

$$q = \alpha_q (t_2 - t_1) \tag{3.11}$$

where: q – heat flux per unit surface area of the human body, W/m²; α_q – heat transfer coefficient, W/(m²·°C); t_1, t_2– surface temperature of the human body and ambient air temperature, °C.

When $t_1 > t_2$, higher air velocity increases cooling both objectively and subjectively. If the air temperature is higher than the body surface temperature, increased velocity causes discomfort, as heat flows from air to body. Considering clothing and exposed skin, average body surface temperature is 27–28 °C.

Thus, at temperatures above 28 °C, increased air velocity causes discomfort, intensified by higher humidity. Heat transfer then occurs mainly through sweat evaporation, and heat stroke may result. Heat stroke is most likely under conditions of high temperature, high humidity, and high air velocity.

Heat Balance Example

A person at rest in an environment of 20 °C releases 450–600 kJ of heat per hour:

- 15.3% via convection;
- 29.1% via evaporation;
- 41.7% via radiation.

Heat transfer coefficient under these conditions: α_q=10–13 W/(m²·°C), which may increaseup to 4 times during heavy work.

From the above heat balance data, it is evident that humans release the largest portion of heat — 41.7% via radiation. Radiative heat transfer occurs between the human body and air or surrounding surfaces according to the fourth power of their absolute temperatures (Kelvin scale).

At high temperatures, cooling screens (cold surfaces) are effective. Cold surfaces are generally more efficient than air conditioning due to this fourth-power law, since convective heat transfer is proportional only to the first power of temperature difference. Additionally, conditioned air increases comfort perception through improved breathing [44-48].

Abnormal temperature conditions reduce labor productivity by 20–30%.

Optimal vs. Permissible Microclimatic Conditions.

- Optimal microclimatic conditions: A combination of parameters that, under long-term and systematic exposure, create comfort and productive working conditions.
- Permissible microclimatic conditions: A combination of parameters that may strain the body’s thermoregulation mechanisms but remain within physiological adaptation limits. No discomfort is felt, mood is not worsened, and productivity is not reduced.

Optimal conditions in workplaces or rest areas can be achieved through ventilation combined with air conditioning systems. Permissible conditions can be maintained with ventilation systems alone.

Air conditioning systems involve not only cooling but also heating, drying/humidifying, ionization, and other adjustments to keep air parameters within optimal ranges.

ISO Connection:

- **ISO 45001:** Requires monitoring workplace microclimate to protect worker health and safety.
- **ISO 7730:** Defines thermal comfort standards (PMV/PPD indices) for indoor environments.

- **ISO 14001:** Links microclimate control to environmental sustainability.
- **ISO 31000:** Frames abnormal microclimate as a quantifiable occupational risk factor.

3.11. Determination of Air Velocity, Flow, and Quantity

In workplaces, periodic monitoring of microclimatic parameters of air is essential. This must be done through reliable measurements and comparison with permissible norms.

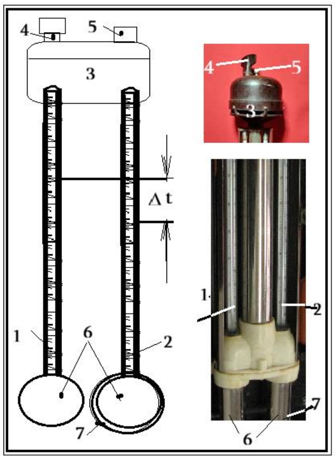

Fig. 3.7. Assmann Psychrometer
1 - dry thermometer; 2 - wet thermometer; 3 – Aspirator; 4 - winding mechanism; 5 - hanging hook; 6 - mercury balls; 7 - a piece of cotton wrapped around a mercury ball; Δt - temperature difference

Temperature Measurement. Air temperature is measured with a thermometer placed in a protective metal casing.

- The thermometer is positioned at the measurement site.
- The first reading is taken after 5 minutes.
- A second reading is taken after another 5 minutes.
- If both readings are identical, the measurement is considered valid.

Relative Humidity Determination. Relative humidity is not measured directly. Instead, air temperature is measured simultaneously with a 'dry' thermometer and a 'wet' thermometer.

- The wet thermometer's bulb is wrapped with a piece of batist cloth, moistened with distilled water using a special pipette.
- The pipette, cloth, and mounting accessories are supplied with the psychrometer, the instrument used to measure relative humidity.

Relative humidity is determined from the difference between the dry and wet thermometer readings.

Measurement procedure:

- fill the pipette with distilled water.
- Moisten the cloth around the wet thermometer bulb.
- Do not touch the dry thermometer.
- Wind the aspirator fan, which begins operating immediately.

• Hang the psychrometer at the desired measurement location.

Important: Holding the psychrometer in hand during measurement causes errors.

After 5 minutes, readings are taken from both thermometers. Relative humidity is determined using Table 3.5 or special formulas, which also require barometric pressure data. Graphs and tables for relative humidity are included in the psychrometer's manual.

Electropsychrometers

Electropsychrometers also exist, which determine relative humidity using the same Assmann method — the difference between readings of wet and dry thermometers (Fig. 3.8b). These instruments can measure relative humidity both outdoors and indoors.

Electric power is used to operate the aspirator, so the device does not require a manual winding mechanism. Unlike the standard psychrometer, it has no hanging hook but is equipped with a special fork for mounting, as shown in the diagram.

Fig. 3.8. Hygrometer and Psychrometer:
A – Hygrometer; B – M-34M type Electro psychrometer; 1 – Mounting point for hanging fork

Table 3.5. Variation of Relative Humidity According to Dry–Wet Thermometer Difference

Dry thermometer reading	Difference between dry and wet bulb thermometer readings							
	0	1	2	3	4	5	6	7
	Relative humidity, %							
0	100	81	63	46	28	12	–	–
5	100	86	71	58	43	31	17	4
6	100	86	72	59	46	33	21	8
7	100	87	74	60	48	36	24	14
8	100	87	74	62	50	39	27	16
9	100	88	75	63	52	41	30	19
10	100	88	77	64	53	43	32	22
11	100	88	79	65	55	45	35	25
12	100	89	79	67	57	47	37	27
13	100	89	79	68	58	49	39	30
14	100	89	79	69	59	50	41	32
15	100	90	80	70	61	51	43	34
16	100	90	80	70	61	53	43	34
17	100	90	80	71	62	55	47	40
18	100	90	80	72	63	55	48	41

19	100	91	81	72	64	57	50	41
20	100	91	81	73	65	58	50	42
21	100	91	82	74	66	58	50	44
22	100	91	82	74	66	58	51	45
23	100	91	83	75	67	59	52	46
24	100	91	83	75	67	59	53	47
25	100	92	84	76	68	60	54	48
26	100	92	84	76	69	62	55	50
27	100	92	84	77	69	62	56	51
28	100	92	84	77	70	64	57	52
29	100	92	85	78	71	65	58	53
30	100	92	85	79	72	66	59	53

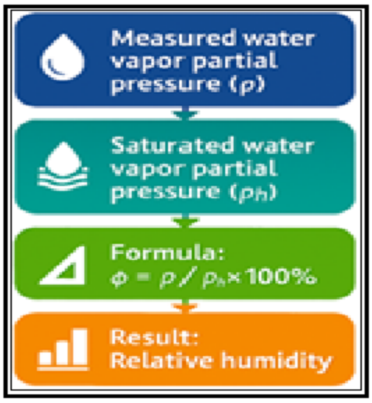

Fig. 3.9. Infographic diagram for calculating relative humidity

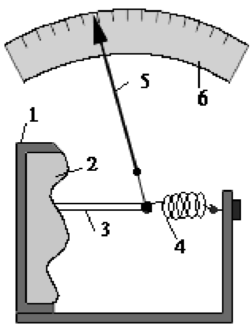

Fig. 3.10. Barometer–Aneroid:
1 – Housing; 2 - Membrane (corrugated, like the housing); 3 – Lever; 4 – Spring; 5 – Pointer; 6 - Graduated scale

Pressure Measurement

It is important to distinguish between barometric pressure measurement and measurement of pressure differences between two cross-sections of an air stream.

The mercury barometer is more precise, with readings directly in millimeters. However, it is inconvenient due to large size, fragility, and limited use in laboratories. For practical purposes, the metal barometer (aneroid) is more convenient, though less accurate.

The main part of the aneroid barometer is a cylindrical chamber evacuated of air, covered with a corrugated membrane acting like a spring. The membrane connects via a lever to a spring fixed at one end to the housing, with the other end connected to a pointer that shows pressure on the scale.

The scale is graduated in millimeters of mercury (600–790 mm) or equivalent values in Pascals.

Since atmospheric pressure decreases with altitude, the barometer scale may also indicate distance above sea level. Such a barometer is called an altimeter, used by mountaineers, parachutists, pilots, etc.

Barometers require correction factors:

1. Temperature correction – accounts for changes per 1 °C.
2. Constant correction – accounts for material properties of the instrument.

Barometers are inertial; readings should be taken 25–30 minutes after placement.

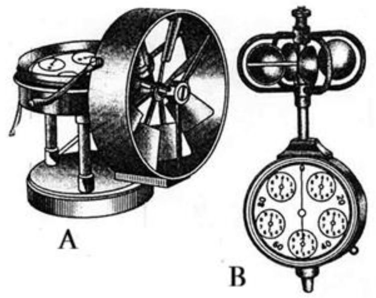

Fig. 3.11. Anemometers
A - Vane type; B - Cup type

Air Velocity Measurement.

Air velocity is measured with an anemometer, of two types (Fig. 3.11):

- Vane type – rotating blade in a cylinder.
- Cup type – four hemispherical cups mounted crosswise.
- Cup anemometers measure high velocities (1–40 m/s).
- Vane anemometers measure low velocities (0.1–5 m/s).

Average Velocity Measurement.

In all sections, the observer moves the anemometer by hand in a motion similar to that shown in Fig. 3.12. Measurement should be completed within 100 seconds.

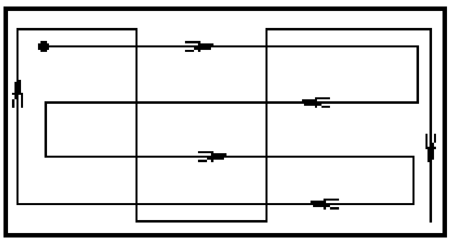

Fig. 3.12. Measuring average air velocity: arrows indicate the direction of hand movement with the anemometer

Velocity measurement refers to the average velocity across a section. If velocity is so low that vane rotation is intermittent, measurement is taken at the center, and average velocity across the section is calculated by

$$\bar{V} = kV \tag{3.12}$$

where: $\bar{V}$– average velocity across the section, m/s; V – velocity measured at the center, m/s; k – coefficient of non-uniform velocity distribution, $k = 1.2 - 1.4$.

This method is less accurate and used only when other methods are impossible.

Velocity can be measured in ducts or any section with noticeable air movement. The observer may stand in the section, or the section may be located 2.0–2.5 m ahead, with the anemometer mounted on a 1.5–2.0 m rod.

Fig. 3.13. Digital Electric Anemometer OMEGA HH-32A

Observation is performed by two people:

- One operates the anemometer, including switching it on/off.
- The other operates the stopwatch, also informing the first about elapsed time to regulate hand movement speed.

The anemometer reading must be divided by 100. Based on this value, the average velocity is determined approximately using the graph provided in the instrument's manual.

For more precise velocity measurement, correction coefficient is applied:

- If velocity is measured with extended hand, then k_1 = 1.14.
- Otherwise, is determined by

$$k_1 = \frac{S-0,4}{S} \tag{3.13}$$

where S is the area of the section.

Recently, various types of electric and digital anemometers have been introduced (see Fig. 3.13).

Air Flow Calculation

Air flow rate is calculated from average velocity and section area using

$$Q = VS \tag{3.14}$$

where: Q – air flow rate, m^3/s; V – average velocity, m/s; S – section area.

It is essential to ensure that no other section allows air movement, i.e., the measured section must carry the entire air flow of the space.

ISO Connection:

- **ISO 5167:** Defines methods for measuring fluid flow in pipes and ducts.
- **ISO 3966:** Specifies measurement of air velocity and flow in ducts using anemometers.
- **ISO 7730:** Links air velocity to thermal comfort indices.
- **ISO 10012:** Ensures accuracy and calibration of barometers and anemometers.
- **ISO 45001:** Requires monitoring workplace air parameters for safety.

3.12. Variability of Climatic Air Parameters

Air temperature, relative humidity, and barometric pressure constantly vary — both within a day and over longer periods. Observation of these variations is carried out using thermographs, hygrographs, and barographs, shown in Fig. 3.14.

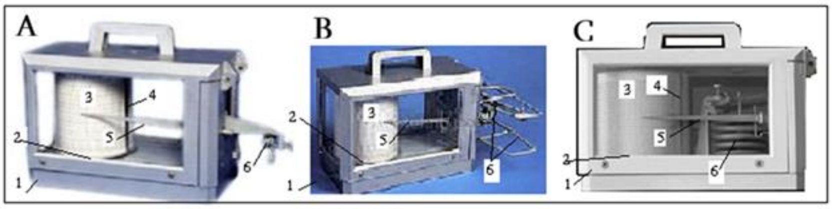

Fig. 3.14. Thermograph, Hygrograph, and Barograph:
A – Thermograph; B – Hygrograph; C – Barograph; 1 – Housing; 2 – Clock mechanism; 3 – Rotating drum; 4 – Special paper belt attached to drum; 5 – Lever with self-recording pen;6 – Sensitive element for temperature, humidity, or pressure variation

Principle of Operation

These instruments do not measure absolute values of temperature, humidity, or pressure directly. Instead, they record the variation of measured parameters over the period defined by the clock mechanism's resource. The drum rotates, and a pen filled with special ink marks the variations on calibrated paper, producing a graph of changes.

Depending on the clock mechanism, instruments are available as daily or weekly thermographs, hygrographs, and barographs.

Installation Procedure

1. Select locations that best represent temperature, humidity, or pressure variations in the space.
2. Define the observation period (daily or weekly).
3. Choose the appropriate instrument and calibrated paper, attach it to the drum.
4. Measure or determine the initial parameter value at the observation site.
5. Adjust the pen mechanism accordingly.
6. Use special ink that remains usable for 2–3 months without drying.
7. On the back of the paper, record the observation site and date.
8. On the front, note the start time and initial parameter value.

ISO Connection:

- **ISO 7726:** Specifies instruments and methods for measuring environmental parameters (temperature, humidity, pressure).
- **ISO 45001:** Requires monitoring workplace climate conditions for safety.
- **ISO 14001:** Links climatic monitoring to environmental management systems.
- **ISO 10012:** Ensures accuracy and calibration of recording instruments.

3.13. Use of Appropriate Protective Measures

Research on air composition, pressure, temperature, humidity, and density variability in the workplace is not limited to physical–chemical data; it is directly linked to occupational safety.

- ISO 45001 (Occupational Health and Safety Management Systems) requires continuous monitoring of air quality. This necessitates compliance with sanitary–hygienic norms and effective operation of ventilation systems, ensuring a safe working environment.
- ISO 31000 (Risk Management) emphasizes the use of quantitative data in determining risk indices, integrating parameters such as partial pressures and humidity levels.

Collective Protective Measures

To reduce harmful effects described in this chapter, collective protective measures must be prioritized, in line with ISO 45001 requirements.

- Objective measures: ventilation, air conditioning, filtration, and similar engineering controls.
- Subjective measures: warning signs, adherence to instructions, compliance with hygiene rules.

Individual Protective Measures

For personnel protection, individual protective equipment is also essential:

- Respirators
- Protective masks

These supplement collective measures and safeguard workers against harmful air conditions.

Global Framework

The World Health Organization (WHO) highlights the necessity of air quality control in both industrial and medical environments to reduce risks of infections, asphyxia, and other health disorders.

Systemic Perspective

This paragraph provides readers with a systemic view: air parameter research is not merely theoretical but directly connected to the correct interpretation of international standards and the proper use of protective measures.

ISO Connection:

- **ISO 45001:** Prioritizes collective protective measures in occupational safety.
- **ISO 31000:** Integrates quantitative air parameter data into risk management.
- **ISO 14001:** Links air quality control to environmental sustainability.
- **ISO 10012:** Ensures accuracy of monitoring instruments used in protective systems.

4. Natural and Artificial Ventilation of Premises

4.1. Guide to Chapter IV

Natural and artificial ventilation of premises, discussed in Chapter IV, is not merely a technical issue but also a subject of research whose purpose is to ensure safe and health-conducive working conditions. Ventilation serves as a practical demonstration of research methods in occupational safety.

To evaluate the effectiveness of ventilation, research methods are applied:

- Quantitative – formulas, calculations, normative data.
- Qualitative – sanitary-hygienic observation and environmental assessment.

Thus, ventilation exemplifies how research methodology operates in real workspaces.

Ventilation calculation formulas represent the key to quantitative research methods used for risk assessment. Formulas (airflow rate, heat assimilation, humidity, dust, toxic admixtures, etc.) must be interpreted as quantitative research tools. Each calculation is a risk assessment — determining whether air exchange is sufficient to reduce harmful factors to permissible levels. Data obtained through calculations are compared with normative requirements, which is the essence of applying risk indices in practice [49-51]. Normative regulation is therefore the decomposition of research results — comparing obtained data with sanitary-hygienic standards. This process constitutes qualitative research, ensuring compliance of safety indices with ISO 45001 requirements.

Through experimental and numerical research methods, the effectiveness of natural and artificial draft can be compared. For example, by observing density variations or numerically modeling the piston effect of trains under defined initial and boundary conditions, it is possible to determine the magnitude and direction of natural draft in complex aerodynamic processes. Mechanical draft efficiency can be established through experimental data on pressure developed by fans. Furthermore, opposing directions of natural and mechanical draft may be interpreted, algebraically combined, and compared with standards to draw appropriate conclusions.

ISO 16000 series establishes internationally recognized standards for indoor air quality, including ventilation requirements and measurement protocols. **ISO 16890** complements this by defining filtration efficiency for air-cleaning devices, ensuring that both natural and artificial ventilation systems are evaluated against validated criteria. By linking the guidance of Chapter IV to these standards, the monograph situates its analysis within a globally harmonized framework. This connection reinforces the scientific credibility of ventilation strategies and highlights their relevance for occupational safety, environmental health, and building design.

4.2. Methods of Creating Air Exchange in Premises

Air exchange means the partial or complete replacement of indoor air with atmospheric air, performed at a defined frequency. To set air in motion, energy must be imparted, which may be obtained naturally or artificially. This energy is expended to overcome aerodynamic resistance — that is, the resistance encountered by air due to friction with stationary or moving surfaces or mixing with other flows along its path. (ISO 31000)

When energy is imparted naturally, it is called natural draft; when imparted artificially, it is called mechanical draft. Mechanical draft may be either greater or less than atmospheric pressure. In the first case, it is supply ventilation; in the second, it is exhaust ventilation. (ISO 45001)

An example of natural draft is a chimney: once fuel is ignited, hot gases are released, which expand and decrease in density, thereby rising naturally under gravitational forces. Thus, where there is fire, there is naturally induced draft. Another example is a moving train in a metro tunnel, which, through the piston effect, imparts high pressure to the air mass ahead and simultaneously creates suction behind due to reduced pressure. Hence, the moving train naturally generates draft. This phenomenon is more difficult to calculate theoretically, while draft induced by density variation can be calculated using the formula

$$h = (\gamma_1 - \gamma_2)gH \tag{4.1}$$

where: h - natural draft depression (Pa); γ_1, γ_2 - average air density in the atmosphere and in the chimney flue (N/m^3); g - acceleration of free fall (m/s^2); H - chimney height (m). For inclined ducts, H is the vertical height.

This formula also enables calculation of draft induced by density variation in any underground or above-ground structure, provided the average densities of moving and atmospheric air are known.

In underground structures, the average density of moving air is less affected by seasonal variation, whereas atmospheric air density changes sharply with the season. The principle of this variation is illustrated in Figure 4.1.

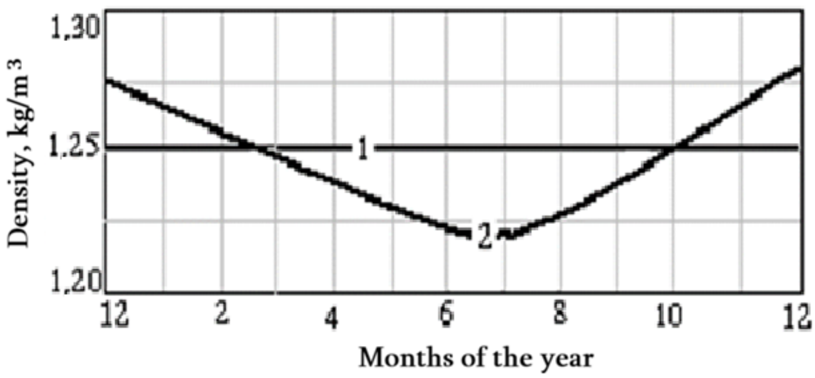

Figure 4.1. Character of Average Air Density Variation: 1 – Underground structure; 2 – Open atmosphere.

The diagram shows that in summer months, atmospheric air density is lower than the density of ventilation air in underground structures, while in the cold season the opposite occurs. Consequently, natural draft changes direction depending on the season. During transitional periods, air movement ceases because the density difference equals zero. A similar variation occurs within the daily cycle, though with smaller amplitude.

From this, it is evident that ventilation based solely on natural draft cannot always be reliably managed; consistent and guaranteed control is possible only through mechanical (artificial) ventilation.

Thus, air exchange in premises may be induced either by natural draft or by mechanical draft. Less intensive, unorganized air exchange can also be achieved by opening windows (aeration) or through gaps and cracks in building structures (infiltration).

Explanatory Notes:

- **Summer** — Atmospheric air density lower than underground → draft flows upward.
- **Winter** — Atmospheric air density higher than underground → draft flows downward.
- **Transitional periods** — Densities equal → no draft.
- **Daily cycle** — Small amplitude variations, draft direction changes slightly.

Traditionally, excess pressure in supply ventilation was called compression, while reduced pressure in exhaust ventilation was called depression. In modern terminology, however, both are referred to as depression, just as in natural draft. Therefore, natural draft depression means the pressure imparted to the airflow, measured in units such as pascals, while mechanical draft depression means the pressure imparted to the airflow by a fan, either greater or less than atmospheric pressure.

The pressure developed by a fan — its depression — in the most powerful models (capacity 1000 m^3/s, diameter 5 m) reaches 100 kPa, approximately equal to atmospheric pressure (101.325 kPa). To ensure safety, such fans are equipped with metal grilles to prevent people from being drawn into the flow. The company *Fläkt Woods* manufactures such fans, including special models for the Channel Tunnel, with a diameter of 4 m, static pressure of about 3 kPa, capacity of 300 m^3/s, and power of 900 kW [52-56].

The energy required to overcome aerodynamic resistance in any air duct is similarly called duct depression. Thus, natural draft depression or fan depression refers to pressure imparted to airflow naturally or mechanically, while duct depression refers to the pressure required to overcome aerodynamic resistance in ducts or similar systems.

The essence of ventilation calculation is to justify whether natural draft is sufficient for the ventilation purposes of a given space, or to select a fan of appropriate capacity capable of overcoming the depression caused by aerodynamic resistance of the duct network. In other words, sufficiency of natural draft also means its ability to overcome the aerodynamic resistance of the premises.

ISO 17772 and **ISO 16890** provide internationally recognized frameworks for methods of creating air exchange in premises. ISO 17772 specifies performance requirements for ventilation and indoor environmental quality, while ISO 16890 defines filtration efficiency for air-cleaning devices used in mechanical ventilation systems. By linking the discussion of air exchange methods to these standards, the monograph ensures that both natural and artificial ventilation strategies are scientifically validated and internationally comparable. This connection highlights the importance of harmonizing theoretical approaches with standardized practices, reinforcing the credibility of ventilation design in occupational and residential environments.

4.3. Ventilation Calculation

Determination of air consumption is carried out according to established norms of air exchange frequency, which vary depending on the purpose of the premises or the technological processes taking place within them.

Air exchange frequency indicates how many times the total volume of air in a room is replaced with fresh ventilation air within one hour. Important parameters for ventilation are air consumption, air velocity, and air exchange frequency. For example, if the air exchange frequency equals 3, this means that the air in the premises is replaced three times within one hour. Air exchange frequency also depends on the total volume of the premises, the number of workers, and the harmful admixtures released during technological processes.

In premises where the volume per worker is 20 m³, during winter and transitional seasons, external air inflow must be at least 30 m³/h per worker. In premises where the volume per worker is 20–40 m³, the minimum requirement is 20 m³/h per worker. Air recirculation is permitted during all seasons.

Air recirculation means reintroducing air extracted from the premises back into it, primarily to save heating energy. Recirculation is mainly applied during the cold season in premises where air is not polluted with harmful admixtures.

Air consumption is calculated based on the need to assimilate excess heat and humidity, as well as to reduce dust and toxic admixtures to safe concentrations. For subsequent calculations, the highest numerical value of air consumption is used. In formulas for excess heat, mass air consumption is applied, calculated as

$$G = Q\gamma \tag{4.2}$$

where: G - mass air consumption (kg/s); γ - average air density (kg/m³), $\gamma = 1.25$.

For excess heat, air consumption is calculated as

$$G = \frac{q_t}{c_p(t_2 - t_1)} \tag{4.3}$$

where: q_t - amount of excess heat released in the premises (kW); c_p - specific heat capacity of air at constant pressure (kJ/(kg·$°C$)); t_1, t_2 - temperatures of supplied and extracted air ($°C$).

For harmful gas emissions, air consumption is calculated as

$$Q = \frac{m}{x_2 - x_1} \tag{4.4}$$

where:

Q - volumetric air consumption, m³/s; m - mass of harmful gases released per unit time, mg/s; x_1, x_2 - gas concentration in atmospheric air and permissible concentration in indoor air, mg/m³.

Tables 4.1 and 4.2 present, respectively, the amount of carbon dioxide released by humans under different conditions and the permissible levels of carbon dioxide content in premises of various purposes.

Table 4.1. Amount of Carbon Dioxide Released by Humans Under Different Conditions

Age/Type of Activity	CO^2 Released (L/h)	CO^2 Released (L/h)
Physical work	45	68
Moderate work in institutions	23	35
At rest	23	35
Child under 12 years	12	18

Explanatory Notes of table 4.1:

- **Physical work** — Highest CO_2 release (45–68 L/h), requires strong ventilation to maintain safe air quality.
- **Moderate work in institutions** — Medium CO_2 release (23–35 L/h), ventilation must balance comfort and safety.
- **At rest** — Similar to moderate work (23–35 L/h), but prolonged exposure still requires adequate air exchange.
- **Child under 12 years** — Lowest CO_2 release (12–18 L/h), yet sensitive health demands careful ventilation control.

Table 4.2. Permissible Carbon Dioxide Content in Premises

Type of Premises	CO^2 (L/h)	CO_2 (g/h)	Relative Humidity (%)
Residential apartment	1.00	1.50	30 - 60
Children's room and hospital	0.70	1.00	30 - 60
Periodic human occupancy (institution)	1.25	1.75	30 - 60
Short-term human occupancy	2.00	3.00	> 95

Explanatory Notes of table 4.2:

- **Residential apartment** — Lowest permissible CO^2 (1.0 L/h, 1.5 g/h), ensures comfort and healthy living conditions.
- **Children's room and hospital** — Stricter limits (0.7 L/h, 1.0 g/h), reflecting higher sensitivity of occupants.
- **Periodic human occupancy (institution)** — Moderate limits (1.25 L/h, 1.75 g/h), suitable for offices and classrooms.
- **Short-term human occupancy** — Highest permissible CO^2 (2.0 L/h, 3.0 g/h), acceptable only for brief stays.

When excess moisture is present, air consumption is calculated as

$$G = \frac{q_m}{d_2 - d_1} \tag{4.5}$$

where: G - mass air consumption (kg/s); q_m - mass of water vapor released in the premises per unit time (mg/s); d_1, d_2 - moisture content of atmospheric and extracted air (mg/kg).

Here, kilograms measure the dry mass of air, while milligrams measure the mass of moisture. Both may be expressed in kilograms; in that case, and are dimensionless values with smaller numerical magnitude compared to the first case.

For dust, air consumption is calculated as

$$G = \frac{g_1}{s_2 - s_1} \tag{4.6}$$

where: G - mass air consumption (kg/s); g_1 - mass of dust released in the premises per unit time (mg/s); s_1, s_2 - permissible dust concentration in indoor air and actual concentration in atmospheric air (mg/m³).

As noted, for subsequent calculations the value requiring the highest air exchange frequency is retained. Based on this, the depression of the ventilation network is calculated as

$$h = RQ^2 \quad (4.7)$$

where: h - depression of the ventilation network, Pa; R - aerodynamic resistance of the network, N·s²/m⁸; Q - air consumption, m³/s.

The aerodynamic resistance of the ventilation network is determined by

$$R = \frac{\alpha PL}{S^3} \quad (4.8)$$

where: α - aerodynamic resistance coefficient, N·s²/m⁴; P- perimeter of the air duct, m; L - length of the air duct, m; S - cross-sectional area of the air duct, m².

For fan selection, the value obtained from formula (4.7) must be increased by adding depressions required to overcome local and frontal resistances, whose calculation formulas are provided below. The resulting value must then be increased by 10%. In this way, the selected fan will operate in the network without interruptions.

ISO 17772 and **ISO 15927** provide internationally recognized methodologies for calculating ventilation rates and indoor environmental parameters. ISO 17772 specifies performance requirements for ventilation and indoor air quality, while ISO 15927 defines methods for calculating climatic data relevant to building ventilation design. By linking ventilation calculations to these standards, the monograph ensures that computational methods are scientifically validated and internationally comparable. This connection reinforces the methodological rigor of air exchange analysis and highlights its relevance for both occupational safety and environmental health.

4.4. Ventilation Standardization

Humans spend most of their lives indoors; therefore, to maintain health, restore energy, and ensure good work capacity, indoor air must meet defined sanitary and hygienic requirements. These requirements are primarily ensured through ventilation, which, as noted in the previous chapter, may be combined with air-conditioning devices (heating or cooling, filtering, humidifying, drying, ionizing).

The purpose of air-conditioning equipment is to provide indoor air temperature appropriate for work and rest depending on the season. The purpose of filtering devices is to supply dust-free air to the premises. In some cases, extracted air is cleaned of dust before being released into the atmosphere to prevent environmental pollution. Humidification or drying of air may be required either for comfort conditions or due to the nature of technological processes. In all cases, clean air supply and removal of unsuitable air are achieved through ventilation. (ISO 31000, ISO 45001)

Air itself has no odor, but various admixtures give it pleasant or unpleasant smells. When air has an unpleasant odor, even if caused by harmless (non-toxic) gases, normal breathing is disrupted. People begin to breathe shallowly and frequently, reducing oxygen intake, which leads to disturbances in physiological processes. Prolonged exposure to this undesirable factor worsens health and reduces work capacity.

Ventilation and air-conditioning (particularly heating) systems in buildings are necessary not only for protecting human health but also for preserving the durability of construction structures. Buildings with poor heating and ventilation deteriorate prematurely due to moisture accumulation, freezing, and deformation of construction materials.

Therefore, ventilation systems are subject to special requirements defined in sectoral norms. These vary widely depending on the industry, so they are not detailed here. For example, woodworking, paper processing, textile, metalworking, printing, food industry, and power generation facilities all have different ventilation requirements based on their technologies and sectoral specifics. Likewise, public buildings such as museums, art galleries, archives, and libraries require specific air temperature and humidity conditions to preserve artistic, cultural, and historical treasures. These requirements are standardized and defined in relevant technical regulations. (ISO 31000, ISO 45001)

ISO 17772 and **ISO 16000** series establish internationally recognized standards for ventilation performance and indoor air quality. ISO 17772 specifies requirements for energy efficiency and environmental parameters in building ventilation, while ISO 16000 defines measurement protocols for pollutants and air exchange quality. By linking the discussion of ventilation standardization to these frameworks, the monograph ensures that both natural and artificial ventilation systems are evaluated against globally validated criteria. This connection reinforces methodological rigor and highlights the international comparability of ventilation practices in occupational, residential, and industrial contexts.

4.5. Static, Dynamic, and Total Pressure in Duct Networks

In duct networks, three types of pressure are distinguished: static, dynamic, and total.

1. Static Pressure acts on the walls of the duct. It shows how much the internal pressure is greater or less than atmospheric pressure. When internal pressure exceeds atmospheric pressure, it has a positive value; when it is lower, it has a negative value. If a hole is made in a section with positive static pressure, air will flow out into the atmosphere; if a hole is made in a section with negative static pressure, air will be drawn into the duct from the atmosphere. Positive or negative static pressure may also be created in premises: positive by compressing air into the room, negative by extracting air from it.
2. Dynamic Pressure differs from static in that it characterizes only moving air. It is proportional to the square of velocity and is always positive. Dynamic pressure acts on any surface placed at an angle to the moving flow. On a plane parallel to the trajectory of the flow, dynamic pressure equals zero, while its maximum value occurs on a plane perpendicular to the flow.
3. Total Pressure is the sum of static and dynamic pressures. It represents the total energy reserve of 1 m^3 of moving air, which may be imparted either by natural draft or by a fan.

Figure 4.2 shows a duct section with air supplied by a fan (direction indicated by arrow). Air movement is caused by excess pressure relative to atmospheric, defined by the formula:

$$\Delta p = p_1 - P_A \quad (4.9)$$

where: Δp - excess pressure, Pa; p_1 - air pressure in the duct; P_A - atmospheric pressure.

Excess pressure in ducts is so small that it cannot be measured with ordinary manometers. For this purpose, manometers filled with light liquids (water or alcohol) are used, called depressiometers or micromanometers.

The simplest depressiometer is a U-shaped glass tube filled with water, shown in the figure. **Fig. 4.2A** illustrates the method of measuring static pressure. One end of the depressiometer is connected to the duct so that dynamic pressure does not act on it. The open end of the tube is bypassed by the airflow, moving parallel to it. Thus, the difference in liquid levels in the U-tube indicates static pressure in the duct relative to atmospheric pressure.

If internal pressure is less than atmospheric, the liquid level in the right limb would be lower than in the left. The scale shown in the figure has divisions of 1 mm. If water is used, the static pressure indicated is 15 + 15 = 30 mm of water column. Pressure readings must always be taken analogously, summing the values of both limbs.

In ventilation, particularly in measuring depressions, pressures are so small that the millimeter of mercury column, used for measuring atmospheric and higher pressures in technical systems, is too coarse. Therefore, pressure is expressed in smaller units — millimeters of water column. In the International System of Units, the pascal is even smaller and more convenient for this purpose.

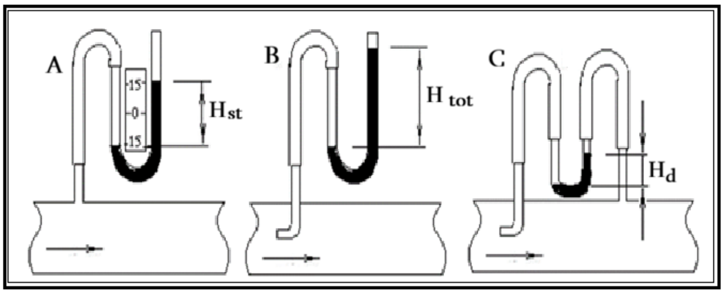

Fig. 4.2. Determination of static, dynamic and total pressure in an air duct

The relationship between units is: $1\,\text{mm}\ H_2\text{O} = 1\,\text{kg/m}^2 = 9.8\,\text{Pa}$Here, 1 kg is considered equal to 9.8 N·m/s².

Total pressure, which is the sum of static and dynamic pressures, is measured when the open end of the tube is placed directly against the airflow (Figure 4.2B). In this case, the left column of liquid receives the total pressure of the duct, and the difference in liquid levels indicates its magnitude

As is known, dynamic pressure equals the difference between total and static pressures. To measure this difference, two tubes are used together with a U-shaped manometer, as shown in Figure 4.2C. The left tube receives total pressure, while the static component is canceled by the right tube, so that the difference in liquid levels indicates the magnitude of dynamic pressure.

All depressiometers shown in Figure 4.2 must have millimeter divisions for practical use, so that readings are taken with an accuracy of 1 mm of water column, equivalent to 9.8 pascals.

Ten times greater accuracy can be achieved if one limb is inclined relative to the other at a ratio of 1:10. In this case, the surface area of the vertical limb must be much larger than that of the inclined tube, and pressure readings are taken only from the inclined tube. The acceptable diameter ratio is 35:1; for example, if the vertical limb has a diameter of 70 mm, the inclined tube must have a diameter of 2 mm. This ratio has been tested and found practical. The micromanometer shown in Figure 4.3 is simple to construct; a wooden ruler can serve as the scale, with a glass tube attached securely. Similarly, the depressiometer shown in Figure 4.2 is easy to make using two straight glass tubes fixed to a ruler, connected by a flexible rubber tube.

Figure 4.3 illustrates the principle of the micromanometer: I – vertical limb with 70 mm diameter; II – inclined tube with 2 mm diameter. The reading shown is 5 mm of water column (the scale does not show zero, since readings are always taken as differences in levels). In the figure, the large vessel shows division 10, while the tube shows division 15. Thus, 1 mm in the vertical limb corresponds to 10 mm in the inclined tube, giving a measurement accuracy of 0.1 mm.

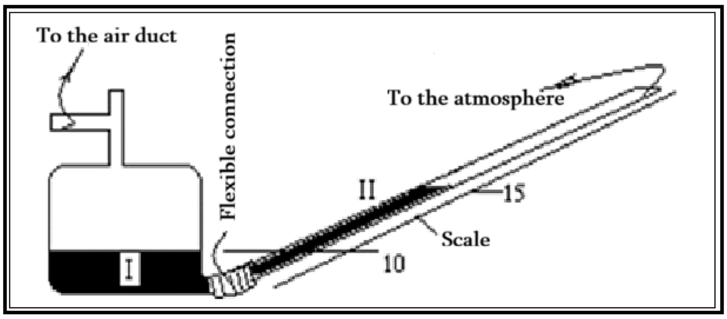

Fig. 4.3. Principle diagram of a micromanometer: I - vertical tube with a diameter of 70 mm; II - inclined tube with a diameter of 2 mm

If alcohol is used instead of water, the reading must be multiplied by the density of alcohol (0.8 kg/L), thereby increasing measurement accuracy. Even higher accuracy (0.665 Pa) is achieved with the M111 type micromanometer, which records pressure variations using aneroid capsules, with readings taken through a magnifying lens included in the instrument set. Instructions for readings and use are provided in the instrument's passport. (ISO 45001)

If static pressure is denoted by H_{st}, dynamic pressure by H_d, and total pressure by H_{tot}, then by definition

$$H_{tot} = H_{st} + H_d \tag{4.10}$$

When air velocity is known, dynamic pressure can be calculated numerically as

$$H_d = \frac{\gamma \cdot V^2}{2} \tag{4.11}$$

where: H_d - dynamic pressure, Pa; γ – air density, kg/m³; V - air velocity, m/s.

Formula (4.11) shows that dynamic pressure is directly proportional to both air velocity and density.

Air velocity is directly proportional to air consumption (Q) and inversely proportional to duct cross-section (S), expressed by the formula

$$V = \frac{Q}{S} \tag{4.12}$$

Thus, if air velocity is known, air consumption can be calculated, and vice versa.

Key points:

1. In supply ducts, total pressure (H_{tot}) is always positive, and static pressure (H_{st}) is also positive, except in rare cases when high air velocity causes local negative values. The absolute value of total pressure exceeds static pressure by the magnitude of dynamic pressure (H_d).
2. In exhaust ducts, total (H_{tot}) and static pressures (H_{st}) are always negative. In this case, the absolute value of total pressure is less than static pressure by the magnitude of dynamic pressure (H_d).
3. Air losses from ducts occur at poorly sealed joints. Losses are beneficial in supply ducts, since clean air leakage adds to the overall ventilation flow of the premises. However, contaminated air containing toxic admixtures must be removed only through exhaust ducts. In such cases, leakage means that clean air enters the duct and mixes with polluted air, preventing its spread into the premises.

Static pressure can easily be converted into dynamic pressure and vice versa by changing the duct cross-section, which alters velocity. This principle is illustrated in Figure 4.4.

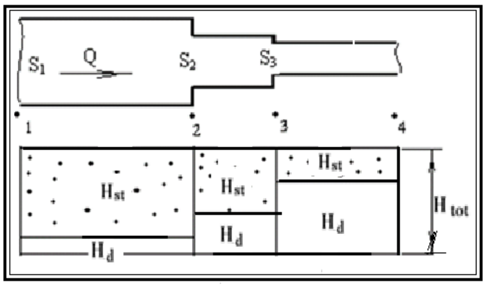

Fig. 4.4. Illustration of static and dynamic pressure variations in a variable cross-section air duct

Explanatory Notes of fig. 4.4:

- **Section 1–2 (larger cross-section)** → Lower velocity, lower dynamic pressure, higher static pressure.
- **Section 2–3 (medium cross-section)** → Velocity increases, dynamic pressure rises, static pressure decreases.
- **Section 3–4 (smallest cross-section)** → Highest velocity, dynamic pressure sharply increases, static pressure drops further.
- **Key principle** → Dynamic pressure ∝ velocity²; static pressure decreases by the same increment.

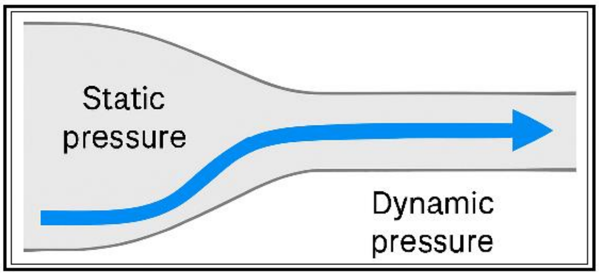

Fig. 4.5. Static and dynamic pressure variations in a variable cross-section air duct

Fig. 4.4 shows the distribution of static and dynamic pressure along a rectangular duct with sections S^1, S^2, S^3. The energy grade line (H_E) and hydraulic grade line (H_Q) are clearly indicated, helping students visualize how static pressure decreases and dynamic pressure increases as the cross-section narrows.

Fig. 4.5 presents the same principle in a simplified, modern style, using a circular duct. Velocity arrows and color-coded zones highlight the rise of dynamic pressure and the drop of static pressure. The clean design emphasizes clarity and ISO terminology.

Together, these figures provide a dual perspective: the first supports intuitive understanding through detailed energy lines, while the second offers a visually appealing, modern interpretation aligned with international standards.If pressure losses (due to friction and local resistances) are disregarded, then total pressure (H_{tot}) in a variable-section duct will have the same numerical value across all segments (1–2, 2–3, 3–4), provided air consumption $Q =$ const. If $S_1 > S_2 > S_3$, then velocities will relate as $V_1 < V_2 < V_3$. Dynamic pressure (H_d) increases with velocity, while static pressure (H_{st}) decreases by the same increment.

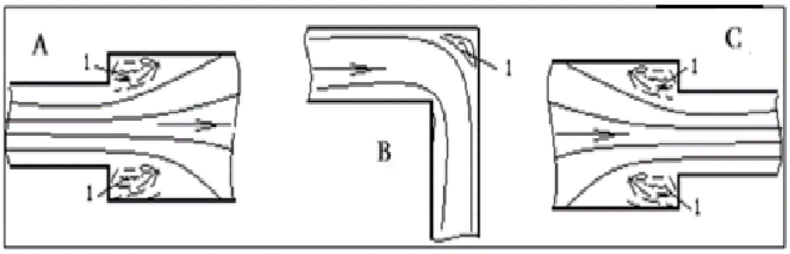

Fig. 4.6. Illustration types of local resistances:
A - sudden expansion; B - 90° bend of flow; C - sudden contraction; 1 - secondary flows independent of the main stream. Arrows indicate flow direction

Explanatory Notes of fig. 4.6:

- **Sudden expansion (A)** → Flow separates, vortices form, energy loss due to turbulence.
- **90° bend (B)** → Sharp change in direction, turbulence increases, resistance rises.
- **Sudden contraction (C)** → Velocity increases, static pressure drops, local energy loss.
- **Secondary flows (1)** → Independent vortices appear, adding extra resistance to the main stream.

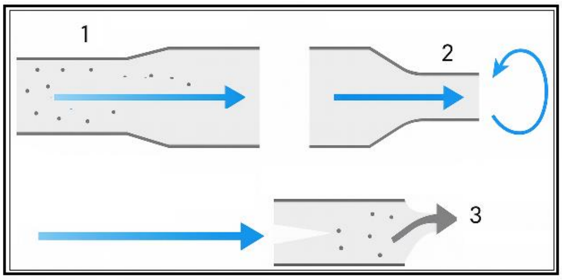

Fig. 4.7. Types of local resistances:
1 - sudden expansion; 2 - sudden contraction; 3 - secondary flows independent of the main stream. Arrows indicate flow direction

For example, dynamic pressure calculated by formula (4.11) is:

- 3.75 Pa in section 1–2
- 15 Pa in section 2–3
- 60 Pa in section 3–4

under the following conditions $Q = 10\,\text{m}^3/\text{s}; \gamma = 1.2\,\text{kg/m}^3; S_1 = 4\,\text{m}^2; S_2 = 2\,\text{m}^2; S_3 = 1\,\text{m}^2$. Clearly, formula (4.12) was also used. Notably, halving the cross-section resulted in a fourfold increase in dynamic pressure, since formula (4.11) shows dynamic pressure is proportional to the square of velocity.

Two complementary diagrams are provided to illustrate the types of local aerodynamic resistances that occur in duct systems. Fig. 4.6 shows sudden expansion, 90° bend, sudden contraction, and secondary vortices in a simplified technical style. It emphasizes the physical mechanism of turbulence and energy loss. Fig. 4.7 presents the same resistances in a clean, vector style with color-coded arrows and labeled turbulence zones. This modern visualization highlights airflow behavior and makes the concept more accessible for students.

Together, these figures combine precision and clarity: the classic version supports analytical understanding, while the modern version provides visual appeal and pedagogical accessibility.

In practice, total pressure always experiences losses, compensated by fan-generated pressure. Without such losses, perpetual motion would occur, meaning air would move indefinitely with a single energy input. Energy losses also accompany conversions between dynamic and static pressure. For example, in sudden duct expansion, the cross-section is not fully filled by airflow, creating vortices in adjacent spaces. This causes energy losses due to expansion and turbulence.

ISO 5221 and **ISO 5801** establish internationally recognized methodologies for measuring static, dynamic, and total pressure in duct networks. ISO 5221 specifies test methods for air distribution and ductwork components, while ISO 5801 defines performance testing procedures for fans, including pressure and airflow characteristics. By linking the discussion of pressure parameters to these standards, the monograph ensures that calculations and measurements are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in ventilation system design and evaluation.

4.6. Types of Aerodynamic Resistance

Viscosity of air is its ability to resist deformation (change of form). Viscosity causes air to adhere to duct walls, which in turn slows down the layer of air moving close to the wall. The braking effect decreases with distance from the wall, and in the central part of the duct it is no longer observed. As a result, shear stress arises, producing a corresponding aerodynamic force — the frictional force. Frictional force also acts within the flow itself, between individual layers and volumes of air moving relative to one another. Thus, air resists deformation both at the walls and internally. Part of the energy imparted to the air is lost to internal friction and wall braking, converted into heat, and dissipated into the environment without useful effect.

This energy loss disrupts the balance of pressure forces characteristic of stationary air, creating an additional pressure difference called the pressure gradient. It must not be confused with aerostatic pressure difference. The pressure gradient is characterized by small numerical values and can only be measured on the surfaces of bodies in contact with air (unlike aerostatic pressure difference, which is measured within the flow). The pressure gradient represents the second component of aerodynamic resistance — the pressure force.

Thus, the total aerodynamic resistance force consists of two components: frictional force and pressure force. Their ratio varies under specific conditions and depends on wall roughness, geometric parameters (cross-sectional area, perimeter, length), presence of bends, contractions or expansions, and shaped duct parts (air outlets, dampers, regulators, etc.).

This phenomenon has three typical forms, distinguished as frictional, local, and frontal resistances. All three are types of aerodynamic resistance, and overcoming them requires energy supplied either by fans or by natural draft.

As noted earlier, formula (4.8) is used to calculate frictional resistance, while formula (4.7) is used to calculate the depression required to overcome it. These formulas show that frictional resistance is determined using geometric parameters (P, L, S), air consumption (Q), and wall roughness accounted for by the aerodynamic resistance coefficient α. Depending on the numerical value of Reynolds' criterion, α varies at different rates. Within certain ranges, called automodel zones, the coefficient may be considered constant. Under developed turbulent flow conditions ($Re > 0{,}5 - 1{,}0x10^5$), the coefficient α is independent of Reynolds' number, while in laminar flow conditions the dependence $\alpha = f(Re)$ must be considered.

Reynolds' criterion is expressed as

$$Re = \frac{VD}{\nu} \tag{4.13}$$

where: V - air velocity, m/s; D - hydraulic diameter of the duct, m; ν - kinematic viscosity coefficient, m²/s.

Since the coefficient α includes kinematic viscosity, gravitational acceleration, and the dimensionless friction coefficient λ, it is preferable to represent the dependence $\alpha = f(Re)$, as $\lambda = f'(Re)$, which has a long history in hydraulics. This dependence is shown in Fig. 4.8, which may be called the graphical representation of the Gagen–Poiseuille–Reynolds–Nikuradze laws.

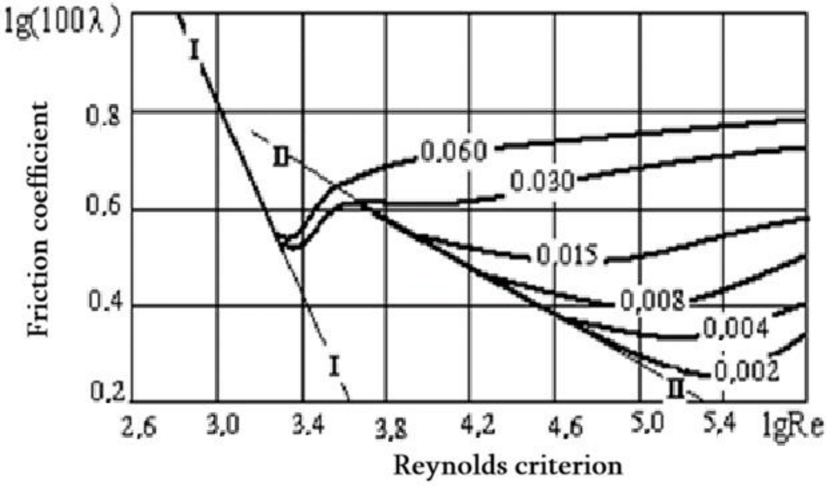

Fig. 4.8. Variation of the Dimensionless Friction Coefficient According to Flow Regime: Values such as 0.002, 0.004, etc. represent roughness calibration — the ratio of wall roughness protrusion to duct hydraulic diameter

Explanatory Notes of fig. 4.8:

- **Laminar regime (Poiseuille law)** — Friction coefficient decreases hyperbolically ($\lambda = 64/Re$), depends only on velocity, unaffected by wall roughness.
- **Transitional regime (Reynolds)** — Coefficient begins to rise at critical Reynolds numbers, influenced both by velocity and wall roughness.
- **Turbulent regime (Nikuradze)** — Friction coefficient depends only on wall roughness, independent of velocity or Reynolds number.

The line I–I in Figure 4.8 corresponds to the law of French scientists Gagen and Poiseuille, according to which the dimensionless friction coefficient decreases hyperbolically ($\lambda = 64/Re$), depends only on flow velocity (V, Re), and is unaffected by wall roughness.

The limitations of the Gagen–Poiseuille law were confirmed experimentally by the English scientist Reynolds, who showed that the rate of decrease of the coefficient slows down at the critical value of the number defined by formula (4.13), beginning around 2000 (modern understanding places the first critical Reynolds number at >2300). Beyond this point, the coefficient begins to increase. At this stage, the coefficient is influenced both by flow velocity (Re) and wall roughness.

Final clarity on this issue was provided by the Georgian émigré Jakob Nikuradze, who lived in Germany. Line II–II in Figure 4.8 corresponds to the beginning of the zone of laws established by Nikuradze. According to him, for the second critical Reynolds numbers, which vary across a wide range, the magnitude of the friction coefficient depends only on wall roughness and is no longer influenced by flow velocity or Reynolds number. This phenomenon is explained by the intensification of turbulence, which reduces the thickness of the laminar boundary layer, causing the main flow to interact more directly with wall roughness protrusions, thereby braking as it overcomes their resistance.

Thus, without exaggeration, it can be stated:

- According to Gagen–Poiseuille, the coefficient depends on air velocity and is unaffected by duct roughness.
- According to Reynolds, it is determined by both velocity and roughness.
- According to Nikuradze, at high velocities the coefficient depends only on duct roughness.

Let us now consider the second form of aerodynamic resistance manifestation — local resistance.

Local resistances include duct contractions, expansions, bends, shaped parts of ducts or fans, filters, casings, etc., which are located locally within ducts or premises. Most local resistances are characterized by flow separation within them due to inertial forces, producing secondary flows independent of the main stream. These flows exhibit turbulence different from the main flow, as shown in Fig. 4.6. The places where different turbulence originates and develops are called dead zones.

For calculating local resistance, a dimensionless value is introduced — the local resistance coefficient, denoted by ξ. It represents the ratio of pressure losses ξ in a given local resistance to the dynamic pressure H_d defined by formula (4.11)

$$\xi = \frac{Z}{H_d} \quad (4.14)$$

Local resistance depression in cases of sudden expansion or contraction may also be calculated bypassing the coefficient, using the Borda–Carnot formula, which is a variation of formula (4.11)

$$h = \frac{\gamma}{2}(V_1 - V_2)^2 \quad (4.15)$$

where, in addition to previously defined quantities, V_1 and V_2 are velocities in the respective cross-sections.

Finally, let us consider the third form of aerodynamic resistance manifestation — frontal resistance.

Frontal resistance occurs when a body is placed in the airflow, obstructing its movement and requiring energy expenditure to overcome. For example, consider a cylindrical body placed in the flow. If the flow is laminar, separation does not occur at the body's boundaries, since viscous forces dominate over inertial forces of air particles (in this case, frictional forces are proportional to the first power of velocity). As velocity increases, the Reynolds number rises, turbulence begins at the boundaries, braking increases at the separation surface (frictional forces become proportional to the square of velocity), and smaller flows detach from the main stream, attempting to move opposite to the main flow (Fig. 4.10). The turbulent zone shown in Fig. 4.9b causes energy dissipation into heat, similar to local resistances.

In the turbulent zone, a turbulent boundary layer forms along the surfaces of solid bodies. Mixing between this boundary layer and the main turbulent flow is less intense than the overall displacement of the turbulent stream, which shifts the first point of flow separation further downstream than shown in Fig. 4.9B. As a result, the turbulent zone decreases, and frontal resistance is reduced. This phenomenon was discovered by Eiffel, the famous builder of the Paris tower.

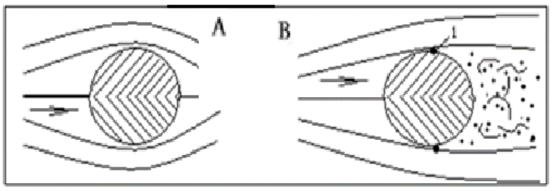

Figure 4.9. Illustration of Frontal Resistance:
A – Laminar flow; B – Turbulent flow; 1 – Point of flow separation.
Arrows indicate flow direction

Frontal resistance depends not only on flow velocity but also on the shape of the body placed in the airflow. Streamlined shapes are characterized by lower resistance under otherwise equal conditions.

Frontal resistance and the depression required to overcome it are calculated using the following formulas

$$R = \frac{c\gamma}{2}\frac{S_M}{S(S-S_M)^2} \quad (4.16)$$

$$h = \frac{c\gamma}{2}\frac{S_M}{S(S-S_M)^2}Q^2 \quad (4.17)$$

where: c - dimensionless coefficient of frontal resistance; γ = air density, kg/m³; S- duct cross-sectional area, m²; S_M - mean cross-sectional area of the body (projection area on a plane perpendicular to airflow, m²; Q - air consumption, m³/s.

Fig. 4.10 shows the variation of coefficient c with Reynolds number, obtained experimentally. Similarly, coefficients of local resistance (ξ) and frictional resistance (α) are determined experimentally, with numerical values provided in specialized references.

Reduction of frictional resistance coefficient can be achieved by increasing duct cross-sectional area and improving wall smoothness. Smoothness is particularly important in long transport tunnels, which themselves serve as large ducts. Tunnel linings must be made of materials with minimal surface roughness. Metal and plastic ducts have better smoothness compared to ducts made of rubber or canvas.

Reduction of local resistance coefficient (ξ) can be achieved by designing shapes that minimize dead zones shown in Figure 4.6. This is possible through gradual transitions in bends, expansions, or contractions, with surfaces in contact with air made especially smooth.

Funnel-shaped devices used for this purpose are called diffusers (for expanding airflow) or confusors (for contracting airflow). Optimal diffuser expansion angles range from 5° to 8°, while confusor contraction angles are about 5°. Such designs are particularly desirable in road tunnels, where 30–60% of operating costs are due to ventilation. Installing guide vanes in bends reduces the numerical value of coefficient ξ by half. Rounding a 90° duct bend with a radius of $0.1D$ (where D - hydraulic diameter) reduces ξ tenfold.

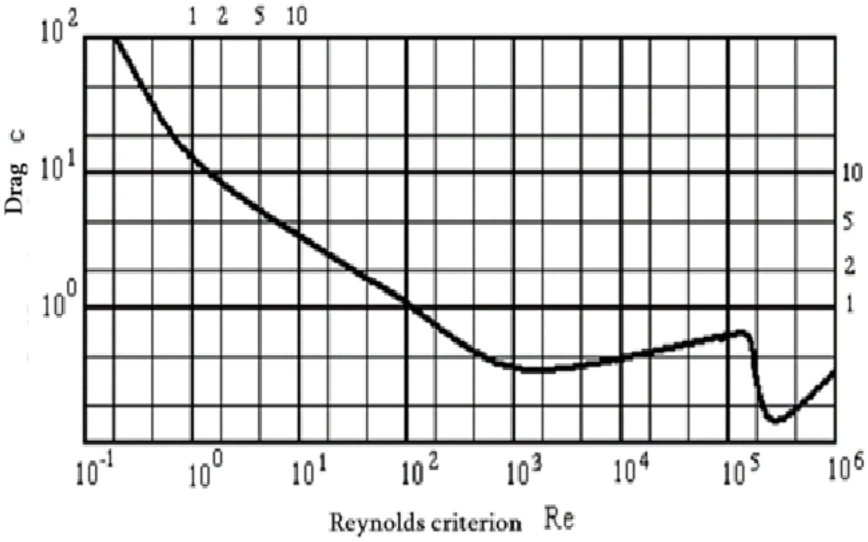

Fig. 4.10. Variation of Dimensionless Frontal Resistance Coefficient with Reynolds Number: Scale divisions shown in the range 1–10 apply equally to other ranges

Passports of shaped parts, filters, and other accessories used in industrial and domestic ventilation directly specify pressure losses (as well as noise and vibration levels), determined through factory testing.

Frontal resistance can be reduced by giving bodies streamlined shapes. For example, if the cross-section of a cylinder shown in Fig. 4.9 is changed from circular to drop-shaped by attaching a metal casing, the coefficient decreases approximately 8–10 times. Reduction of frontal resistance is particularly effective at high air velocities. The coefficient c is also reduced by smoother surfaces. (ISO 31000, ISO 45001)

ISO 5221 and **ISO 5802** provide internationally recognized methodologies for evaluating aerodynamic resistance in ventilation systems. ISO 5221 specifies test methods for air distribution and ductwork components, while ISO 5802 defines procedures for measuring airflow and pressure losses in duct networks. By linking the classification of aerodynamic resistance types to these standards, the monograph ensures that both theoretical analysis and practical calculations are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in designing efficient ventilation systems.

4.7. Ventilation Schemes of Premises

Ventilation can be implemented with pressure greater than atmospheric, called supply ventilation, or with pressure lower than atmospheric, called exhaust ventilation. By combining supply and exhaust, various ventilation schemes are obtained. (ISO 31000, ISO 45001)

Suppose technological equipment installed at three points in a room (Figure 4.11) releases harmful substances. Clean air is supplied from the atmosphere in direction 1 (arrows), while the same amount of contaminated air is removed in direction 2.

Fig. 4.11A corresponds to a general ventilation scheme, the simplest to arrange, since both clean and contaminated air flows move in the same direction, allowing natural draft to be used. In the left part of the room, air is cleaner than in the right part. This characteristic is typical of all general ventilation schemes: zones near clean air inlets have cleaner air compared to other zones. Even in these zones, however, harmful substances must not exceed permissible limits.

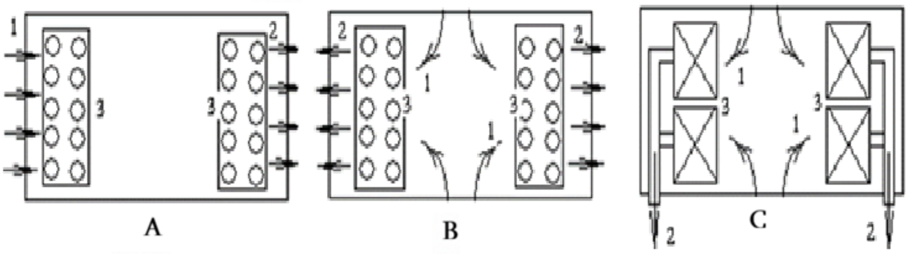

Figure 4.11. Ventilation Schemes of Premises:
A, B – general; C – local; 1 – clean air; 2 – contaminated air; 3 – sources of toxic and harmful substances

Fig. 4.9b shows a better general ventilation scheme, where clean and contaminated air flows move in different directions. Implementation of this scheme requires fans.

The most effective method of removing harmful substances is local ventilation, in which a hood is placed directly over the source of toxic emissions. These substances are extracted by the fan before spreading into the workspace (Fig. 4.9c). Figure 4.10 illustrates a local supply-exhaust ventilation scheme.

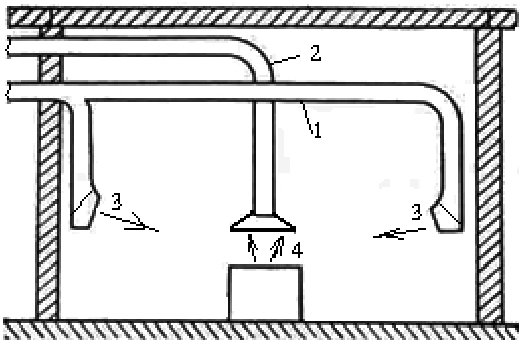

Fig. 4.12. Local Ventilation Scheme:
1 – supply duct; 2 – exhaust duct; 3 – clean airflow; 4 – contaminated airflow

If the room volume is large, with few workers whose workplaces are fixed, then for technical-economic reasons clean air zones may be created only at workplaces. This type of ventilation is called local or partial ventilation, and the air jet directed at workplaces is called an air shower.

Depending on technological conditions, emergency ventilation may be required in case toxic or harmful substances spread into the workspace due to equipment failure. Such ventilation is usually integrated with the technological line and often activated automatically when insulation is breached.

Combinations of the above schemes may also be used in specific enterprises. For example, general and local systems may be combined, yielding excellent results. Examples of combined supply, exhaust, and supply-exhaust ventilation systems are shown in Fig. 4.13. (ISO 45001)

Thus, the following basic ventilation schemes are found in premises: 1. General; 2. Local; 3. Partial (local); 4. Emergency; 5. Combined.

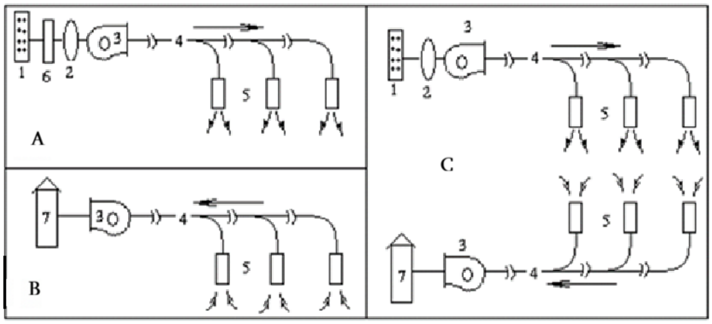

Fig. 4.13. Illustration of General and Local Ventilation Systems:
A – supply; B – exhaust; C – supply-exhaust; 1 – air intake kiosk; 2 – air heater and humidifier; 3 – fan; 4 – main ducts; 5 – regulating shaped parts; 6 – air filter; 7 – shaft

Ventilation schemes, with or without fans, are referred to as ventilation systems. Hence, five types of ventilation systems have been introduced.

When using local ventilation, air extraction must be arranged as follows:

1. From the upper zone: for gases lighter than air and water vapor; for high-temperature gases regardless of density; for dust generated under high-temperature conditions; in residential, public, and auxiliary premises.
2. From the lower zone: in all premises where dust is released.
3. From both upper and lower zones simultaneously: for gases denser than air. (ISO 45001)

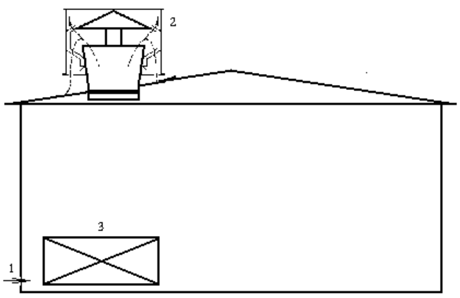

Fig. 4.14. General Ventilation Scheme of a Thermal Workshop:
1 – clean air; 2 – contaminated air; 3 – source of high-temperature harmful substances

These schemes may also be applied in general ventilation systems using natural draft. Figure 4.12 shows a general ventilation scheme of a thermal workshop operating on natural draft.

Unlike Figure 4.11A, in Figure 4.14 clean air enters from below, absorbs heat at workplaces, and moves toward a deflector installed at the roof. The deflector is a simple mechanical device compensating for wind effects. It may also include a vane compensator, operating on natural draft to equalize flow. The deflector is always a local resistance in the airflow path, characterized by the following coefficients: ξ = 0,61 for circular cross-sections; ξ = 0,70 for square cross-sections.

The combined draft developed by natural forces and a deflector can be calculated using the formula

$$h = \Delta p + (\gamma_1 - \gamma_2) g H + p_2 \qquad (4.18)$$

where: h - depression of combined draft developed by the natural deflector, Pa; Δp - excess pressure at the deflector inlet, Pa; γ_1, γ_2 - average air density in the atmosphere and in the deflector, kg/m³; g - gravitational acceleration, m/s²; H - deflector height, m; p_2 - draft developed by wind, Pa.

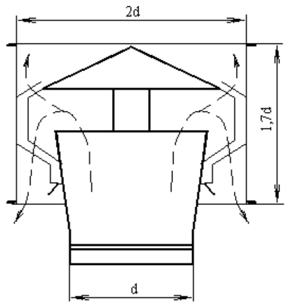

Fig. 4.15. Deflector:
d – diameter of the deflector inlet duct

As seen, formula (4.18) incorporates formulas (4.1) and (4.9). The depression is expended to overcome local resistances at the deflector inlet, aerodynamic resistance of the deflector shaft, and the local resistance of the deflector itself. The deflector is shown in Figure 4.15. (ISO 45001) As the figure shows, all dimensions of the deflector are multiples of its inlet duct diameter. Therefore, to calculate the deflector, its diameter must be determined using the balance of depressions. The sum of resistances must equal the draft calculated by formula (4.18). The balance of depressions has the following form

$$h = \left(\sum \xi_1 + \frac{\lambda}{d} H + \xi\right) H_d \qquad (4.19)$$

where: $\sum \xi_1$ - dimensionless sum of local resistances at the deflector inlet; λ - dimensionless friction coefficient, whose variation with flow regime and velocity is shown in Fig. 4.6; d - diameter of deflector inlet duct (m); H - deflector height (m); ξ - dimensionless coefficient of local resistance of the deflector; H_d - dynamic pressure in the deflector inlet duct, defined by formula (4.11), which here takes the form

$$H_d = \gamma \frac{V_1^2}{2} \qquad (4.20)$$

where V_1 - air velocity in the deflector inlet duct, determined by

$$V_1 = \sqrt{\frac{2h}{\left(\Sigma\xi_1 + \frac{\lambda}{d}H + \xi\right)\gamma}} \quad (4.21)$$

Using velocity calculated by formula (4.21) and the required air consumption (either known in advance or calculated by formulas (4.3) – (4.6)), the cross-sectional area of the inlet duct is determined. From this, the diameter *D* is obtained, and according to Fig. 4.15, the dimensions of the deflector are established. (ISO 31000, ISO 45001)

ISO 16494 and **ISO 17772** provide internationally recognized frameworks for designing and evaluating ventilation schemes in premises. ISO 16494 specifies performance requirements for air-handling units, while ISO 17772 establishes criteria for indoor environmental quality and ventilation effectiveness. By linking the discussion of ventilation schemes to these standards, the monograph ensures that both natural and mechanical ventilation layouts are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in building design, occupational safety, and environmental health.

4.8. Local Exhausts

Local ventilation is implemented using local exhaust devices, consisting of two main parts: the duct and the air intake. Depending on the placement of the intake near the source of toxic emissions, local exhausts are known by different names:

1. Exhaust enclosure (hood or chamber) — used when the technological process can be confined within a limited space.
2. Exhaust hood — applied when localization of the process is impossible or economically impractical.
3. Combination of enclosure and hood, known as covered hoods, where removable panels may be attached to one or more sides of the hood.

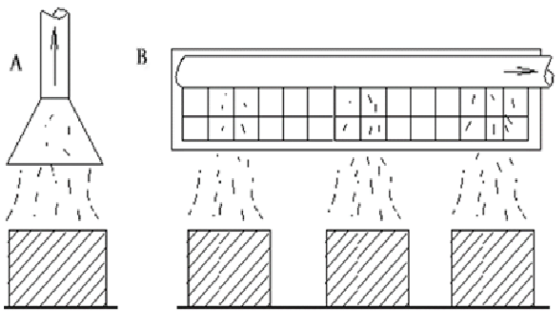

Fig. 4.16. Exhaust Hoods:
A – individual; B – group (with glazed frames)

All these devices may have various shapes adapted to the workplace, but their purpose is the same: to hinder the spread of toxic and harmful gases into the working zone, primarily by reliable collection in the intake and subsequent removal through the duct network.

The most advanced form of local exhaust chamber is the fume cupboard. In this case, personnel have no direct contact with the air moving inside the cupboard, which allows higher concentrations of toxic substances than permissible in the general workspace. For safety, air pressure inside the cupboard must always be lower than atmospheric, preventing unauthorized leakage and spread of gases into the workspace.

The group of exhaust cupboards also includes various technological chambers, such as drying and painting chambers, bunkers, etc.

In chemical fume cupboards, air extraction may occur from either the lower or upper zone. If gases heavier than air are released and the reaction is endothermic (low temperature inside the cupboard), extraction must be from the lower part. If hot surfaces are present, both heavy and light gases must be extracted from the upper part.

In practice, exhaust hoods are widely used due to their simplicity (Fig. 4.16). However, when using hoods, the source of toxic or harmful substances is not isolated from the workspace. Strong air currents may deflect the jet toward the hood, but admixtures can still spread into the working zone. To ensure uniform suction, hood expansion angles must be within 60°.

ISO 16000 and **ISO 14644** provide internationally recognized frameworks for evaluating local exhaust systems in premises. ISO 16000 specifies methodologies for measuring indoor air quality and pollutant removal, while ISO 14644 establishes standards for cleanroom ventilation and localized exhaust performance. By linking the discussion of local exhausts to these standards, the monograph ensures that both design and operation are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in controlling contaminants at their source, thereby improving occupational safety and environmental health.

4.9. Fans and Auxiliary Devices

The main part of a fan is the impeller, on which blades are mounted at a certain angle. With the help of the bladed impeller, air is set in motion and partially compressed. The displaced air volume and the pressure developed by the fan depend on the impeller's peripheral speed and its dimensions.

By construction, fans are generally divided into axial and centrifugal types. The former are used when high capacity and relatively low pressure are required, while centrifugal fans develop higher pressure but have lower capacity. Axial fans are also characterized by higher noise levels compared to centrifugal fans.

Centrifugal fans are classified into low-pressure (up to 1000 Pa), medium-pressure (up to 3000 Pa), and high-pressure (above 3000 Pa) fans. This wide range of pressures is achieved by varying the blade outlet angle: blades may be forward-curved (<90°), radial (90°), or backward-curved (>90°). Forward-curved blades allow higher pressure coefficients.

Low-pressure fans are mainly used to provide high air consumption, for example in civil and industrial supply and exhaust ventilation systems. Their geometric dimensions are relatively large; to reduce them, blades are forward-curved and their number maximized (48–64 blades). To ensure strength and low noise, the impeller's peripheral speed must not exceed 30 m/s.

Medium-pressure fans have smaller geometric dimensions than low-pressure fans. The number of blades does not exceed 24, and they are trapezoidal in shape, ensuring structural rigidity. Medium-pressure fans are widely used for extracting dust-laden air. Dust fans typically have 6–8 blades and are designed to prevent clogging and mechanical admixtures (chips, sawdust, fibers, etc.). Dust fans may also be used for smoke extraction. For strength, the impeller's peripheral speed must not exceed 50 m/s.

High-pressure fans differ from other types particularly in casing geometry. The casing width and inlet/outlet diameters are much smaller than those of low- and medium-pressure fans. The impeller's peripheral speed reaches 100 m/s. High-pressure centrifugal fans used in ventilation technology are also applied in pneumatic transport.

The impeller and motor may be mounted on the same shaft. Such fans are more compact, economical, and quieter under equal conditions. This arrangement is possible in low-capacity fans. In high-capacity fans, the impeller is connected to the motor shaft through an intermediate coupling.

An ***axial fan*** consists of a bladed impeller placed in a cylindrical casing. During rotation, air is moved axially by the blades. The impeller, usually a metal tube with welded blades, is most often directly attached to the motor shaft. In some cases, the motor is placed outside the airflow and connected to the impeller by a belt drive.

Unlike centrifugal fans, axial fans are reversible, since changing the rotation direction of the impeller also changes the airflow direction. If the blade profile is asymmetric, productivity drops sharply during reverse operation. In modern fans, however, up to 80% of productivity can be maintained in reverse mode. Axial fans are recommended for large air volumes within the pressure range of 100–300 Pa. Their efficiency is higher than that of centrifugal fans.

By execution, fans may be of standard or explosion-proof design. Explosion-proof fans are made of plastic or aluminum; in case of failure, friction between parts does not produce sparks, eliminating explosion risk. Such fans are used where explosive gases must be extracted (painting operations, paint production, organic solvent industries, etc.). Explosion-proof fans are also applied in mining, where explosion safety mainly concerns the motor.

Mechanical supply ventilation systems include the following auxiliary devices and structural elements:

1. Air intake device, supplying atmospheric (external) air to the ventilation system.
2. Air supply chamber, containing the fan with electric motor and devices for air treatment — filters, heaters, ionizers, water sprayers, etc.
3. Duct network.
4. Supply openings and outlets.
5. Louvred grilles and meshes installed at supply openings.
6. Regulating devices installed at duct branches and air intake openings — throttle valves and dampers.

Mechanical exhaust ventilation systems include the following structural elements:

1. Exhaust openings with louvred grilles and meshes.
2. Duct network through which extracted air flows into the exhaust chamber.
3. Exhaust chamber containing the fan and electric motor.
4. Air-cleaning devices, used when air is recirculated or when emission of harmful admixtures into the atmosphere is restricted for environmental protection.

5. Exhaust shaft, discharging air into the atmosphere.
6. Regulating devices — throttle valves and dampers.

Not all of the above elements are present in every ventilation system. For example, supply ventilation systems do not always include filters or devices for humidification and ionization of air. (ISO 31000, ISO 45001)

ISO 5801 and **ISO 13350** establish internationally recognized methodologies for testing and evaluating fans and auxiliary ventilation devices. ISO 5801 specifies performance testing procedures for fans, including airflow, pressure, and efficiency characteristics, while ISO 13350 defines requirements for industrial fans used in ventilation and air-cleaning systems. By linking the discussion of fans and auxiliary devices to these standards, the monograph ensures that design and operational parameters are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in optimizing ventilation systems for occupational, residential, and industrial applications.

4.10. Air Cleaning from Impurities

Various devices are used for air purification, such as cyclones, filters, and others. Cleaning is required both for air supplied into premises and for air discharged into the atmosphere. Norms define the maximum permissible dust concentration (MPC) in workplace air, in supply jets, and in discharged air, denoted respectively as n_j, n_f and n_a.

For medium-level cleaning, cyclones are used, operating on the principle of centrifugal separation. The cyclone is shown in Fig. 4.17.

Table 4.3. Variation of Dustiness Coefficient k According to MPC

MPC of dust in workplace air c_2 (mg/m³)	Numerical value of dustiness coefficient k
<2	0.3
2 - 4	0.6
4 - 6	0.8
>6	1.0

For two-stage cleaning, efficiency is calculated as

$$\eta = \eta_1 + \eta_2 - \eta_1 \eta_2 \tag{4.23}$$

where: η_1, η_2 - cleaning efficiency after the first and second stages.

Cyclones are not effective for fine dust removal; they are mainly used to separate coarse dust such as sawdust, shavings, sand, and similar particles from air discharged into the atmosphere.

Greater dust separation capability is achieved with wet cyclones, which utilize coagulation forces in addition to centrifugal forces. Their cleaning efficiency ranges from 0.85–0.95, meaning 85–95% of dust in the air is removed.

Fig. 4.17 shows the spiral trajectory of dust-laden air, the separation process inside the cyclone body, and the outlet of clean air. It emphasizes the physical accuracy of centrifugal force and particle deposition.

For separation of medium and fine dust particles, various types of filters are used, differing in design and purpose. The filter surface area is determined by

$$S_f = \frac{Q}{q_f} \tag{4.24}$$

where: S_f - filter surface area, m²; Q - air flow through the filter, m³/s; q_f - specific load on the filtering surface, m³/(m²·s).

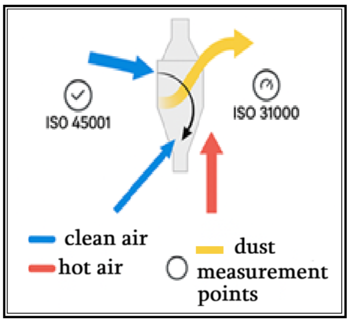

Fig. 4.17. Scheme of processes occurring in a cyclone

A cassette-type oil filter is used when the initial dust concentration does not exceed 20 mg/m³. Its cleaning efficiency is 0.95–0.98. The filter consists of cassettes containing several layers of steel mesh, steel shavings, or porcelain rings, wetted with spindle oil. Dust remains in the filter during operation and must be periodically cleaned with a 10% caustic soda solution at 60–70 $°C$.

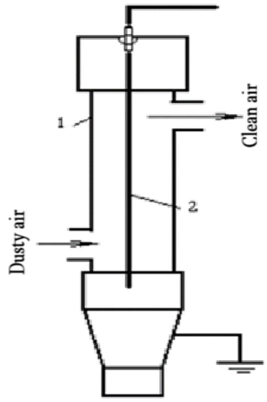

Figure 4.18. Principle Scheme of Electro filter:
1 – casing; 2 – electrode

With cassette-type fabric filters, practically complete air purification can be achieved, with efficiency $\eta = 99{,}9\%$. The fabric is made of lavsan or foamed polyurethane.

The electrostatic filter is distinguished by very high efficiency. It consists of a casing made of negatively charged metal mesh and positively charged plates (Fig. 4.18). The casing and electrode plates are insulated from each other. Dust particles acquire an electric charge as they pass through the filter, deposit on the casing, and clean air is discharged into the atmosphere. (ISO 31000, ISO 45001)

ISO 16890 and **ISO 29463** establish internationally recognized standards for air cleaning and filtration efficiency. ISO 16890 defines performance criteria for general ventilation filters, while ISO 29463 specifies test methods for high-efficiency particulate air (HEPA) and ultralow penetration air (ULPA) filters. By linking the discussion of air cleaning from impurities to these standards, the monograph ensures that both natural and mechanical purification methods are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in improving indoor air quality, occupational safety, and environmental health.

4.11. Protective Measures to Be Applied

Protective measures are divided into three categories: objective, individual, and subjective.

- Objective measures: natural and mechanical ventilation systems, local exhausts, air filtration devices, automatic sensors and alarms. If sensors and alarms control processes, they are considered objective measures; if they only provide signals requiring conscious action by personnel, they are classified as subjective protective measures.
- Individual measures: respirators, protective masks, and special clothing to protect against dust and toxic substances.
- Subjective measures: proper instruction of employees, adherence to ventilation regimes, and suspension of work in case of insufficient air exchange. (ISO 31000, ISO 45001)

ISO 45001 and **ISO 15265** provide internationally recognized frameworks for protective measures in ventilation and occupational environments. ISO 45001 establishes requirements for occupational health and safety management systems, ensuring that protective measures are systematically integrated into workplace practices. ISO 15265 defines methodologies for assessing thermal environments and protective strategies against heat stress, which are directly relevant when designing ventilation systems. By linking protective measures to these standards, the monograph ensures that safety protocols are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers and building occupants.

5. Explosions and Fires

5.1. Explanatory Notes (Integration, Harmonization)

Theoretical Integration:

- Chapter 5 Explosions and Fires continues the logical sequence of the previous chapters.
- Chapter 1: Research Methods → The principle of defining indices introduced there is applied here (expressed through explosibility limits).
- Chapter 2: Traumatism → It is evident that explosions and fires represent one of the main sources of injuries.

• Chapter 3: Air Composition → The concentration of explosive mixtures is directly determined by the components of air.

• Chapter 4: Ventilation → Emergency ventilation is essential to prevent explosive aerosols and to create a safe working environment.

Integration with Standards:

• Chapter 5 Explosions and Fires is directly linked to the requirements of ISO 31000 and ISO 45001, since explosions and fires constitute one of the most critical risks in the workplace.

• The ISO 31000 framework is applied here for risk identification and index definition (e.g., lower and upper explosibility limits, ranges of hazardous concentrations).

• ISO 45001 emphasizes preventive measures: ventilation management, control of combustible mixtures, training, and adherence to safety rules.

• Thus, the study of explosions and fires is not only an explanation of physical-chemical processes but also a practical example of standardized risk management.

Pedagogical Integration:

• Questions and short answers provide quick self-check opportunities.

• Practical examples (sugar factory, flour warehouse) reinforce real-world context.

• The manual as a whole is conceived as a unified instructional guide aligned with international standards.

• Concise notes ensure that the reader maintains the overall perspective and sees the place of each topic within the context of international standards.

Final Note: Identifying the necessary conditions for combustion (fuel, oxygen, impulse) represents a practical example of implementing ISO 31000 requirements — determining the source of hazard and formulating a risk index.

Ignition impulses may be thermal, chemical, or microbiological.

• **Thermal impulses:** open flame, spark, heated surface, residues of incompletely burned fuel, etc.

• **Chemical impulses:** oxidation of oil under pure oxygen, ignition of sawdust under concentrated nitric acid, etc.

• **Microbiological processes:** heat release in substances that serve as nutrient media for microorganisms, e.g., peat.

ISO 45001 and **ISO 31010** provide internationally recognized frameworks for integrating protective measures and harmonizing risk management in the context of explosions and fires. ISO 45001 establishes requirements for occupational health and safety management systems, ensuring that preventive strategies are systematically embedded in workplace practices. ISO 31010 defines methodologies for risk assessment, including hazard identification and consequence analysis, which are directly relevant to explosion and fire scenarios. By linking the explanatory notes of Chapter V to these standards, the monograph situates its analysis within a globally harmonized framework. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers, facilities, and the environment.

5.2. Explosibility of Coal Dust

Coal dust is present in ventilation air in mines, coal enrichment plants, coal-fired thermal power stations, and other facilities.

When coal dust particles of 1 mm or smaller are present at concentrations ranging from 16–96 g/m³ up to 2000 g/m³, the aerosol can burn and explode. In addition, coal dust and other carbon-containing aerosols release 15% or more volatile substances upon heating, which are explosive gases. The ignition temperature of coal dust is 750–850 $°C$, while the explosion wave velocity during detonation reaches approximately 1000 m/s, exceeding the speed of sound at that temperature and producing great destructive force.

The greatest destructive effect occurs when dust concentration is in the range of 300–400 g/m³.

The more humid the aerosol or the higher its content of inert substances (such as ash), the less hazardous it is in terms of explosion and ignition.

It has been established that:

1. Coal dust is capable of exploding without methane.
2. Coal dust can transform a small methane explosion into a powerful one.
3. The presence of coal dust lowers the lower explosibility limit of methane-air mixtures to below 5%.
4. The products of coal dust explosions contain large amounts of carbon monoxide, which poses additional danger both in terms of explosion and poisoning of humans.

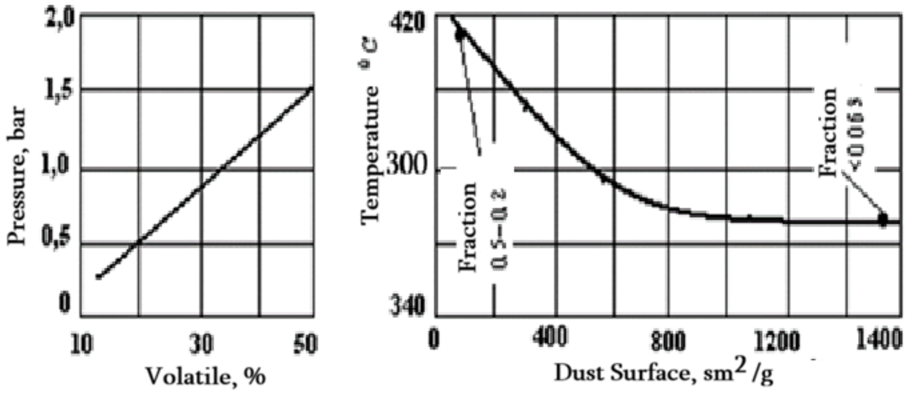

Fig. 5.1. Left — pressure development during coal dust explosion depending on volatile yield; Right — variation of ignition temperature with specific surface area

The combustion process of aerosols differs somewhat from that of gases, but they share many similarities. In particular, their thermal effects are analogous: a 1 m³ air mixture with 10% methane concentration theoretically produces nearly the same thermal effect in an explosion as the amount of coal dust that can potentially burn in 1 m³ of air (111.5 g of carbon). The thermal effect of coal dust is 34,078 kJ/kg (8,140 kcal/kg). For methane, the corresponding values are 54,425 kJ/kg (13,000 kcal/kg).

Coal dust explosions are characterized by the following features:

1. Explosion strength depends on dust dispersity (degree of fragmentation), volatility (release of volatiles), moisture or inert admixtures (ash), volume of the explosive space, and ignition source intensity.
2. The chemical composition of the dust determines the type of volatile gases released, which participate in the explosion.
3. Explosions are preceded by heat accumulation due to oxidation reactions and volatile release.

4. In coal dust clouds, particle friction generates static electrical charges, whose discharge can produce sparks and initiate explosions without external intervention.

5. Coal dust explosions predominantly produce carbon monoxide.

The main components of volatiles are methane, hydrogen, carbon monoxide, ethane, as well as tars and other heavy hydrocarbons. The lower explosibility limit of coal decomposition products is practically constant at 4.2%. The concentrations of hydrogen sulfide and carbon monoxide in coal decomposition products vary randomly, especially when coal is at an advanced stage of metamorphism and volatile yield is below 15%. Only methane yield follows a certain regular.

According to the yield of volatiles, coal dust is classified as:

- Slightly explosive when the volatile yield is less than 15%.
- Highly explosive when the volatile yield exceeds 15%.

The finer the dispersion of coal dust, the greater its specific surface area, and consequently, its explosibility increases. This is expressed by higher explosion-site pressure with decreasing particle size, and by lower ignition temperature for the same reason. This relationship is illustrated in Fig. 5.1 (right). Thus, dust is more dangerous not at its generation site, but at a distance, where only fine fractions are carried by air (coarse fractions settle).

Therefore, the degree of dust explosibility can also be characterized by the magnitude of pressure at the explosion site, which increases with higher release of combustible substances (see Fig. 5.1).

Among the protective properties of water droplets, the most important is their ability to cause coagulation.

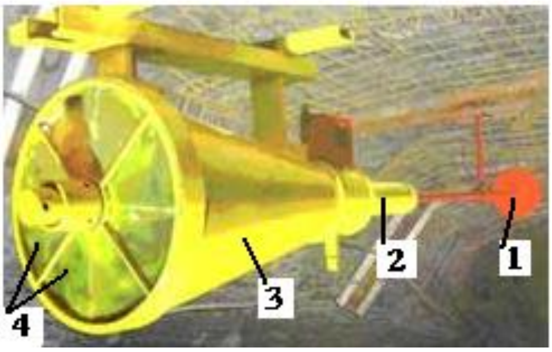

Fig. 5.2: General view of an automatic inert dust dispersion system:
1 — sensors and control panel; 2 — compressed air reservoir; 3 — container of inert dust; 4 — nozzles, normally sealed hermetically

Ash content also reduces coal dust explosibility, but natural ash content alone is generally insufficient to prevent dust explosions.

The composition of atmospheric air at the explosion site is of great importance in coal dust explosions. If methane is present in the air, explosions can occur even at low dust concentrations. It has been established that the lower limit of explosibility for highly explosive dust is 17–18 g/m^3, but in the presence of methane, air containing only 5–6 g/m^3 of dust becomes hazardous. For slightly explosive dust, with volatile yield in the 10–15% range, the lower explosibility limit is 50 g/m^3.

Moisture in the air significantly reduces the explosibility of coal dust. Moisture acts as an inert additive, lowering the overall dust concentration. Additionally, moisture reduces explosibility in two ways:

1. Water has higher heat capacity than inert dust of the same mass, and considering the heat required for evaporation, moisture absorbs about five times more heat from the mixture compared to inert dust.

2. Moisture promotes coagulation of dust particles, reducing their specific surface area and thereby diminishing oxidation processes.

Coal dust explosions have specific stages, distinguished by flame front propagation speed:

1. **Ignition** — slow combustion under oxygen deficiency.
2. **Flaming combustion** — 4–10 m/s flame speed at 15 kPa pressure.
3. **Explosion** — flame speed exceeding 100 m/s.
4. **Detonation** — flame front propagates at 1000 m/s or more.

To prevent coal dust explosions in mines, methods such as air humidification or saturation with inert dust are used. Containers filled with inert dust are arranged so that the explosion wave can overturn them, dispersing inert dust into the air and preventing detonation. Containers may also be overturned manually.

For localization of coal dust explosions, automatic systems are also used (see Fig. 5.2). Sensors detect the primary explosion wave and transmit a mechanical impulse to the activation mechanism, which breaches the system's integrity within 15–20 milliseconds, releasing compressed air and approximately 25 kg of inert extinguishing powder. This fills the space where the primary explosion occurs, eliminating the possibility of detonation in volumes of about 180–200 m³. Such automatic systems are mainly used in mines and coal-fired power plants.

Note: Determining the lower and upper concentration limits of explosibility represents a quantitative risk index assessment within the ISO 31000 framework.

ISO 80079 and **ISO 6184** provide internationally recognized frameworks for evaluating the explosibility of coal dust. ISO 80079 specifies requirements for equipment and protective systems intended for use in explosive atmospheres, while ISO 6184 defines test methods for determining explosion indices of dust clouds. By linking the discussion of coal dust explosibility to these standards, the monograph ensures that both theoretical analysis and practical calculations are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in preventing dust explosions in industrial and mining environments.

5.3. Explosibility of Sulfur and Its Compounds Dust

During the processing of copper and sulfur-pyrite deposits, especially when the latter contain a high proportion of pyrite (50–90%), there is a danger of sulfide dust explosions, which are characterized by the release of large amounts of sulfurous gas. The primary source of ignition for sulfide dust is gaseous products released during blasting operations. Other sources, such as open flames or sparks, are comparatively less hazardous. Practice has shown that due to its high density, sulfide dust does not spread far from its point of origin. The explosibility of sulfide dust depends on its sulfur content, particle size, ash content, and moisture. With increasing sulfur content, the flame length in the test tube grows, while the lower explosion limit is a 30% sulfur concentration. The influence of dust dispersion composition on explosibility is illustrated in Fig. 5.3. The most dangerous sulfide dust has particle sizes ranging from 10–100 μm, while dust particles larger than 250 μm are practically safe in terms of explosion risk.

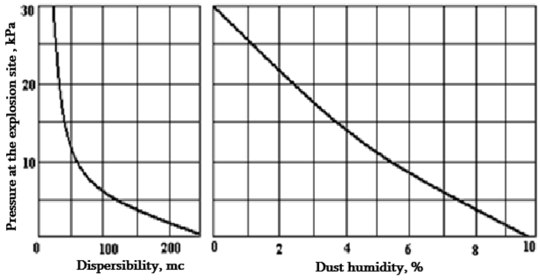

Fig. 5.3. Left – dependence of sulfur dust explosion pressure on its dispersion; Right – dependence of the same parameter on dust moisture

The explosibility of sulfide dust decreases with increasing moisture. At 9.0–9.5% moisture, sulfide dust ceases to explode. The dependence of explosion intensity on the humidity of the air mixture is shown in the right-hand graph of Fig. 5.3. Sulfur dust is more hazardous than coal or sulfide dust because its explosion temperature and lower explosive concentration limit are lower. The minimum ignition and explosion temperatures of sulfur dust are presented in Table 5.1.

Table 5.1. Minimum Ignition and Explosion Temperatures of Sulfur Dust

Type of Sulfur	**Minimum Ignition Temperature (°C)**	**Minimum Explosion Temperature (°C)**
Lump (Massive)	290	340
Crystalline	275	320
Flotation Concentrate	275	320

Explanatory Notes:

- Lump (Massive) sulfur — Higher ignition and explosion temperatures; relatively lower risk under normal conditions.
- Crystalline sulfur — Ignites more easily; requires strict control of storage and handling.
- Flotation concentrate — Similar to crystalline sulfur in ignition behavior, but more common in industrial practice, thus demanding special preventive measures.

The dust control regime in sulfide and sulfur mines includes the following measures:

1. Elimination or significant reduction of dust formation causes (wet drilling, watering of the working space, washing dust from tunnel walls and ceilings).
2. Minimization of ignition sources (use of protected explosives, application of electric blasting methods, prohibition of open flames).

Note: Minimum ignition and explosion temperatures of sulfur dust illustrate ISO 45001 preventive principles — control of ignition sources and dust management.

ISO 80079 and **ISO 6184** provide internationally recognized frameworks for evaluating the explosibility of sulfur dust and its compounds. ISO 80079 specifies requirements for equipment and protective systems intended for use in explosive atmospheres, ensuring that sulfur-handling processes are safeguarded against ignition sources. ISO 6184 defines test methods for determining explosion indices of dust clouds, which are directly applicable to sulfur and its derivatives. By linking the discussion of sulfur dust explosibility to these standards, the monograph ensures that both theoretical analysis and practical calculations are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in preventing dust explosions in chemical, industrial, and mining environments.

5.4. Preventive Measures Against Aerosol Explosions

The list of substances and materials most frequently transported and stored, as well as the rules for their separation during storage and transportation, are provided in specialized literature Fire Safety Rules in Force in Georgia.

All types of aerosol explosions are dangerous, but mining enterprises are particularly hazardous due to the complexity of ventilation. Elevators and other facilities where products or materials are stored without containers — i.e., in large undivided volumes — are also highly vulnerable. In such cases, once an explosion occurs, it cannot be stopped and continues as a series of explosions. In mines, the preventive measure against explosion series is the use of various **phlegmatizers** (inert dust or gas, water, etc.).

Note: Interpretation of combustion theories (thermal, chain) explains the mechanism of risk self-propagation, which in the ISO 31000 context represents analysis of the probability of risk realization.

A serious case of explosion series occurred in 1988 at the Tomilovo elevator in the Russian Federation. Three explosions occurred consecutively in a sunflower seed silo. During attempts to localize the explosions, another blast followed, killing all personnel present — 30 people. For a year and a half, local fires and explosions continued at the site until the elevator was completely destroyed.

Therefore, one way to prevent such situations is to store products or materials in **separate compartments**, making it impossible for fire or explosion to spread from one section to another.

The majority of primary explosions — about 50% — occur in equipment, while more than 40% occur in storage facilities, silos, and bunkers.

The most destructive secondary effects were recorded in:

- Elevators — 45%
- Flour mills — 35%
- Compound feed factories — 20%

Main causes of destructive secondary effects:

- Ineffectiveness or absence of explosion-protection devices in equipment.
- Lack of easily removable structures in silos, bunkers, and buildings (e.g., lightweight roofs or detachable walls), which significantly reduce explosion strength.
- Absence of explosion localization systems.

Fire and explosion safety of technological processes and equipment is achieved through:

- Proper design.
- Operation in compliance with regulatory requirements.
- Use of fire- and explosion-prevention rules and devices.
- Systems that minimize personnel injury in case of accidents.
- Above all, personnel qualification at all stages and levels of work.

Fire and explosion prevention rules and measures include:

1. Removal of dust within equipment and devices — by cleaning or ventilation.
2. Dust neutralization — by inert dust, phlegmatizers (carbon dioxide, nitrogen, other inert gases), or water spraying where applicable.
3. Prohibition of ignition sources — sparks, open flames, etc.

Additionally, protective systems must be installed with the following functions:

1. Protect equipment and devices in case combustion begins inside them.
2. Safely relieve excess pressure (e.g., venting through pipelines to areas not hazardous for fire or explosion).
3. Extinguish fire or eliminate explosion inside equipment and devices if the first two measures fail.

Installation of protective systems must be preceded by predictive calculations of possible fire or explosion sources.

Organizational and technical measures include:

1. Periodic cleaning of equipment and devices within the timeframes specified in technical documentation, with visible indicators (labels, posters, etc.).
2. Timely scheduled inspection and repair of fire- and explosion-prevention and protective devices.
3. Periodic testing of the operability of fire- and explosion-prevention devices.
4. Improvement of personnel qualifications through examinations and training drills.

It must be considered that, apart from oxygen, oxidizers include substances such as perchlorates, nitrates, gunpowder, thermite, and certain chemical elements (e.g., phosphorus, bromine).

For the assessment of the safe distance from the explosion site, the data of W. Baker, which he obtained in 1995 for the conditions of the explosion of a 5-ton fuel tank, are very important.

The following distances characterize fire damage:

- up to 45 m. Incompatible with life,
- up to 95 m. 3rd degree burn,
- up to 145 m. 2nd degree burn,
- up to 150 m. 1st degree burn,
- up to 240 m. Retinal burn.

The appropriate indicators for the shock wave are as follows:

- up to 45 m. Incompatible with life,
- up to 95 m. Barotrauma of the lungs and abdominal cavity,
- up to 140 m. Perforation of the eardrum.

ISO 80079 and **ISO 45001** provide internationally recognized frameworks for preventive measures against aerosol explosions. ISO 80079 specifies requirements for equipment and protective systems intended for explosive atmospheres, ensuring that aerosol-generating processes are safeguarded against ignition sources. ISO 45001 establishes occupational health and safety management.

5.5 Assessment of Combustible Dust Hazards

1. Suspended Combustible Dust in Air

To characterize combustible dust suspended in air (dust-air mixtures), the following explosion and fire hazard indicators are used:

- N — Lower concentration limit of dust ignition in the mixture, g/m³;
- W_{min} — Minimum ignition energy, millijoules;
- P_{max} — Maximum explosion pressure, kPa;
- $V\frac{dP}{d\tau}$ — Rate of pressure rise during explosion, kPa/s;
- N_O — Minimum explosive oxygen content in the mixture, % by volume.

2. Deposited Combustible Dust

To characterize deposited combustible dust, the following indicators are used:

- t — Self-ignition temperature, $°C$;
- W_{min} — Minimum ignition energy, millijoules;

Additionally, ignition temperature, self-heating temperature, decomposition temperature, thermal self-ignition conditions, and heating rate under water interaction may be applied.

Table 5.2 — Explosion and Fire Hazard Indicators of Combustible Dust Suspended in Air (Dust-Air Mixtures)

Substances	N, **g/m³**	W_{min}, **mJ**	t, ℃	P_{max}, **kPa**	$dp/d\tau$, **kPa/s**	N_O, %
Inorganic substances						
Boron	100	60	400	630	17000	_
Sulfur	17	_	190	460	13300	5,0
Silicon (Silicon)	100	2,1	790	530	84000	11,0
Phosphorus Penta sulfur	20	_	265	510	40000	5,0
Red phosphorus	14	0,05	305	700	33000	4,0
Metals						
Aluminum	10	0,025	470	660	63000	2,0
Aluminum-magnesium alloy	25	0,047	280	600	70000	$+CO_2+A$
Bronze powder	1000	_	190	300	9000	_
Vanadium	220	60	490	340	4200	10,0
Zinc	480	0,15	460	350	13000	10,0
Thorium	75	5	270	350	23000	2,0
Cadmium	_	4000	250	49	700	_
Tin	190	80	430	260	9000	16,0
Magnesium	25	10	490	500	70000	$+CO_2$
Manganese	90	180	240	340	20000	15,0
Reduced iron	66	80	475	250	50000	11,0
Carboline iron	105	20	310	300	17000	10,0
Silicocalcium	42	150	490	660	30000	8,0
Stibium	420	1920	330	56	700	16,0
Tantalum	190	140	290	400	28000	14,0
Titanium	60	25	510	371	23800	$+CO_2$
Ferromanganese	130	0,25	240	330	30000	_
Ferrosilicon	150	280	860	620	26000	15,0
Ferrotitanium	140	80	400	370	67000	13,0
Zirconium	40	5	190	450	44500	$+CO_2+A$
Plant protection chemicals						
Diazinon 40% powder	99	96,4	395	_	_	16,1
Dynos (technical)	52	8	325	436	7600	10,5
Karbofos 30% powder	300	100	295	_	_	_
Lenacil (technical)	15	3,2	432	_	_	9,0
Metaphors 30% powder	300	100	385	_	_	_

Niklosin 30% powder	460	100	495	_	_	_
Polycarbacin 80% powder	92	21,3	195	912	41000	14,5
Polyhom 80% powder	250	7,5	185	_	_	14,1
Simazine (technical)	26	9,0	530	550	7600	13,5
Topsin 70% powder	61	8,6	457	_	_	16,1
Hexathiuram 80% powder	87	6,2	297	_	_	12,1
Organic substances						
Adipic acid	35	70	410	630	19300	_
Azobenzodicarboxylic acid	113	_	365	470	6766	13,0
Aminoanthraquinone	38	_	612	650	15600	13,0
1-Aminoatraquinone (sulfate)	254	_	600	170	4800	16,0
1-Amino-4-acetylaminoanisole	29	_	438	175	_	14,0
1-Amino-5-benzolaminoanthraquinone	34	_	545	350	6000	12,0
1-Amino-4-mesidineanthraquinone	55	_	545	540	6600	16,0
Amino salicylic acid (technical)	98	_	450	250	_	11,0
2-Aminophenol	55	_	390	830	_	11,0
4-Aminophenol	40	_	500	568	5884	16,0
1-Amino-4-chloroanthraquinone	60	_	684	550	35000	16,5
N-Benzoyl-2-aminobenzoic acid	74	_	520	650	60000	13,5
Benzoic acid	20	_	532	640	_	9,0
Beryllium acetate	80	100	620	600	15000	15,0
Diaminobenzene	15	20	_	790	70000	_
Diaminoanthrorufin	79	_	260	330	10000	14,5
Dextrin	40	_	400	680	19300	10,0
Dimethyl isophthalate	25	15	_	580	5520	13,0
Dimethyl terephthalate	30	20	_	725	82680	12,0
Dihydrostreptomycin (sulfate)	52	_	230	_	10000	7,0
1,2-diaminoanthraquinone	61	_	628	800	77000	_
1,4-diamino-2-benzoanthraquinone	50	_	650	680	23700	13,0
2,4-dioxybenzoic acid	31	_	530	583	13000	12,5
1,5-Diphenoxyanthraquinone	18	_	590	380	17700	11,0
2,4-Dichlorobenzoxyethylbenzoate	45	60	_	680	15200	_
Vanillin	40	3,3	280	460	68000	_
Casein	45	60	_	760	35000	17,0
Lilados	35	_	230	300	_	13,0
Luminophore Green	103	_	385	800	4500	19,0
Gum Flour	74	2	377	550	20000	14,0
Resorcinol	25	_	515	147	14710	12,0
Ferric Dimethyl Carbonate	15	25	150	600	41500	_
Salicylic Acid	50	_	543	500	30000	10,0
Simazine (Technical)	26	_	530	550	7600	13,5
Sorbic Acid	30	_	425	551	34475	12,0
Terephthalic Acid	50	20	496	579	55160	15,0
Trans-Butanoic Acid	85	35	375	710	17250	15,0
Urotropine	15	10	683	700	_	14,0
Phthalic Anhydride	12	15	595	490	_	14,0
Phthalic Acid	26	_	535	640	20400	13,0
Chlorobenzoylbenzoic Acid	24	_	579	392	_	13,0
4-Chloro-2-Aminophenol	89	_	588	637	_	18,6
Cellulose Acetobutyral	35	30	410	586	18630	7,0
Cellulose Ethyl	45	_	310	588	14710	15,3
Cellulose Methyl	30	20	360	917	37950	13,0
Cellulose Carboxymethyl	110	440	320	338	20200	_

Cellulose Hydroxyethyl	25	40	410	703	17940	_
Cellulose Hydroxypropyl	20	30	400	662	15870	_
Cellulose Hydroxypropyl methyl	80	_	430	276	13800	_
Hexamethylenetetramine	15	10	340	680	76000	14,0
4-Hydroxybenzoic Acid	26	_	550	600	_	12,0
Plastics						
Acrylamide polymer	40	30	240	600	17580	_
Copolymer of acrylamide and ammonium chloride vinylbenzyltrimethyl	1000	8000	500	90	700	_
Polymer of acrylonitrile	25	20	_	630	77330	13,0
Copolymer of acrylonitrile and vinyl pyridine	20	25	240	600	42180	_
Epoxy resin without catalyst	20	15	540	647	41340	12,0
Vinyl chloride acrylonitrile (emulsion)	35	15	470	660	51800	15,0
Polymer of methyl methacrylate	30	20	_	590	14000	8,0
Copolymer of methyl methacrylate and ethyl acrylate	30	10	_	600	42180	11,0
Copolymer of methyl methacrylate, styrene, butadiene and ethyl acrylate	25	25	480	590	30230	13,0
Copolymer of methyl methacrylate, ethyl acrylate and styrene	25	20	_	630	31930	_
Copolymer of methyl methacrylate, styrene, butadiene and acrylate	25	20	480	600	33000	11,0
Polyacetal	60	_	470	642	56650	_
Polyether	45	50	485	640	_	_
Polyethylene	12	30	440	560	_	13,0
Polyvinylpyrrolidone (high molecular weight)	56	_	370	450	31600	11,0
Polyisobutylene methacrylate	160	_	319	200	_	15,0
Polymerize (technical)	137	8,2	265	580	7500	18,0
Polypropylene	32,7	3,4	395	_	_	_
Polystyrene	25	15	488	720	29000	10,0
Phenolic resin	25	10	460	550	12000	_
Phenol formaldehyde resin	55	10	420	650	33300	14,0
Phenol formaldehyde powder	47	_	355	700	9500	14,0
Resin	71	_	_	700	28000	13,0
Urea-formaldehyde resin	135	1280	_	370	3520	15,0
Medicinal preparations						
Ethylcymate	21	27	_	120	53600	_
Vitamin A	45	80	250	570	35000	_
Vitamin B1	35	60	360	680	41500	_
Vitamin B2	106	80	510	840	32500	_
Vitamin C	60	20	280	610	33200	_
Agricultural products						
Peanuts	45	50	210	810	56000	_
Peas	79,0	_	525	562	20700	12,5
Cork flour	35	45	260	700	_	10,0
Cereal starch	40	30	625	770	_	10,0
Corn husks	50	23,4	355	570	9800	10,5
Soybeans	35	40	215	700	17200	15,0
Sorghum husks	36	17,2	_	575	8000	19,5
Peat dust	50	41	205	250	9200	11,0
Barley flour	47,26	11,6	470	635	17600	12,5

Barley husks	47	14,2	470	435	7100	12,5
Wheat flour	28,8	50	380	650	13000	11,0
Wheat husks	33	23,5	415	470	5300	13,5
Wheat bran	45	50	210	810	56000	_
Rye husks	79,0	_	525	562	20700	12,5
Wood flour	35	45	260	700	_	10,0

Note: *+CO_2 indicates combustibility in carbon dioxide.*

- *+A indicates combustibility in nitrogen.*

ISO 80079 and **ISO 12100** provide internationally recognized frameworks for assessing combustible dust hazards. ISO 80079 specifies requirements for equipment and protective systems intended for explosive atmospheres, ensuring that dust-handling processes are safeguarded against ignition sources. ISO 12100 establishes general principles for risk assessment and risk reduction in machinery, including methodologies for identifying combustible dust hazards and implementing preventive measures. By linking the assessment of combustible dust hazards to these standards, the monograph ensures that both theoretical evaluations and practical safety strategies are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in protecting workers, facilities, and the environment.

5.6. Prevention of Dust Explosions in Technological Equipment

Note: According to ISO 45001, technological deficiencies, lack of training, and violations of discipline are classified as organizational risks requiring systematic management.

Grinding Machines

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures.
- Spread of explosive concentrations beyond the machine due to high pressure, which may be caused by:
- Ejection during raw material loading.
- Heating of air by friction between machine parts.
- Airflow generated by rapidly moving parts or fans.
- Explosion of the air-dust mixture.
- Self-ignition of pulverized material at accumulation points (loading areas) or throughout the machine when stopped.
- Sparks generated by impact (loading of metal objects or stones, or damage to machine parts).
- Sparks from operating electrical equipment.
- Sparks from static electricity discharge caused by friction and electrification of pulverized material.
- Heated surfaces due to friction (especially bearings, caused by improper installation, insufficient lubrication, or dust ingress).

- Combustible gases and vapors released from heating and thermal decomposition of pulverized material.

Sieves

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures.
- Spread of explosive concentrations beyond the sieve due to high pressure, caused by ejection during raw material loading or explosion of the air-dust mixture.
- Self-ignition of sifted material at accumulation points or throughout the machine when stopped.
- Sparks from operating electrical equipment.
- Sparks from static electricity discharge.
- Self-ignition of dust at accumulation points.

Convective Dryers (belt, channel-type, hollow)

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures during increased heat-carrier velocity, or during loading/unloading and turning of drying material.
- Spread of explosive concentrations beyond the dryer due to insufficient sealing of its units or explosion of the air-dust mixture.
- Self-ignition of drying material due to increased heat-carrier temperature, heating of equipment by friction surfaces, or prolonged retention in a stopped dryer.
- Sparks generated by impact and friction.
- Sparks from operating electrical equipment.
- Sparks from static electricity discharge.
- Sparks from decomposition caused by heating with the heat-carrier.
- Self-ignition of dust at accumulation points.

Convective Dryers (spray, fluidized-bed spray, grating, drum-type)

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures.
- Disturbance of hydrodynamic interaction between phases due to overloading or underloading of the apparatus, leading to variations in air supply velocity.
- Spread of explosive concentrations beyond the dryer due to insufficient sealing of its units or explosion of the air-dust mixture.
- Self-ignition of drying material at accumulation points or due to prolonged retention in a stopped dryer.
- Sparks generated by impact and friction.
- Sparks from static electricity discharge.
- Sparks from decomposition caused by heating with the heat-carrier.

Conductive Dryers (roller, screw, tubular)

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures.
- Spread of explosive concentrations beyond the dryer due to insufficient sealing of its units, at loading/unloading points, or by explosion of the air-dust mixture.
- Self-ignition of drying material due to increased temperature of heating surfaces, friction of units, or exothermic chemical reactions of the material with apparatus surfaces.
- Sparks generated by impact and friction.
- Sparks from operating electrical equipment.

Conductive Dryers (shelf-type, volumetric, with heaters)

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures during loading and unloading.
- Spread of explosive concentrations into the production area due to insufficient sealing of apparatus units, at loading/unloading points, or by explosion of the air-dust mixture.
- Self-ignition of drying material at accumulation points or due to exothermic chemical reactions with heating surfaces.
- Excessive increase of heating surface temperature above permissible levels.
- Sparks generated by impact and friction.

Dust Collection Chambers

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures during chamber cleaning.
- Spread of explosive concentrations beyond the dryer due to excessive fan pressure or during chamber cleaning.
- Self-ignition of dust deposited on surfaces.
- Sparks from thermal decomposition carried by airflow from preceding apparatus.

Cyclones

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures inside the cyclone.
- Spread of explosive concentrations beyond the cyclone from its central part or due to excessive fan pressure.
- Self-ignition of dust accumulated in the conical section of the cyclone.
- Sparks from thermal decomposition carried by airflow from preceding apparatus.
- Sparks generated by impact during cyclone cleaning.

Bag Filters (filter sleeves)

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures during filter shaking.
- Heavy dust formation at dust removal points, especially in the lower part of the shaken filter.
- Self-ignition of dust accumulated in sleeves, or in downward ducts when clogged.
- Sparks from static electricity discharge.
- Sparks from thermal decomposition carried by airflow from preceding apparatus.

Electrostatic Filters

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures.
- Sparks from electrode discharges, which may occur due to conductor breakage, supply of highly humid air, condensation of water droplets from air, short-circuiting by wet dust agglomerates, or poor electrode alignment.
- Sparks from thermal decomposition generated in the upper particle flow.
- Self-ignition of dust in the bunker due to incomplete emptying.

Elevators

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures during dust scooping with buckets or during discharge, when dust is entrained by airflow.

- Spread of explosive concentrations beyond the apparatus due to insufficient sealing of its units and casing.
- Self-ignition of dust in the vertical elevator bunker or at friction points of units.
- Sparks generated by impact when buckets detach or belts break.
- Sparks from static electricity discharge in the drive system.
- Sparks from operating electrical equipment.

Horizontal and Inclined Conveyor Belts

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures due to dust entrainment by airflow, during belt transfer over guide rollers, material agitation, transfer from one belt to another, or loading into bunkers.
- Self-ignition of dust caused by static electricity discharge, with electrification occurring through belt friction.
- Sparks from operating electrical equipment.

Pneumatic Transport Systems

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures.
- Spread of explosive concentrations beyond pipelines due to insufficient sealing of units or explosion of the air-dust mixture.
- Sparks from static electricity discharge.
- Sparks generated by impact and friction.

Mixing Apparatus

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures.
- Spread of explosive concentrations beyond the apparatus due to excessive fan pressure, airflow induced by ejection during raw material loading, or dust explosion.
- Self-ignition of mixing materials due to thermochemical reactions, incomplete unloading, or accumulation.
- Sparks generated by impact.
- Heated surfaces caused by friction.

Bunkers

Potential hazards:

- Formation of explosive concentrations of air-dust mixtures during loading or self-discharge.
- Spread of explosive concentrations beyond the bunker through dust feeders during transfer.
- Self-ignition due to prolonged storage.
- Sparks from thermal decomposition carried by airflow from preceding apparatus.
- Sparks from static electricity discharge.

Table 5.3. Preventive Measures Against Explosions and Fires in Case of Combustible Dust Emission During Technological Processes and Apparatuses

Measures	Technological Processes and Apparatuses	Short Description
	Grinding; Sieving; Convective dryers (belt, channel, hollow); Convective dryers (spray, air-	

Hermetization	jet, fluidized bed, grate-type, drum); Conductive dryers (roller, screw, tubular); Conductive dryers (shelf-type, volumetric, heater-equipped); Cyclone; Electrofilter; Elevator; Hopper; Pneumatic transport; Mixing apparatus.	Sealing equipment to prevent dust leakage and accumulation.
Chambers made of fire-resistant material	Convective dryers (belt, channel, hollow); Convective dryers (spray, air-jet, fluidized bed, grate-type, drum); Conductive dryers (roller, screw, tubular); Cyclone; Pneumatic transport.	Construction with fireproof materials to resist ignition.
Placement in isolated rooms	Electrofilter; Bag filter (sleeve filter).	Locating equipment in separate rooms to limit fire spread.
Local dust removal	Grinding; Sieving; Conductive dryers (roller, screw, tubular); Conductive dryers (shelf-type, volumetric, heater-equipped); Elevator; Hopper; Horizontal and inclined conveyor belt; Mixing apparatus.	Installing suction/extraction systems to remove dust at its source.
Elimination of static charge accumulation	Grinding; Sieving; Convective dryers (spray, air-jet, fluidized bed, grate-type, drum); Dust settling chamber; Bag filter; Elevator; Horizontal and inclined conveyor belt; Hopper; Mixing apparatus; Pneumatic transport.	Grounding and discharge systems to avoid electrostatic sparks.
Elimination of sparks from impact and friction	Grinding; Sieving; Conductive dryers (roller, screw, tubular); Mixing apparatus.	Preventing mechanical sparks by proper design and maintenance.
Prevention of spark transfer by air from thermal decomposition in upstream apparatus	Convective dryers (belt, channel, hollow); Convective dryers (spray, fluidized bed spray, grate-type, drum); Bag filter.	Blocking hot particles from entering downstream units.
Prevention of dust deposition by reducing unventilated areas	Grinding; Convective dryers (belt, channel, hollow); Convective dryers (spray, air-jet, fluidized bed, grate-type, drum); Conductive dryers (roller, screw, tubular); Conductive dryers (shelf-type, volumetric, heater-equipped); Electrofilter; Pneumatic transport; Mixing apparatus.	Ensuring ventilation to avoid dust settling in dead zones.
Avoidance of overload or underload	Grinding; Elevator; Horizontal and inclined conveyor belt; Hopper.	Maintaining optimal load to prevent overheating or instability.
Prevention of overheating of rubbing parts	Grinding; Dust settling chamber.	Monitoring moving parts to avoid excessive heat.
Prevention of explosive concentrations of air–dust mixtures	Convective dryers (belt, channel, hollow); Convective dryers (spray, air-jet, fluidized bed, grate-type, drum); Dust settling chamber; Bag filter; Elevator; Horizontal and inclined conveyor belt; Hopper.	Controlling air–dust mixture concentration below explosive limits.
Use of phlegmatizing additives	Conductive dryers (roller, screw, tubular); Pneumatic transport; Mixing apparatus.	Adding inert materials to reduce dust explosibility.
Thermal insulation of apparatus to		

prevent steam condensation and dust adhesion to walls	Cyclone; Bag filter; Electrofilter; Hopper; Pneumatic transport.	Preventing condensation and dust adhesion on walls.
Use of chemically passive surfaces	Convective dryers (belt, channel, hollow); Conductive dryers (roller, screw, tubular); Conductive dryers (shelf-type, volumetric, heater-equipped).	Applying non-reactive surfaces to reduce ignition risk.

Table 5.4. Preventive Measures Against Explosions and Fires in Case of Combustible Dust Emission During Technological Processes and Apparatuses

Measures	Technological Processes and Apparatuses	Short Description
Use of equipment designed for explosion pressure	Grinding; Convective dryers (spray, air-jet, fluidized bed, grate-type, drum); Conductive dryers (shelf-type, volumetric, heater-equipped); Bag filter; Mixing apparatus; Hopper.	Equipment built to withstand explosion pressure safely.
Use of emergency pressure relief devices	Grinding; Sieving; Convective dryers (belt, channel, hollow); Conductive dryers (roller, screw, tubular); Conductive dryers (shelf-type, volumetric, heater-equipped); Cyclone; Bag filter (sleeve filter); Electrofilter; Elevator; Hopper; Pneumatic transport; Mixing apparatus.	Devices that release excess pressure to prevent rupture.
Use of flame-arresting devices	Convective dryers (belt, channel, hollow); Convective dryers (spray, air-jet, fluidized bed, grate-type, drum); Conductive dryers (shelf-type, volumetric, heater-equipped); Dust settling chamber; Pneumatic transport; Mixing apparatus.	Barriers that stop flame propagation inside equipment.
Localization of fire and explosion with inert gases	Grinding; Sieving; Convective dryers (spray, air-jet, fluidized bed, grate-type, drum); Conductive dryers (roller, screw, tubular); Cyclone; Bag filter; Electrofilter; Hopper.	Flooding systems with inert gases to suppress combustion.
Use of fire-extinguishing devices	Grinding; Sieving; Convective dryers (belt, channel, hollow); Conductive dryers (roller, screw, tubular); Conductive dryers (shelf-type, volumetric, heater-equipped); Dust settling chambers; Pneumatic transport; Elevators; Hoppers.	Installing extinguishers to suppress fires quickly.
Use of active explosion suppression systems	Grinding; Sieving; Conductive dryers (roller, screw, tubular); Conductive dryers (shelf-type, volumetric, heater-equipped); Mixing apparatus.	Automatic systems that detect and suppress explosions.

ISO 80079 and **ISO 14491** provide internationally recognized frameworks for preventing dust explosions in technological equipment. ISO 80079 specifies requirements for equipment and protective systems intended for use in explosive atmospheres, ensuring that machinery and installations are safeguarded against ignition sources. ISO 14491 defines design and safety measures for dust explosion prevention in processing plants, including requirements for containment, suppression, and isolation systems. By linking the prevention of dust explosions to these standards, the monograph ensures that both engineering solutions and operational practices are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in protecting workers, facilities, and the environment.

5.7. General Fire Resistance of Building Structures and Industrial Facilities

Construction materials are classified into three groups according to combustibility: non-combustible, hardly combustible, and combustible.

- Non-combustible materials are those that do not burn under the action of an ignition source. These include artificial and natural inorganic materials such as brick, concrete, reinforced concrete, metals, etc.
- Hardly combustible materials are those that can burn under the influence of an ignition source but do not continue burning independently once the source is removed. Examples include asphalt concrete, wood impregnated with fire-retardant compositions, cement fibrolite, etc.
- Combustible materials are those that continue burning even after the ignition source is removed, such as wood, roofing felt, bitumen, etc.

The ability of building structures to perform their designated functions during a fire is called fire resistance. Fire resistance is characterized by the fire resistance limit, defined as the time during which a structure maintains its function under fire conditions.

Signs of Fire Resistance Limit for Partition Structures

- Formation of through holes and cracks, allowing combustion products or flames to pass into adjacent rooms.
- Temperature increase on the opposite side of the structu re reaching an average of 140 $°C$, or 180 $°C$ at any point, or 220 $°C$ as the overall room temperature.

For load-bearing structures, the fire resistance limit is reached when collapse occurs.

Fire Safety Condition

The following inequality must be satisfied:

$$P_f \geq P_{sz}$$

where: P_f - actual fire resistance limit of designed or functioning structures (hours); P_{sz} - required fire resistance limit defined by standards or safety conditions (hours).

Determination of Fire Resistance

Fire resistance of building structures can be determined either by calculation or experimentally.

Experimental method: A full-scale sample of the structure is heated in a special furnace under normative load. The time from the start of the test until one of the fire resistance limit signs appears is measured.

Calculation method: The aim is to determine the time after which the structure loses its function — whether as a partition, enclosure, or load-bearing element.

Partition structures are calculated based on their ability to contain fire.

Some structures serve both as enclosures and load-bearing elements. In such cases, fire resistance is calculated by both methods, and the **actual fire resistance limit** is taken as the smaller value.

- **Loss of enclosure ability** is calculated as the time during which the opposite side of the structure heats to critical temperature.
- **Loss of load-bearing ability** is calculated as the time after which the structure loses strength due to material degradation under fire conditions.

ISO 834 and **ISO 3008** provide internationally recognized frameworks for assessing the fire resistance of building structures and industrial facilities. ISO 834 specifies standard fire-resistance test methods for structural elements, while ISO 3008 defines procedures for evaluating fire doors and protective barriers under controlled conditions. By linking the discussion of general fire resistance to these standards, the monograph ensures that both theoretical evaluations and practical safety measures are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding buildings, industrial installations, and occupants against fire hazards.

5.8. Fire Barriers

To protect buildings from the spread of fire, fire barriers are used, which include non-combustible walls and floors. To limit fire spread between floors, non-combustible partitions are installed.

For determining optimal distances, compliance with fire-prevention and explosion-prevention standards must be observed. In many cases, minimum distances are allowed, but special attention is given to ensuring that fire-extinguishing equipment is ready for immediate use.

To prevent fire from spreading from one building to another, fire-prevention trenches are constructed between them. The minimum distance between buildings is determined by their fire resistance rating, as shown in Table 5.5.

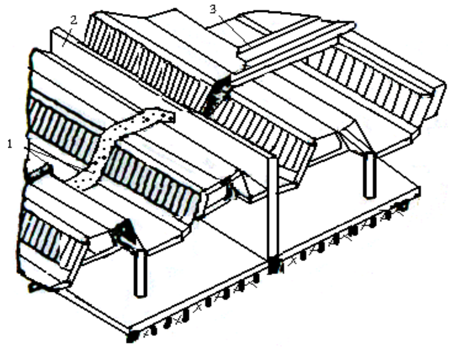

Fig. 5.4. Fire-prevention walls (grandmauers):
1. Transverse grandmauer; 2. Longitudinal grandmauer; 3. Fire bridge

Table 5.5. Variation of Minimum Distances Between Buildings According to Fire Resistance Rating

Fire Resistance Rating of Buildings	Distance Between Buildings (m)
I – II vs I – II	10
I – II vs III	12
I – II vs IV – V	16
III vs I – II	12
III vs III	16
III vs IV – V	18
IV – V vs I – II	16
IV – V vs III	18

IV – V vs IV – V	20

The fire-prevention distance between buildings (structures) is determined by the formula

$$r = K\sqrt{F} \quad (5.1)$$

where: K - coefficient depending on fire temperature and relative positioning of objects ($K = 0.85–0.90$); F = area of the object, m².

Barriers are constructed in the form of complete fire-prevention walls, partitions, doors, gates, valves, sluices, and windows. Their purpose is to limit fire spread. Barriers may be vertical or horizontal, longitudinal or transverse.

In addition to special barriers, **local barriers** are also used as parts of building structures. These include reinforced concrete belts, various dampers, valves, shutters, diaphragms, recesses, etc. They prevent linear flame propagation.

Fire-prevention walls (grandmauers) are used to divide workshops into fire-prevention sections. Such walls rest on continuous or beam foundations and extend through the full height of the building (see Fig. 5.4).

ISO 3008 and **ISO 10294** provide internationally recognized frameworks for evaluating fire barriers in building structures and industrial facilities. ISO 3008 specifies test methods for fire doors and protective barriers, ensuring their resistance under standardized fire conditions. ISO 10294 defines procedures for assessing fire dampers and other barrier components used in ventilation systems. By linking the discussion of fire barriers to these standards, the monograph ensures that both design and operational parameters are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding buildings, industrial installations, and occupants against fire spread.

5.9. Fire-Extinguishing Substances and Means

To extinguish fires, liquid, gaseous, foam substances, and solid powders are used. Fire suppression with these agents is achieved by:

1. Lowering the temperature of the fire source.
2. Restricting air supply to the fire source.
3. Reducing the partial pressure of oxygen in the airflow directed at the fire source.
4. Or by a combination of these methods.

Depending on the extinguishing agent used, fire extinguishers differ in their principle of operation (see Fig. 5.5).

Types of Fire Extinguishers

1. By activation principle:

- Automatic: Installed in places where fire is likely to occur, activated by sensors detecting fire. The most common sensor reacts to sudden temperature increases. Sensors may also respond to absolute temperature, smoke (soot), or carbon dioxide content in the air.
- Manual: Mounted on special fire-prevention stands and operated by hand.

2. By body volume:

- Standard handheld extinguishers up to 5 liters.
- Industrial handheld extinguishers of 5–10 liters.

- Stationary and portable extinguishers with volumes greater than 10 liters.

3. By agent delivery method:

- Pressure generated by chemical reaction inside the extinguisher.
- Pressure from a small compressed gas cylinder inside the extinguisher body.
- Pressure from compressed gas stored directly in the extinguisher body.
- Pressure of the extinguishing agent itself.
- For powders, gravity may also be used for delivery.

Marking and Maintenance

Fire extinguishers are marked with letters and numbers:

- Letters indicate the type of extinguisher.
- Numbers indicate capacity.

Each extinguisher must also display:

- Date of charging with extinguishing agent.
- Date of next inspection and recharging.
- Warning about fire types for which the extinguisher must not be used.

Fig. 5.5. General view of a hand-held fire extinguisher

Extinguishing Agents

- **Water:** Highly effective and widespread due to its high heat capacity, sharply reducing fire source temperature compared to other agents. High-pressure water jets also have mechanical effects, breaking and dispersing burning material. Water can be applied as a compact jet or as a spray. Spray is more effective, since when water vapor reaches 30% or more in air, oxygen content drops sharply and combustion ceases. Thus, spraying extinguishes fire faster and uses less water.
- **Inert gases:** Reduce the partial pressure of oxygen in the fire zone, effectively displacing oxygen and creating an environment where combustion is impossible. Inert gases do not damage products or equipment, as they are non-reactive.
- **Foam:** Used not only for solid materials but also for fuels and easily flammable liquids. Foam covers the surface of combustible material, isolating it from oxygen, cooling the source, and ultimately stopping combustion. Foam is produced either chemically or mechanically, consisting of nitrogen, carbon dioxide, or air bubbles enclosed in thin water films. Foam-forming agents give elasticity, viscosity, and stability to bubbles.
- Chemical foam composition: 80% CO^2, 19.7% water, 0.3% foaming agent.
- Mechanical foam composition: 90% air, 9.8% water, 0.2% foaming agent.

Foam is electrically conductive and must not be used on live electrical equipment, nor on substances that burn in CO^2 or nitrogen environments.

- Powders and carbon dioxide: Provide cooling, isolate combustible surfaces from oxygen, and help stop combustion. Carbon dioxide compounds are used to extinguish nearly all chemical substances. When mixed with combustible materials, CO^2 snow does not form harmful compounds. Fire extinguishers can produce dry ice at –70 $°C$ if foam is discharged into insulated containers.

Primary Fire-Extinguishing Means

For small-scale fires, primary extinguishing means are widely used: handheld or portable fire extinguishers, sand-filled boxes, asbestos covers, water reservoirs, etc. Responsibility for the serviceability of fire equipment and primary extinguishing means lies with the organization's management. Use of fire equipment for purposes other than fire safety is strictly prohibited.

Fig. 5.6. Fire extinguishers:
A - carbon dioxide type OU-2, weight 7 kg, service life 10 years, recharge after 5 years; B - powder type OP-5, charge weight 5 kg; volume 6 l, action time 10 s, gloves included; C - powder type OP-5, charge weight 10 kg; volume 11.9 l, action time 15 s

Currently, the following extinguishers are widely used:

- Handheld chemical foam extinguisher ОХП-10.
- Air-foam extinguishers ОВП-5, ОВП-10.
- Carbon dioxide extinguishers ОУ-2, ОУ-5, ОУ-8.
- Portable CO_2 extinguishers УП-2.
- Powder extinguishers ОПС-6, ОПС-10.

Designed to extinguish fires at the initial stage. It consists of a steel body and a handle, sealed with a cast-iron cap. The valve system includes a rubber seal, a lever, and a spring mechanism.

To operate: the extinguisher is inverted, the valve opens, acid mixes with the alkaline component, foam is generated, pressure builds, and foam is expelled through the valve.

Air-Foam Extinguishers ОВП-5, ОВП-10, and Stationary ОВПС-250А

Used to extinguish various substances and materials. They must not be used for burning alkali metals, fires in live electrical installations, or substances that burn without oxygen.

Carbon Dioxide Extinguishers ОУ-2, ОУ-5, ОУ-8

These extinguishers are designed to suppress combustion of various substances. They cannot extinguish fires involving materials that burn in CO^2 environments.

Operation: the extinguisher is directed at the burning object, the valve is fully opened, liquid CO^2 is released, rapidly evaporates, and expands 400–500 times its original volume. Evaporation absorbs heat from the fire source, lowering temperature and reducing oxygen partial pressure — effectively displacing oxygen from the fire zone.

Portable CO^2 extinguishers are intended for:

- Fires of fuels and flammable liquids up to 5 m².
- Fires in small electrical installations.
- Fires in internal combustion engines.

Models УП-1М and УП-2М are single- and double-cylinder portable CO^2 extinguishers. Cylinders are equipped with protective valves, connected to a collector and distribution pipe. Operation requires two people: one directs the hose toward the fire, the other opens the valve fully.

Fire Safety Requirements

Regulations require at least one foam or CO^2 extinguisher per 50 m², with a minimum of two extinguishers per room. Additionally, each 100 m² must contain a 0.5 m³ sand box, with at least one per room.

Powder Extinguishers

Used for fires involving gases, fuels, flammable liquids, solvents, and other materials. Powder extinguishers are of two types:

- Stored-pressure type (pressurized with nitrogen, air, or CO^2 at 1.6 MPa).
- Gas-generator type (gas generated inside the container).

Stored-pressure extinguishers include a manometer indicating nominal pressure (1.6 MPa) to confirm serviceability. They can extinguish fires of Class A (solid materials); Class B (flammable liquids or fusible solids); Class C (flammable gases). The fire extinguisher is easy to use, safe, and the tap is easy to open.

Depending on the characteristics (brand) of the powder, these extinguishers can also be used to extinguish fires in electrical equipment with a maximum voltage of 1000 V.

Fire extinguishing powder is made up of finely dispersed mineral salts and various additives that prevent the powder from caking. The main components of the powder are: sodium or potassium carbonates or bicarbonates, sodium or potassium chlorides, phosphoammonium salts, etc., and the additives are: silicon compounds, metal stearates, white carbon black, talc, etc.

ISO 7165 and **ISO 14520** provide internationally recognized frameworks for evaluating fire-extinguishing substances and means. ISO 7165 specifies performance requirements and test methods for portable fire extinguishers, ensuring their reliability and effectiveness in diverse fire scenarios. ISO 14520 defines design, installation, and maintenance criteria for gaseous fire-extinguishing systems, including clean agents used in industrial and building facilities. By linking the discussion of fire-extinguishing substances and means to these standards, the monograph ensures that both practical applications and theoretical evaluations are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding lives, property, and the environment against fire hazards

5.10. Automatic Fire Extinguishing and Fire Alarm Systems

Successful fire suppression depends on the speed of notification about its onset and the immediate use of effective extinguishing means. The use of automatic devices ensures timely fire suppression and reduction of material losses. Equally important is the reliable and uninterrupted operation of the fire alarm system, which reduces material damage and saves lives. The fire alarm system is one of the essential components of an automatic extinguishing system.

In particularly fire-hazardous enterprises, where extinguishing must begin immediately and water is permissible as an agent, **sprinkler and drencher systems** are used. In energy pipelines and other areas without human presence, **powder extinguishers** are applied. In principle, other extinguishing methods may also be used in automatic devices, but water-based suppression has gained the widest application.

Sprinkler Systems

Sprinkler devices are used in premises of all types and purposes. In heated premises, the sprinkler head is constantly filled with water. If the temperature in the building drops below 0 °C, air is pumped into the pipes; after the sprinkler opens, air is released first, followed by water.

The sensitive element of the sprinkler — the sensor — may react to key fire indicators such as temperature or its increase, smoke, or carbon dioxide concentration. Thus, sprinklers are designed to activate according to different fire indicators.

Drencher Systems

Drencher devices are used especially in fire-hazardous enterprises. At the onset of fire, water is supplied simultaneously from all drenchers in one section. Consequently, water consumption is significantly higher compared to sprinklers.

Sprinkler and drencher systems, in addition to supplying water during fire, also issue a fire alarm signal, thus functioning as part of the fire notification system.

Fire Alarm Systems

In enterprises, large warehouses, and administrative buildings, digital and analog automatic fire alarm systems are used as fire notification devices.

Notification occurs immediately upon detection by the sensor, usually within seconds of fire ignition. Digital systems allow both centralized and decentralized control and are highly convenient.

Depending on the activation impulse, automatic sensor elements may respond not only to temperature increase or absolute value, but also to smoke or carbon dioxide concentration in the air, light, or a combination of these indicators.

ISO 14520 and **ISO 7240** provide internationally recognized frameworks for automatic fire extinguishing and fire alarm systems. ISO 14520 specifies requirements for gaseous fire-extinguishing systems, including design, installation, and maintenance criteria to ensure reliable suppression in industrial and building environments. ISO 7240 establishes performance standards for fire detection and alarm systems, covering components such as smoke detectors, control panels, and signaling devices. By linking the discussion of automatic fire extinguishing and fire alarm systems to these standards, the monograph ensures that both preventive and responsive measures are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding lives, property, and the environment against fire hazards.

5.11. Rules for Fire Extinguishing

Extinguishing with Water:

At the beginning of fire suppression, the primary task is to prevent its spread. Therefore, extinguishing always starts from the periphery toward the center. The water jet must be directed from the edges of the fire toward its center, gradually reducing the burning area. Care must be taken to ensure that burning objects displaced by the water jet do not ignite new fire sources.

Extinguishing with Foam and Liquid Extinguishers:

The same principle applies here, as these agents are as effective as water. The jet must be directed from the periphery toward the center, specifically at the base of the flames rather than their tips. In water extinguishing, this distinction is less critical, but for foam and liquid agents it is essential.

Extinguishing with Carbon Dioxide Extinguishers:

Again, action must begin from the periphery. The CO^2 jet should be directed from above downward at the base of the flames. The opposite direction is less effective, since high temperature causes the gas to rise.

Extinguishing with Powder Extinguishers:

Here too, suppression begins from the periphery. Powder is first applied around the fire source, then directly onto the flames. The same method applies when extinguishing with sand or soil.

ISO 11601 and **ISO 14520** provide internationally recognized frameworks for establishing rules for fire extinguishing. ISO 11601 specifies performance requirements and test methods for portable fire extinguishers, ensuring their reliability and effectiveness in diverse fire scenarios. ISO 14520 defines design, installation, and maintenance criteria for gaseous fire-extinguishing systems, including clean agents used in industrial and building facilities. By linking the rules for fire extinguishing to these standards, the monograph ensures that both procedural guidelines and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding lives, property, and the environment against fire hazards.

5.12. Demolition of Buildings by Explosion

For the redevelopment of densely populated areas, preparation of construction sites, and reconstruction of resort facilities, the demand for special blasting operations has significantly increased in order to reduce the time required for dismantling amortized structures. Explosive demolition of outdated buildings, compared to traditional dismantling methods, is much more economical and advantageous for the rapid restoration of urban life rhythm. At the same time, it is distinguished by a high level of safety in execution.

During demolition of amortized structures, the following must be considered:

- The explosion should ensure the destruction of only load-bearing structures, while the building itself must collapse under its own weight.
- The arrangement of explosive charges and their sequence of detonation must ensure complete collapse of the building in a predetermined direction.

In addition, measures must be developed both for localization of fragment scattering and for reducing the impact of seismic and air shock waves on protected objects. Therefore, each building demolition requires an individual approach.

In 1985, in connection with the reconstruction of old districts of Tbilisi, explosive demolition was carried out on a three-story brick building of the knitwear factory. The building was located between N. Baratashvili and Shavteli streets and the right bank of the Mtkvari River.

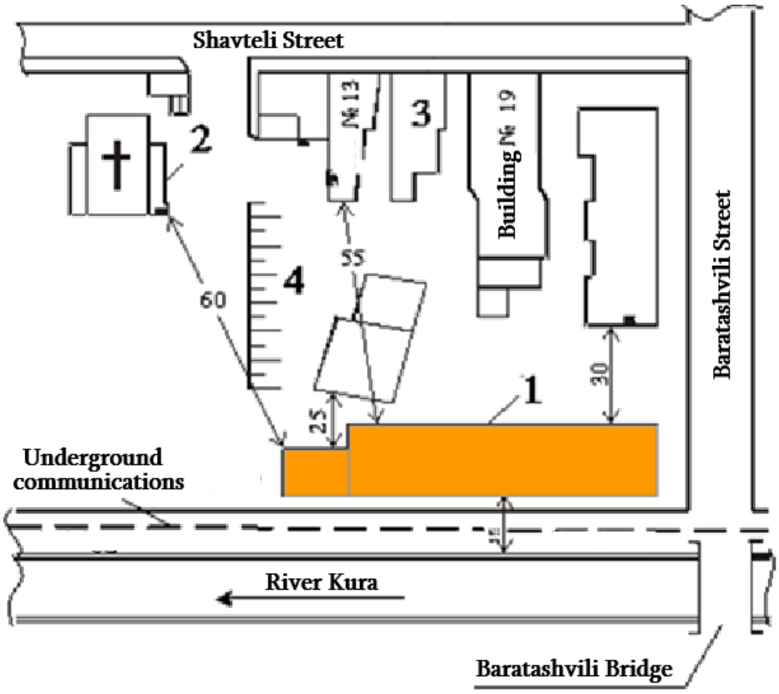

Fig. 5.7. Situational plan of the knitwear factory and protected objects: 1 – Knitwear factory building; 2 – Anchiskhati Church (6th century); 3 – Residential brick houses built in the 19th and early 20th centuries; 4 – Locations of seismic receivers

Among the protected objects, the most vulnerable and least seismically resistant were two three-story brick houses (Shavteli St. #13 and #19), the Anchiskhati Church, as well as the decorative parapet of the Mtkvari embankment and underground communications, including water pipelines of 200 and 300 mm diameter, a 300 mm diameter gas pipeline, and an international communication cable (Fig. 5.7).

To predict the seismic impact of the explosion on these protected structures, test explosions were conducted in the same area using ammonite N6 ЖВ charges placed at a depth of 1 m in the soil. The equivalent mass of the experimental charges and those placed in the knitwear factory walls was identical. The soil and protected objects' vibration velocities during the test explosions are presented in Table 5.6.

Table 5.6. Parameters of Seismic Waves During Test Explosions of Ammonite N6 ЖВ Charges Embedded in Soil

Location of Seismic Receiver	**Distance from Explosion Center r, m**	**Charge Mass, TNT Equivalent Q, kg**	**Reduced Charge Mass ρ, kg·0.333·m⁻¹**	**Frequency of Vibrations, Hz**	**Vibration Velocity V, cm/s**
House #13, 3rd floor	11.5/16.5	1.0/2.0	0.087/0.076	1-2/1-1.3	1.04-0.52/ 1.03-1.43
House #13, 1st floor	11.0/11.0	1.0/2.0	0.091/0.114	2-2.5/2.0	0.5-0.63/0.6
Anchiskhati Church (foundation)	20.0/15.5	1.0/2.0	0.049/0.081	2-2.5/10.0	1.2/2.5

Soil	7.7/2.7	2.0/1.0	0.162/0.370	4.5/5.0	7.0/24.0

Brief description of the table 5.6. by table rows:
1. Shows vibration impact on upper floors of residential buildings.
2. Indicates ground-level vibration effect on building foundations.
3. Demonstrates seismic sensitivity of historical structures.
4. Reflects direct soil vibration intensity near charges.

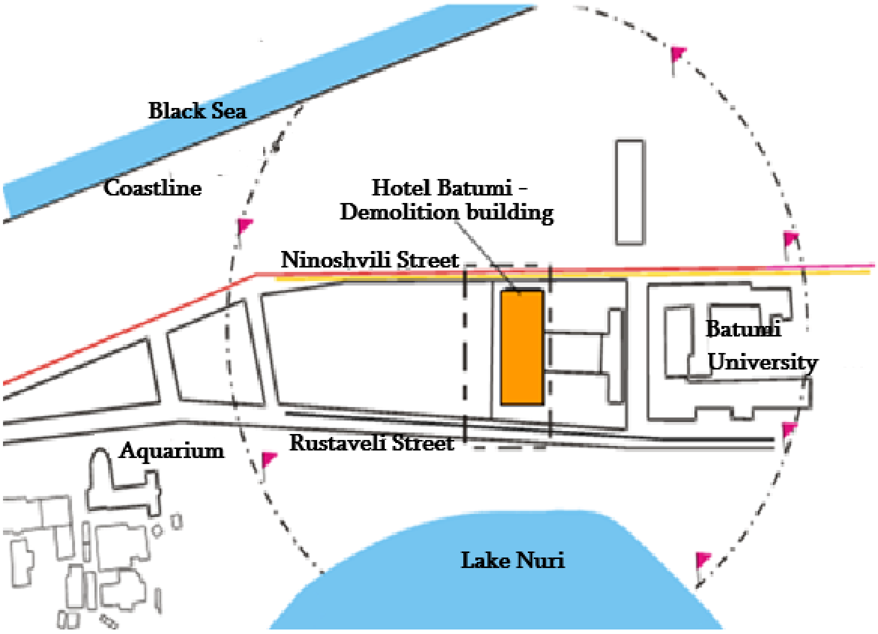

Fig. 5.8. Situational plan for the demolition of the Batumi Hotel building by explosion

From the data in the table 5.6, it is evident that with variation of reduced charge mass in the interval ρ = 0.049–0.114 kg·0.333·m⁻¹, the vibration velocity of protected buildings ranges between 0.50–2.51 cm/s. For soil, with reduced charge mass variation in the interval ρ = 0.370–0.162 kg·0.333·m⁻¹, vibration velocities reach 7–24 cm/s, which is hazardous for protected structures, especially old buildings. For old buildings, as well as pipelines located 3–5 m from the explosion center, vibration velocity must not exceed 1.5 cm/s.

Considering this, additional protective measures were included in the demolition project of the knitwear factory: excavation of a trench 2 m deep and 1.5 m wide between the collapsing walls and underground communications to screen seismic waves generated by basement charges; displacement of the plane of charge placement around the building perimeter by 0.5 m above ground level; and division of charges placed in the building walls into two groups with detonation delayed by 500 microseconds (one-thousandth of a second).

During the demolition of the knitwear factory building by explosion, the additional protective measures included in the project were implemented. As a result, the seismic waves generated by the charges placed in the basement were screened by the trench, and the vibration impact on underground communications and nearby protected structures was reduced to permissible limits. This eliminated the danger of damage to historical and residential buildings, as well as to pipelines and communication cables.

The demolition was organized so that the explosion destroyed only the load-bearing structures, while the building itself collapsed under its own weight. The arrangement of explosive charges and their sequence of detonation ensured the complete collapse of the building in the predetermined direction. This minimized the scattering of fragments and reduced the influence of seismic and air shock waves on the surrounding protected objects.

The charges placed in the building walls were divided into two groups and detonated with a delay of 500 microseconds (one-thousandth of a second). This method allowed the collapse to occur in a controlled manner, further reducing the destructive impact on nearby structures.

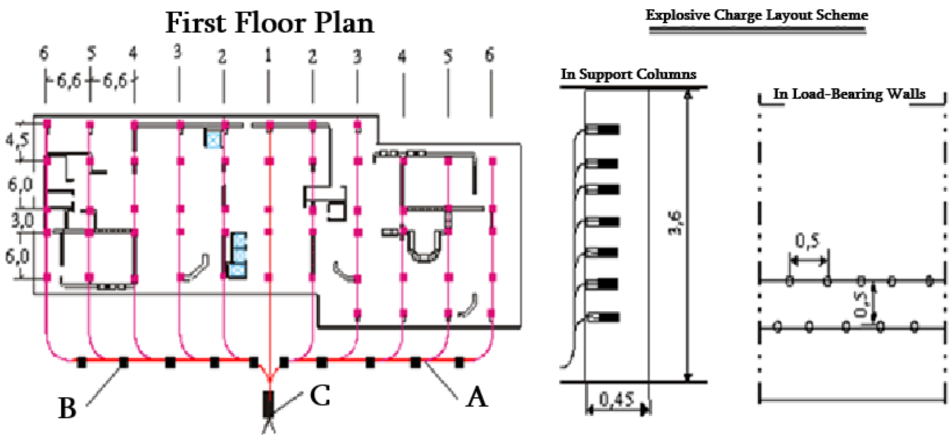

Fig. 5.9. Layout of explosive charges in supporting structures of the Batumi hotel and their slightly delayed detonation scheme:
1–6 - sequence of column explosions; A - detonating cord type ДШ-A; B - Nonel LP detonator with 100 ms delay; C - electric detonator (Dimensions shown in meters)

In recent years, as part of the reconstruction of the Adjara resort zone, explosive demolition was carried out in Kobuleti on four reinforced concrete frame buildings: two sixteen-story blocks of the Horizonti hotel complex, a sixteen-story residential building of the Academy of Sciences' rest house, and a ten-story residential building in the village of Bobokvati. In Batumi, the nine-story frame building of the Batumi hotel was demolished by explosion. The demolition projects were developed by specialists of G. Tsulukidze Mining Institute.

Fig. 5.8 shows the situational plan of the Batumi hotel building and the protected objects, while Fig. 5.9 presents the layout of explosive charges and the scheme of their slightly delayed detonation according to the first floor. To simplify Fig. 5.9, only the charges placed in the supporting columns are shown on the floor plans.

Explosive Charges and Parameters

Explosive material used: Powergel Magnum-365.

- Specific consumption: 2.0 kg/m³
- Borehole diameter: d = 38 mm
- Charge mass per borehole: Qsh = 0.245 kg
- Number of charges per column: nm = 7
- Total explosive per column: 1.75 kg

Altogether, 133 supporting columns were blasted: 56 on the first floor, 44 on the second, and 39 on the third. In addition, explosive charges were placed in the load-bearing walls of the first three floors. In each blasting sequence, the average charge mass in the walls was about 49 kg, while the total mass of simultaneously detonated charges did not exceed 140 kg.

Fig. 5.10 shows fragments of the demolition of the Batumi hotel building, while Table 5.7 presents the vibration velocities of protected objects. As a result of the explosion, the building collapsed entirely onto its foundation, ensuring complete safety of nearby structures. The scattering distance of individual fragments did not exceed 20 meters.

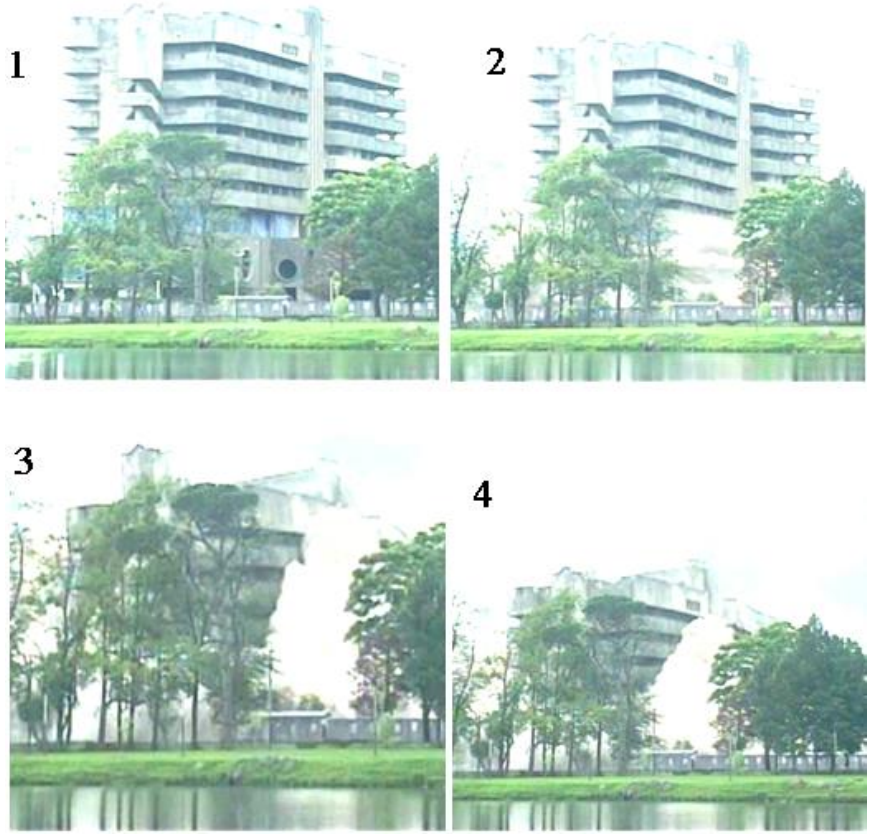

Fig. 5.10. Fragments of the demolition of the Batumi Hotel building by explosion

Table 5.7. Variation of Soil Vibration Velocities at Foundations of Protected Objects

Location of Seismometer	Blast Sequence	Charge Mass (TNT Equivalent), kg – Columns	Walls	Total	r (m)	ρ (kg^0.33·m⁻¹)
Ferris Wheel attraction	1	21	21	70	85	0.048
	2	42	42	140	85	0.061
	3	42	42	140	85	0.065
	4	42	42	140	80	0.065
	5	42	42	140	75	0.069
	6	42	42	140	75	0.069
Batumi University building	1	21	21	70	120	0.030
	2	42	42	140	120	0.040
	3	42	42	140	120	0.040
	4	42	42	140	120	0.040
	5	42	42	140	120	0.040
	6	42	42	140	120	0.040

Notes:

- r – distance from blast center, m;

- ρ – reduced mass of simultaneously detonated charges, kg^0.33·m^{-1};
- K – seismic coefficient;
- V – soil vibration velocity, cm/s.

Seismic Coefficient and Safety Measures

From Table 5.7 it is evident that during explosions in load-bearing structures, the numerical range of the coefficient K (which reflects soil properties and blasting conditions) varied between 26–56. For the same magnitude of charges placed deeper in the ground, $K = 200$. For example, under Tbilisi rock conditions, explosions of embedded charges yield $K = 106$. This variation is due to the dependence of vibration velocity on rock structure and water saturation. Therefore, for each specific case, the value of coefficient K must be determined experimentally in advance, enabling the development of effective protective measures against harmful seismic wave impacts during blasting in densely populated areas.

Safety Measures During Explosive Demolition

1. Limiting the propagation of seismic waves (by distancing the blast center from the surface by at least 0.5 m, or by creating artificial barriers such as trenches).
2. Preventing scattering of fragments (by wrapping the building in mesh, surrounding it with sandbags, or boarding).
3. Reducing the harmful effect of air shock waves (by installing tarpaulin covers over the object to be demolished).

Explanatory Notes for Table 5.7

- r (distance from blast center, m):

Indicates how far the observation point is from the explosion source. Greater distance generally reduces vibration intensity.

- ρ (reduced mass of simultaneously detonated charges, kg^0.33·m^{-1}):

A calculated parameter that normalizes the explosive mass to account for simultaneous detonation effects. It helps compare different blasting conditions.

- K (seismic coefficient):

Reflects the relationship between soil vibration velocity and explosive charge characteristics. Higher values mean stronger seismic wave propagation.

- V (soil vibration velocity, cm/s):

Shows the actual measured ground vibration speed at the foundation of protected objects. This is the critical indicator for assessing potential damage risk.

Comparison of sites:

- At the Ferris Wheel attraction, vibration velocities (V) ranged from 0.3–0.8 cm/s, with K values between 26–47.
- At the Batumi University building, vibration velocities were lower (0.15–0.5 cm/s), but seismic coefficients reached u p to 56, showing stronger soil response despite similar charge masses.

Practical implication:

These parameters demonstrate that soil type, distance, and charge placement significantly affect vibration intensity. Therefore, experimental determination of K for each site is essential to design safe demolition strategies in densely populated areas.

ISO 22320 and **ISO 31010** provide internationally recognized frameworks for managing demolition of buildings by explosion. ISO 22320 establishes requirements for emergency management and incident response, ensuring that demolition activities are coordinated, safe, and systematically controlled. ISO 31010 defines methodologies for risk assessment, including hazard identification and consequence analysis, which are directly applicable to explosive demolition scenarios. By linking the discussion of building demolition by explosion to these standards, the monograph ensures that both planning and execution are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers, surrounding communities, and the environment during controlled demolition operations.

5.13 Protective Means to Be Used

To reduce the risks of explosions and fires, the following protective means are applied:

Objective measures:

- Fire-prevention systems (automatic extinguishing).
- Fire-extinguishing devices.
- Fire resistance of structures.
- Ventilation.
- Filling with inert gases.

Individual measures:

- Protective clothing.
- Heat-resistant suits.
- Helmets.
- Gloves.
- Breathing apparatus.

Subjective measures:

- Alarm systems.
- Notification systems.
- Knowledge of safety rules.
- Proper training and instruction.
- Ability for rapid response.
- Coordination among employees.

ISO 45001 and **ISO 15265** provide internationally recognized frameworks for protective means to be applied in environments with fire and explosion hazards. ISO 45001 establishes requirements for occupational health and safety management systems, ensuring that protective equipment and procedures are systematically integrated into workplace practices. ISO 15265 defines methodologies for assessing thermal environments and protective strategies against heat stress, which are directly relevant when selecting and applying protective means in hazardous conditions. By linking the discussion of protective means to these standards, the monograph ensures that both theoretical guidance and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers, facilities, and the environment.

6. Radiation and Protection Against It

6.1. Guide for Chapter Six

Objective: To introduce readers to the types of radiation, their harmful effects, and protective measures.

Structure: Types of hazardous and harmful radiation; harmful effects of electromagnetic radiation; sources of electromagnetic radiation; protective measures (shields, suits, standards); radiation safety and international standards.

Main Themes:

- Physical foundations (wave/particle nature);
- Biological effects;
- Technological sources;
- Principles of protection — quantity, time, distance.
- Integration with international standards:

ISO 31000 (Risk Management): Identification, assessment, and control of radiation risks.

ISO 45001 (Occupational Health & Safety): Regulation of radiation exposure in the workplace and protection of personnel.

- Harmonization with ISO standards and practical application.

The **International Commission on Non-Ionizing Radiation Protection (ICNIRP)** establishes threshold values in the ICNIRP Guidelines, which define safe levels for human health. Their recommendations emphasize that exposure to electromagnetic fields must be determined by frequency range, intensity, and duration. This fully aligns with the principle described in the manual — protection of personnel by time, distance, and quantity.

The **International Atomic Energy Agency (IAEA)** sets safety standards (IAEA Safety Standards) for the control of ionizing radiation and the management of radioactive waste. Requirements include dosimetric monitoring, individual protective equipment for personnel, and safe storage as well as disposal of waste. This directly corresponds to the principle described in the manual — protection by quantity, since reducing activity and strictly controlling waste are the foundations of radiation safety.

The **World Health Organization (WHO)**, in its WHO Radiation Guidelines, emphasizes that protecting human health requires not only compliance with technical standards but also organizational and hygienic measures. WHO recommends that particular attention be paid to the eyes and brain, as the most sensitive organs to electromagnetic field exposure. It is also necessary to conduct regular health monitoring of personnel to detect fatigue, cardiovascular disorders, and other symptoms in time. These recommendations fully correspond to the risk described in our work — reduction of labor productivity.

Thus, both the guide and the brief notes provided in each paragraph directly highlight the connection of the discussed issues with international standards and, in our view, should help readers to fully and thoughtfully assimilate the material.

6.2. Types of Hazardous and Harmful Radiation

In industrial conditions, radiation may be both hazardous and harmful. As already noted, a hazardous factor causes physical injury or rapid and severe deterioration of health, while the effect of a harmful factor manifests after a long period in the form of occupational disease. A harmful industrial factor may acquire a hazardous character depending on its intensity and duration of action.

In production, the following types of hazardous and harmful radiation may be encountered:

- Electromagnetic radiation
- Ultraviolet radiation
- Infrared radiation
- Ionizing radiation

It should be noted that all types of radiation (including light) possess both wave and corpuscular (quantum) nature. The wave nature is manifested in the fact that electromagnetic waves exhibit interference, diffraction, dispersion, polarization, and mechanical pressure on the surface upon which they fall. The quantum nature is manifested in the fact that radiation energy is emitted in portions (photons), i.e., quanta. A quantum has the properties of a material point, and its energy ε depends on the frequency ν of radiation

$$\varepsilon = h\nu \tag{6.1}$$

where $h = 6.625.10^{-27}$ is Planck's constant.

The ranges of industrial radio frequencies are presented in Table 6.1.

Table 6.1. Radio Frequency Ranges

Main Term	**Parallel Term**	**Main Term**
1st Range	Extremely Low Frequency	3 - 30 Hz
2nd Range	Super Low Frequency	30 - 300 Hz
3rd Range	Infra Low Frequency	0.3 - 3 kHz
4th Range	Very Low Frequency	3 - 30 kHz
5th Range	Low Frequency	30 - 300 kHz
6th Range	Medium Frequency	0.3 - 3 MHz
7th Range	High Frequency	3 - 30 MHz
8th Range	Very High Frequency	30 - 300 MHz
9th Range	Ultra-High Frequency	0.3 - 3 GHz
10th Range	Super High Frequency	3 - 30 GHz
11th Range	Extremely High Frequency	30 - 300 GHz
12th Range	Hyper High Frequency	0.3 - 3 THz

Note: Each frequency range covers the maximum value and never equals the minimum value.

It is known that current flowing through a conductor simultaneously creates electric and magnetic fields around it. Under direct current conditions, these fields are independent of each other, while under alternating current conditions they are interdependent, forming a unified electromagnetic field with specific energy. This field is characterized by two mutually perpendicular components: the electric component E and the magnetic component H.

The unit of measurement for electric field intensity is volts or kilovolts per meter (V/m, kV/m), while for magnetic field intensity the unit used is amperes per meter (A/m).

Let us generally consider the characteristics of the wave nature of light. Interference is the vector summation of the electric E and magnetic H components of two or more waves of the same frequency in space, such that at certain points the amplitude of the resulting wave increases, while at other points it decreases.

Diffraction is the deviation of light waves from a straight-line trajectory after passing through openings (so-called diffraction gratings). **Dispersion of light** refers to the phenomenon in which the speed of light propagation in a given medium depends on the wavelength.

The classification of hazardous and harmful radiation by wavelength is presented in Table 6.2. Alpha, beta, neutron, proton, and other ionizing radiation are conventionally referred to as corpuscular, while the rest are considered wave-like.

Polarization of light is the ability of the E and H vectors to assume any direction in space, provided they are always mutually perpendicular. Moreover, the plane in which these vectors lie must be perpendicular to the direction of light propagation. Such light is called natural light.

Table 6.2. Classification of Hazardous and Harmful Radiation by Wavelength

Wavelength Range Name	**Wavelength and frequency ranges**	
General Category – Electromagnetic Radiation		
Radio waves:	**Wavelength Range**	**Frequency Range, Hz**
Myriametric (very long)	>10 km	$3\text{-}3x10^4$
Kilometric (long)	10 - 1 km	$3X10^4$ - $3X10^5$
Hectometric (medium)	1000 - 100 m	$3X10^5$ - $3X10^6$
Decametric (short)	100 - 10 m	$3X10^6$ - $3X10^7$
Metric	10 - 1 m	$3X10^7$ - $3X10^8$
Decimetric	100 - 10 cm	$3X10^8$ - $3X10^9$
Centimetric	10 - 1 cm	$3X10^9$ - $3X10^{10}$
Millimetric	10 - 1 mm	$3X10^{10}$ - $3X10^{11}$
Submillimetric	1 – 0.1 mm	$3X10^{11}$ - $3X10^{12}$
Optical Radiation:	**Wavelength Range**	**Frequency Range, Hz**
Infrared rays	100 - 0,76 μm	$3X10^{12}$ - $3{,}9X10^{14}$
Visible light	0,76 - 0,39 μm	$3{,}9X10^{14}$ - $7{,}7X10^{14}$
Ultraviolet rays	0,39 - 0,001 μm	$7{,}7X10^{14}$ - $3X10^{17}$

Ionizing Radiation:	Wavelength Range	Frequency Range, Hz
X-rays	0,001- 1X10-6 μm	$3X10^{17}$ - $3X10^{20}$
Gamma rays	1X10-6 μm and smaller	$3X10^{20}$ and higher
General Category – Corpuscular Radiation		
Alpha, beta, neutron, proton, and others		

The magnitude of radiation pressure can be calculated using the formula

$$p = \frac{W}{c}(1 + \rho) \qquad (6.2)$$

where: p - radiation pressure, dyn/cm; W - radiant energy incident per second per cm of surface, dyn;; c - speed of light in vacuum; ρ - reflection coefficient.

On a clear day, the pressure exerted on the Earth's surface by solar radiation amounts to approximately 0.4 dyn/cm.

The above-mentioned properties of radiation are applied in practice to reduce their harmful effects.

It should be emphasized that protection from all types of radiation, or reduction of exposure to a minimum, can be achieved through the following principles:

Protection by quantity — reducing the activity of the radiation source.

Protection by distance — increasing the distance from the radiation source.

Protection by time — reducing the duration of work in the radiation exposure area.

In conclusion, these protective measures fully correspond to the recommendations of the **World Health Organization (WHO)**, which specifically notes that health protection requires not only compliance with technical standards but also the implementation of organizational and hygienic measures.

ISO 21348 defines the categories of solar and space radiation, while **ISO 4037** specifies reference radiation fields for calibrating protection instruments. By linking the classification of hazardous and harmful radiation to these standards, the monograph ensures that research is aligned with internationally validated definitions and measurement protocols. This connection provides researchers with a structured framework for analyzing radiation risks in both occupational and environmental contexts.

6.3. Harmful Effects of Electromagnetic Radiation

Humans cannot perceive electromagnetic fields through their sensory organs (vision, hearing, etc.), and therefore cannot always avoid their harmful effects. Under the influence of electromagnetic radiation, blood — which by nature is an electrolyte — experiences ion flow, causing heating of body tissues. Beyond a certain intensity threshold, known as the **thermal limit**, the body can no longer assimilate the released heat. This is particularly dangerous for the eyes, brain, stomach, and other vital organs.

In addition to thermal effects, electromagnetic radiation negatively impacts the nervous system, disrupts cardiovascular function, and causes metabolic disorders. After prolonged exposure, individuals may experience chest pain, changes in pulse and blood pressure, and pronounced fatigue, which reduces productivity and the quality of work performed.

The harmful biological effects of electromagnetic fields depend on the frequency range of the waves, their intensity, duration of exposure, the nature of the radiation, and the exposure regime. Across all radio frequency ranges, deviations from normal functioning of the central nervous and cardiovascular systems are characteristic.

It has been established that industrial-frequency currents (3–300 Hz) can also negatively affect the human body. The key parameter characterizing the harmful biological effect of industrial-frequency electromagnetic fields is **electric field intensity**. The magnetic component has little noticeable effect on the body, since in industrial-frequency devices magnetic field intensity does not exceed 25 A/m, whereas harmful biological effects manifest only at intensities of 150–200 A/m or higher. It has been determined that in any point of industrial-frequency electrical installations, the magnetic field energy absorbed by the human body is nearly 50 times less than the energy of the electric field.

The final assessment of the harmful effects of electromagnetic fields is based on the amount of electromagnetic energy absorbed by the human body. To reduce this, various types of shielding are used, which fall under the principle of **protection by quantity**, since shielding reduces the intensity of radiation in the direction where people are located.

Short Note

It is important to note that the **International Commission on Non-Ionizing Radiation Protection (ICNIRP)** establishes threshold values that define safe levels for human health. ICNIRP recommendations emphasize that the limits of electromagnetic field exposure must be determined by frequency range, intensity, and duration. For example, in industrial-frequency fields (50–60 Hz), permissible electric field intensity is strictly limited to prevent functional disorders of the nervous and cardiovascular systems. These recommendations fully correspond to the principle described in the manual — **protection by time, distance, and quantity** — ensuring that industrial standards are harmonized with international guidelines.

ISO 7010 and **ISO 21348** provide internationally recognized frameworks for identifying and classifying electromagnetic radiation hazards. ISO 7010 establishes standardized safety symbols for radiation warnings, ensuring clarity in communication, while ISO 21348 defines categories of electromagnetic radiation relevant to both occupational and environmental exposure. By linking the discussion of harmful effects to these standards, the monograph situates its analysis within a globally validated system, reinforcing the scientific credibility of research findings and ensuring comparability across international studies.

6.4. Sources of Electromagnetic Radiation

Sources of electromagnetic radiation include radio-technical and electronic devices, transformers, antennas, capacitors of thermal installations, ultra-high-frequency generators, and others. High-frequency transmitting elements also create electromagnetic fields, the magnitude of which depends on various factors: the quality of shielding, the type of transmitters and antennas, their proper installation, operation, and so forth.

Ultra-high-frequency energy is used in radar, radionavigation, radio spectroscopy, meteorology, nuclear technology, astronomy, and geodesy. For example, in a ship's radar station, shortwave and medium-wave transmitters are widely used, generating powerful electromagnetic fields.

The main source of radiation in a radar station is the antenna system. During antenna rotation and scanning, service personnel are exposed to microwaves. When several radar systems operate simultaneously, the density of the energy flux increases. The intensity of crew exposure varies widely and depends on the height of antenna suspension, its type, radiation power, antenna gain factor, ship design, and reflection of electromagnetic waves from the ship's metallic structures.

In civil aviation, ground-based radar systems include various types of radar stations (surveillance, landing, dispatch, and meteorological). The antenna equipment of ground-based radio installations represents a powerful source of microwave radiation.

Another source of electromagnetic radiation is the aircraft antenna, whose emissions are variable. The level of energy flux density depends on the power of the radar device, the height of antenna elevation, its orientation, radiation direction, and distance from the source.

Radar systems operating in the centimeter and millimeter wave ranges are widely used in hydrometeorological services to detect cloud systems, thunderstorm centers, observe them, and determine their location. In these cases, as well, antennas are the primary sources of radiation.

ISO 21348 provides a comprehensive framework for defining sources of solar and space radiation, while **ISO 4037** specifies reference radiation fields for calibration of protective instruments. By linking the classification of electromagnetic radiation sources to these standards, the monograph ensures that research findings are grounded in internationally validated definitions and measurement protocols. This connection allows researchers to systematically analyze natural and artificial sources of radiation, reinforcing the scientific credibility and comparability of their work across global studies.

6.5. Protective Measures Against Electric Field Exposure

According to sanitary and hygienic standards, exposure to electromagnetic fields is regulated by the magnitude of field intensity and the duration of exposure. The permissible limit of electric field intensity from industrial-frequency currents depends on the time interval during which a person remains in the hazardous zone. For an 8-hour period, personnel may remain if the electric field intensity is $E \leq 5$ kV/m. If the electric field intensity varies within the range of 5–20 kV/m, then the maximum permissible time for personnel in such a work zone, expressed in hours, is calculated using the empirical formula

$$\tau = \frac{50}{E-2} \quad (6.3)$$

The permissible duration of workers' presence in an electric field without protective equipment, depending on the level of field intensity, is presented in Table 6.3.

Table 6.3. Permissible Duration of Workers' Presence by Electric Field Intensity

N	Electric Field Intensity, kV/m	Permissible Duration per Day, hours
1	5	Unlimited
2	10	7.1
3	15	3.8
4	20	2.7
5	25	2.1

If the electric field intensity at the workplace exceeds 25 kV/m, the use of protective equipment is mandatory. These norms are valid provided that during the remaining time the person stays in an area where the background electric field intensity is 5 kV/m or less. The primary collective protective measure against industrial-frequency electric fields is the installation of **screens**. Screens may be arranged as either separate or common. In the first case, high-frequency equipment is placed in a separate room and operated remotely. A common screen means enclosing the equipment in a metallic casing, with operation carried out through specially designed windows in the casing. For safety reasons, the metallic casing must be grounded.

Absorbing screens are also manufactured from materials with low electrical conductivity. Such screens are made from pressed sheets of specially formulated rubber, as well as porous rubber plates filled with carbonyl iron. These materials are attached to a frame or directly to the surface of the emitting device.

At the workplace, the radiation source's screen must be interlocked with the switching device, which ensures that the emitting equipment cannot operate when the screen is opened.

A common screen, depending on its design, may take the form of a complete enclosure, a roof, a mesh, a system of stretched cables, and other variations. For a solid barrier, the thickness of the metal sheet must not be less than 0.5 mm. Portable board-like screens may also be manufactured and placed temporarily at the worksite.

Alongside stationary and portable screens, **individual protective equipment** is also used: special clothing, footwear, helmets or hoods, as well as special gloves and masks. Their purpose is to protect against electric fields with intensities not exceeding 60 kV/m. This protective set is made of metallized fabric. All elements are electrically connected to each other for grounding purposes, and grounding is achieved through contact of the footwear with a metallic grid placed on the floor.

For eye protection, special safety glasses are used, with lenses coated by a semiconducting layer of tin oxide.

All types of shielding equipment require periodic technical inspection, with results recorded in a special logbook.

During field geodetic work, personnel may enter zones influenced by high- and ultra-high-voltage transmission lines. Such lines are characterized by magnetic and electric field intensities of approximately 25 A/m and 15 kV/m (often measured up to 2 meters above ground level). Consequently, when working near transmission lines of 400 kV or higher, the use of individual protective equipment is necessary.

ISO 1995 and **ISO 61000** series establish internationally recognized limits and protective measures against electric field exposure. ISO 1995 provides guidance on occupational exposure thresholds, while ISO 61000 defines electromagnetic compatibility requirements that indirectly safeguard against harmful field intensities. By linking protective strategies to these standards, the monograph ensures that research findings are not only theoretical but also embedded in globally validated safety practices. This connection strengthens the scientific foundation of protective measures and highlights their relevance for both laboratory and industrial environments.

6.6. Shielding Devices

A shielding device (screen), depending on its construction, dimensions, placement, and operating conditions, serves as a collective protective measure against the influence of high-intensity industrial-frequency electric fields. In certain cases, a screen may also be used as an individual protective device.

Principle of Protection:

The protective properties of shielding devices are based on the reduction of electric field intensity around a grounded metallic object, caused by the effect of field line distortion.

When a grounded metallic object is introduced into an electric field, induced charges are separated on its surface, with charges of one sign flowing into the ground. The remaining charges are unevenly distributed across the surface, resulting in a distorted electric field around the grounded object (Fig. 6.1a). On one side of the object, field intensity increases sharply, while on the opposite side it decreases significantly.

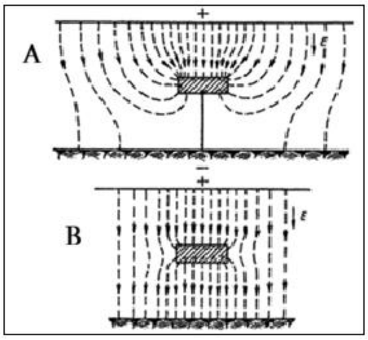

Fig. 6.1. Distortion of the Electric Field by Introducing a Grounded (A) and Ungrounded (B) Metallic Object

With appropriate dimensions, shapes, and placement, the space protected by a shielding device can be sufficiently large and characterized by low field intensity. Accordingly, work performed within this zone will be safe.

Grounding of the shielding device is of great importance, since in an environment enclosed by an ungrounded metallic object, the field does not practically weaken (Fig. 6.1B). Therefore, an ungrounded object does not provide the effect of shielding.

It should also be noted that unlike a grounded screen, whose potential equals zero, an ungrounded screen may have a high potential and thus itself pose a danger to humans.

Shielding devices, depending on their purpose, may be stationary or portable. Their function is to reduce electric field intensity, including lowering it to 5 kV/m within the protected environment.

A **stationary screen** is an essential part of the construction of electrical installations and protects personnel during operational tasks (inspection of equipment, operational switching, etc.), as well as during current and major repairs of switches. Screens are made in the form of flat metal panels. These may be front panels, curtains, partitions, suspended shields, and others. Their dimensions must be sufficient to ensure human protection.

A **portable screen** protects workers during operational, repair, and installation tasks in areas where the use of stationary screens is impractical. They are manufactured in the form of portable panels, shields, partitions, curtains, and similar structures, made of the same materials as stationary screens.

Construction and Placement:

Both temporary and permanent screens must be installed with the following insulation distances from live parts:

- 4.5 m for installations with voltages of 400–500 kV
- Up to 6 m for installations with voltages of 750 kV

At the same time, stationary screens must not obstruct the movement of machinery and equipment, while temporary panels and partitions should be placed close to the protected zone, which increases the effectiveness of the screens and the insulation distance from live parts.

Creating a protective zone depends critically on the **grounding of the screen**, which must be especially reliable. In stationary screens, grounding is achieved using steel, with connections between grounding device components made by welding or bolts. For temporary screens, special conductors are used, equipped with grounding clamps. The resistance of the grounding conductor must not exceed **10 Ohms**.

ISO 7195 and **ISO 4037** provide internationally recognized frameworks for shielding against radiation exposure. ISO 7195 specifies requirements for protective containers and shielding materials used in handling radioactive substances, while ISO 4037 defines reference radiation fields for testing and calibration of shielding effectiveness. By linking the discussion of shielding devices to these standards, the monograph ensures that research findings are grounded in validated international methodologies. This connection highlights the importance of standardized design and testing procedures, reinforcing the scientific credibility of protective technologies in both laboratory and industrial contexts.

6.7. Shielding Suit

To protect against the radiation of high-voltage industrial-frequency electric fields and during work near overhead transmission lines, an individual protective device — the **shielding suit** — is used.

Principle of Protection:

The protective properties of the suit are based on the principle of electrostatic shielding. As is known, when a conductive body is introduced into an electric field, electrons undergo short-term displacement (rearrangement), resulting in the formation of charges on the surface of the body. On the side facing the external charges that generate the field, charges of opposite sign accumulate, while on the opposite side, charges of the same sign as the external charges appear.

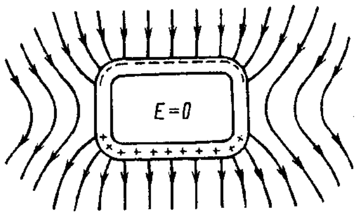

Fig. 6.2. Electrostatic Shield

The field created inside the conductive body is equal in magnitude and opposite in sign to the external field. As a result, the intensity inside the body becomes zero, regardless of whether the body is solid or hollow (Fig. 6.2).

Thus, to protect a body from the influence of an electric field, it must be placed within a thin metallic enclosure (screen).

Experiments have shown that the screen may be not only solid but also mesh-like. If the mesh is sufficiently dense, the electric field lines (lines of intensity) connect to its wires and cannot penetrate inside. For reliability of the screens and to neutralize the potential induced on them, the screen must be grounded.

Suit Construction. The shielding suit is made of special conductive fabric, in which insulating micro-wires are interwoven in a mesh pattern along with ordinary threads. Metallized fabric is also used — ordinary cotton fabric with a thin layer of metal applied to its surface. All parts of the shielding suit — cap, jacket, gloves, trousers, and footwear — specifically their conductive elements, must be reliably connected to each other by special conductors.

The suit is worn over underwear so that the human body is insulated from it. If necessary, other clothing such as a warm jacket, robe, or coat may be worn over the suit.

Conditions of Use. The shielding suit is used for tasks such as inspection, maintenance, and cleaning of open distribution devices; repair, installation, and other construction work on overhead lines; inspection of insulators on line supports, and similar operations. The use of the shielding suit is also mandatory during short-term tasks that require climbing onto equipment or structures. This is because climbing without the suit can cause discharge currents that produce painful sensations and fear, potentially leading to personnel falling.

The permissible time for workers to remain in an electric field without protective equipment can be determined through calculations and measurements.

During operation, the conductive elements of the suit must be grounded.

If a person touches grounded objects while working, the shielding suit has special grounding depending on whether the person is insulated from the ground or not. Work in the suit can be prolonged, provided that the worker’s thermoregulation is not disrupted.

The proper condition of the shielding suit must be checked periodically. Every two months, the reliability of electrical connections between all elements must be verified. A coverall made with insulated micro-wires should be tested with an ohmmeter to confirm galvanic connection between the upper and lower parts of the metallic fabric. Footwear must also be tested with an ohmmeter to check the connection between metallic soles and conductors. If the sole is made of conductive rubber, a 2500 V megohmmeter is used, and the resistance must not exceed **50 kΩ.**

ISO 11612 and **ISO 14116** define performance requirements for protective clothing against heat and flame, while **ISO 13688** specifies general requirements for protective garments. By linking the discussion of shielding suits to these standards, the monograph ensures that research findings are aligned with internationally validated criteria for material resistance, ergonomic design, and durability. This connection highlights the scientific foundation of shielding suits as protective devices, reinforcing their relevance in both laboratory and industrial environments where electromagnetic radiation exposure is a critical hazard.

6.8. Radio-Frequency Electromagnetic Fields and Personnel Protection

As noted, sources of radio-frequency electromagnetic fields include radio and television broadcasting, radar, radio control, geological electrical prospecting, and others.

In addition, during metal heating, tempering, and melting, as well as stamping and welding, low-frequency (1–12 kHz) pulsed electromagnetic energy is used, which also serves as a source of harmful electromagnetic fields. For dielectric heating of various materials (drying of moist materials, bonding of wood, heating of plastics, thermo-fixation, and melting), equipment operating in the frequency range of 3–150 MHz is employed.

To assess potential undesirable effects, permissible parameters of such electromagnetic fields have been established. For different frequency ranges, these parameters include **electric or magnetic field intensity** and **energy flux density**.

To ensure safety when working near sources of radio-frequency electromagnetic radiation, it is necessary to systematically measure and monitor actual radiation levels at workplaces. When designing workplaces, zones should be selected where radiation is normally minimal. If regulatory requirements are violated, the following protective measures must be implemented:

- Installation of screens at workplaces or around radiation sources
- Increasing the distance between the radiation source and the workplace
- Use of special energy absorbers that reduce the energy of the radiation source
- Application of remote and automatic control systems

The final line of defense in engineering protection measures is the use of **individual protective equipment**. For eye protection, special glasses are used, with lenses coated with a thin layer of gold or tin dioxide, reducing radiation by 20–25 decibels. Protective clothing (coveralls, robes, hooded jackets with built-in protective glasses) is made of metallized fabric, which reduces radiation by 20–30 decibels.

For the prevention of occupational diseases, personnel must undergo preliminary and periodic medical examinations. Women during pregnancy and breastfeeding must be transferred to other work, since according to the **Labor Code of Georgia**, it is prohibited to conclude labor contracts with minors, pregnant women, or breastfeeding women for heavy, harmful, and hazardous work. For the same reason, young people under 18 years of age are not permitted to work with radio-frequency generators.

Personnel working with high- and ultra-high-frequency radiation are entitled to a **shortened workday** and **additional leave**.

ISO 1999 and **ISO 7010** provide internationally recognized frameworks for personnel protection against radio-frequency electromagnetic fields. ISO 1999 establishes exposure limits and health risk assessment methodologies, while ISO 7010 specifies standardized safety symbols to ensure clear communication of hazards. By linking the discussion of RF field exposure to these standards, the monograph situates its analysis within a globally validated system. This connection reinforces the scientific credibility of protective measures and highlights their relevance for occupational safety research and international comparability.

6.9. Optical Range Radiation and Protection

Infrared Radiation, Its Harmful Effects, and Protective Measures.

Infrared radiation is emitted by any heated body, with its temperature determining the spectrum and intensity of the electromagnetic energy released.

Based on the wavelength of emitted waves, industrial energy sources are divided into four groups:

- **≤ 500** °C (outer surfaces of furnaces, etc.): spectrum contains infrared rays of 1.9–3.7 μm.
- **500–1300** °C (flame, molten cast iron, etc.): spectrum predominantly contains infrared rays of 1.9–3.7 μm.
- **1300–1800** °C (molten steel, etc.): spectrum contains infrared rays of 1.2–1.9 μm, along with bright visible rays.
- > **1800** °C (flames of electric arc furnaces, welding flames, etc.): spectrum contains infrared and visible rays, as well as ultraviolet rays.

One quantitative characteristic of radiation is **thermal radiation intensity**, defined as the energy emitted per unit area per unit time. In the International System of Units, its dimension is W/m². Measurement of thermal radiation intensity is called **actinometry** (from Greek actinos – ray, and metrio – measure). The instrument used is an **actinometer**.

Infrared radiation penetration varies by wavelength. Short-wave infrared radiation (0.76–1.4 μm) penetrates human tissue to several centimeters. Long-wave radiation (9–420 μm) cannot even penetrate the skin.

Radiation effects may be **general** or **localized**. Long-wave radiation increases surface body temperature, while short-wave radiation alters the temperature of internal organs such as the lungs, brain, kidneys, and others.

Significant changes in body temperature occur under high-intensity radiation, with increases of 1–2 °C. Short-wave radiation affecting brain tissue can cause **sunstroke**, leading to headache, dizziness, rapid pulse and breathing, darkening of vision, impaired coordination, and possible loss of consciousness. Prolonged intense exposure may produce symptoms of meningitis and encephalitis.

For the eyes, short-wave radiation is most dangerous, causing **infrared cataracts**.

Thermal radiation generally raises environmental temperature, worsens microclimate conditions, and may cause overheating of the body. Approximately **60% of thermal energy** is transmitted into the environment via infrared radiation. Radiant energy crosses space almost without loss and converts back into thermal energy upon striking a surface. Because of this lossless transmission, it does not directly affect the air but penetrates it freely.

Main Measures to Reduce Harmful Effects of Infrared Radiation:

- **Reduce source intensity** (replace outdated technologies with modern ones, etc.)
- **Shield the source or workplace** (install metal mesh screens, cover furnace surfaces with asbestos, etc.)
- **Use individual protective equipment** (face and eye shields with light filters, linen clothing, etc.)
- **Apply medical and preventive measures** (organize rational work-rest schedules, conduct periodic medical examinations, etc.)

Ultraviolet Radiation, Its Harmful Effects, and Protective Measures.

The natural source of ultraviolet radiation is the **sun**. Invisible ultraviolet rays are emitted from heated sources above **1500** ℃, and their intensity becomes significant at temperatures exceeding **2000** ℃. Artificial sources of ultraviolet radiation include **electric arcs, lasers, and** others.

Ultraviolet radiation exhibits different biological effects depending on its spectrum. Three main types are distinguished by wavelength:

- **0.390–0.315 µm:** weak biological effect
- **0.315–0.280 µm:** antirachitic effect (prevents rickets)
- **0.280–0.200 µm:** ability to destroy microorganisms

A wavelength of **0.344 µm** has a bactericidal effect 1000 times greater than that of 0.39 µm ultraviolet radiation, while the maximum bactericidal effect occurs at **0.254–0.257 µm**. To achieve bactericidal effectiveness, an exposure of **50 µW·min/cm²** is sufficient.

For the human body, both deficiency and excess of ultraviolet radiation are harmful. Large doses cause **skin diseases** (various forms of dermatitis). Increased doses affect the **central nervous system**, with symptoms such as vomiting, fatigue, fever, and others.

Ultraviolet radiation with wavelengths shorter than **0.32 µm** negatively affects the retina, causing painful inflammatory processes. In the early stages, individuals experience pain and a sensation of sand in the eyes. The condition is accompanied by excessive tearing and may develop into **snow blindness** (photophobia). This condition usually disappears within 2–3 days after exposure ceases.

Deficiency of ultraviolet radiation manifests as **avitaminosis**, disturbances in calcium-phosphorus metabolism, and impaired bone formation. These lead to reduced work capacity and decreased resistance to disease. Such deficiencies are typical in autumn and winter, when exposure can be supplemented by **fluorescent lamps**. Mercury-quartz lamps are not recommended, as their radiation is difficult to control and regulate.

The effects of ultraviolet radiation can be quantitatively assessed by the **Ultraviolet Index (UV Index)** and visually. The latter is based on observed experience: first the skin reddens, then pigmentation (tanning) occurs.

The UV Index is a daily forecast of expected solar ultraviolet radiation intensity, rated on a scale from **1 to 11+**. Higher values indicate greater risk to skin and eyes. A value of **1** represents minimal risk, while **11+** indicates extremely high risk. The index helps people understand when and how to protect themselves from the sun.

Protective Measures Against Excess Ultraviolet Radiation:

- **Sun protection screens:** chemical (substances in creams and ointments) and physical (barriers that scatter, reflect, or absorb rays);
- **Special clothing:** fabrics such as poplin, which poorly transmit ultraviolet rays;
- **Eye protection in industrial conditions:** light filters in glasses or helmets made of dark green glass.

ISO 21348 defines categories of optical radiation, while **ISO 17123** and **ISO 4037** provide standardized methodologies for measurement and calibration of optical exposure. By linking the discussion of optical range radiation to these standards, the monograph ensures that protective measures are scientifically validated and internationally comparable. This connection highlights the importance of harmonizing theoretical analysis with standardized protective practices, reinforcing the credibility of research outcomes in both occupational and environmental contexts.

6.10. Types and Properties of radiation

Substances with heavy nuclei (uranium, thorium, radium) undergo natural disintegration, producing new substances accompanied by radiation. This radiation may consist of **alpha particles, beta particles**, and short-wavelength electromagnetic waves (**gamma radiation**). Beta radiation is accompanied by the emission of **neutrinos** and **antineutrinos**. Natural radioactive decay does not depend on external conditions such as temperature, pressure, or chemical interactions; it is entirely determined by the inherent properties of radioactive substances with heavy nuclei.

In the case of **alpha radiation**, the newly formed substances occupy a position in the periodic table with an atomic number two units lower. In **beta radiation**, the atomic number increases by one, while in **positron radiation**, the atomic number decreases by one.

In addition to natural radioactivity, **artificial radioactivity** can be induced, which is not determined by the properties of the substances themselves but depends entirely on external conditions. Artificial radioactivity can be produced by exposing substances to gamma rays, or by irradiating them with protons, neutrons, or nuclei of deuterium, helium, or heavier elements. In this way, radioactive isotopes can be obtained that do not occur naturally on Earth. Artificially radioactive substances are generally characterized by **beta** and **gamma radiation**.

In all the above cases, nuclear disintegration occurs, releasing nuclear energy. These processes are called **nuclear reactions**.

The opposite process is also possible: the **fusion of light nuclei** (such as hydrogen) to form heavier nuclei, which requires temperatures of tens or hundreds of millions of degrees. This reaction is called **thermonuclear fusion**. Like artificial radioactivity, it depends on external conditions, specifically extremely high temperatures.

Alpha radiation is a stream of helium atoms consisting of two protons and two neutrons, carrying a positive charge of +2. The velocity of alpha particles is one order of magnitude lower than the speed of light in a vacuum, approximately 2×10^9 cm/s (20,000 km/s). Their energy ranges from **3–9 MeV**. To illustrate this energy: when passing through water, alpha radiation ionizes approximately every third molecule, splitting it into positive and negative ions. Accordingly, ionization of blood leads to its salting. Alpha radiation has the highest energy, but protection against external exposure is relatively easier because of its short range. The penetration distance of alpha particles in air is **8–9 cm**. Therefore, alpha radiation is not dangerous in the air environment but is extremely hazardous if radioactive substances enter the body through food or inhalation.

Beta radiation is a stream of electrons moving at a velocity close to the speed of light (**approximately 250,000 km/s**). The maximum penetration distance of beta particles in air is **1800 cm**, and their charge is negative. Compared to alpha particles, beta particles have much greater penetrating ability, significantly lower mass (about 7,300 times less), lower energy, and therefore a reduced ionization capacity. When passing through water, beta radiation ionizes approximately **every 1,000th molecule**.

Gamma radiation accompanies alpha radiation and especially beta radiation, emitted in quanta (discrete portions). It consists of electromagnetic waves propagating through space at the speed of light in a vacuum, 3×10^{10} cm/s (300,000 km/s). Gamma radiation has the greatest penetrating ability, while its ionization capacity is intermediate — it ionizes approximately every **300th water molecule**. Gamma radiation carries no **electric charge**.

Neutron radiation is a stream of electrically neutral elementary particles. Its initial velocity is about **15,000 km/s**. When interacting with atomic nuclei, it often induces gamma radiation. For example, when acting on a nitrogen nucleus, neutron radiation can eject a proton (the positively charged hydrogen nucleus).

Radioactive isotopes are denoted by attaching a numerical indicator to their chemical formula, e.g., **Radium-22**, **Radium-106**, etc. Over time, the activity of all radioactive substances or their isotopes decreases, since the number of atoms diminishes as they decay. This reduction in activity follows an **exponential law**, meaning radiation never fully reaches zero.

All natural and artificial radioactive substances are characterized by a **half-life** — the time interval after which the initial intensity of radiation decreases by half. The duration of the half-life depends on the type of substance and varies widely. For example:

- **Radium-106** has a half-life of **29.9 seconds**
- **Uranium-238** has a half-life of **4.5 billion years**

The first group is classified as short-lived radioisotopes, while the second group is long-lived. Biologically, the most dangerous isotopes are short-lived ones with half-lives ranging from several days to about ten years. Therefore, both Radium-106 and Uranium-238 are relatively less hazardous.

It is noteworthy that in the first days following the **Chernobyl nuclear power plant explosion on April 26, 1986**, the most dangerous isotope was short-lived radioactive **Iodine-131** (half-life of 8.06 days), which accounted for **52–55%** of the released radioisotopes.

As noted, radioactive decay is accompanied by **alpha, beta, and gamma radiation**. Gamma radiation can also be generated during **annihilation processes** (interaction of matter and antimatter). The disintegration of heavy nuclei in reactors is accompanied by **neutron radiation**. In X-ray tubes, electron accelerators, and similar devices, **bremsstrahlung**

radiation (continuous spectrum photon radiation) is produced, caused by changes in the kinetic energy of charged particles. **Characteristic radiation** (discrete spectrum photon radiation) occurs during changes in the energy states of atoms. All these types of radiation differ in nature, energy, propagation speed in the medium, biological effects, and other factors.

ISO 21348 establishes internationally recognized categories for radiation across the electromagnetic spectrum, while **ISO 4037** provides reference radiation fields for calibration and testing. By linking the classification of radiation types and their properties to these standards, the monograph ensures that research findings are scientifically validated and internationally comparable. This connection reinforces the methodological rigor of radiation studies, allowing researchers to analyze both natural and artificial sources with precision and consistency.

6.11. Units of Radiation

An important indicator of radioactive decay is the number of nuclei disintegrating per unit of time, quantitatively described by the term **activity.** The activity of a substance is defined by the number of atoms decaying per unit of time. The unit of activity is the **curie (Ci).** A radioactive substance has an activity of 1 curie if 3.7×10^{10} nuclei (37 billion) disintegrate per second. This corresponds to the decay products of 1 g of radium under standard conditions. Thus, the activity of 1 g of pure radium equals 1 curie, which in turn equals 3.7×10^{10} **becquerels (Bq)**

$$1\,\text{Ci} = 3.7 \times 10^{10}\,\text{Bq}$$

In practice, derived units of the curie are used:

- **1 millicurie (mCi)** = $10^{-3}Ci = 3.7 \times 10^{7}$ disintegrations/s
- **1 microcurie (μCi)** = $10^{-6}Ci = 3.7 \times 10^{4}$ disintegrations/s
- **1 nanocurie (nCi)** = $10^{-9}Ci = 37$ disintegrations/s
- **1 picocurie (pCi)** = $10^{-12}Ci = 3.7$ disintegrations/s

In atomic physics, the unit of energy is the **electron volt (eV).** One electron volt is the kinetic energy gained by an electron when accelerated through a potential difference of 1 volt. For nuclear transformations, multiples of the electron volt are used:

- **1 keV = 10^3 eV**
- **1 MeV = 10^6 eV**

All types of ionizing radiation are characterized by **radiation doses**, measured by the ionization of air. This is called the **exposure dose**, with the unit **roentgen (R).**

A roentgen is defined as the dose of radiation that, under normal conditions (760 mmHg pressure and 0 °C temperature), produces **2.08 billion ion pairs** in 1 cm^3 (0.0012932 g) of dry air, each carrying one electrostatic unit of charge of opposite signs.

Derived units of the roentgen include:

- **1 R = 10^3 mR = 10^6 μR**

The **dose rate** is the dose per unit of time, measured in R/h, R/min, R/s, etc.

The **absorbed dose** is the amount of ionizing radiation energy absorbed per unit mass of irradiated material. The unit is the **rad (rd)**, defined as 100 ergs absorbed per gram of material:

$$1 \text{ rad} = 100 \text{ erg/g}$$

Derived units:

- **1 millirad (mrad) = 10^{-3} rad = 0.1 erg/g**
- **1 microrad (μrad) = 10^{-6} rad = 0.0001 erg/g**

The absorbed dose per unit of time is called the **dose rate**, measured in rad/s, rad/min, rad/h.

As noted, the unit of exposure dose is the **roentgen**, which reflects the ionization of air. However, its biological effects on living organisms vary, since the number of ionized particles differs across tissues. For this reason, a special unit was introduced — the **biological equivalent of the roentgen**, sometimes called the **equivalent dose.** This unit is the **rem (Roentgen Equivalent Man)**, abbreviated from the Russian term 'beri' (бр).

Thus:

- The **roentgen** is the exposure dose, representing radiation effects on non-living matter.
- The **rem (beri)** is the equivalent dose, representing radiation effects on living organisms.

One rem (Roentgen Equivalent Man, 'beri' in Russian abbreviation) is defined as the absorbed dose of any type of radiation that produces the same biological effect under chronic exposure as 1 rad of X-rays or gamma radiation.

Derived units:

- **1 rem = 10^3 millirem (mrem) = 10^6 micro roentgen equivalent (μrem)**

The **equivalent dose rate** is determined analogously to the exposure dose rate, with units expressed as rem/hour, rem/minute, rem/second, etc.

The biological effect of all types of radiation depends on **linear energy transfer (LET)**, i.e., the linear density of ionization — the number of ion pairs produced per unit length of the radiation path in matter. To evaluate the biological effects of different types of radiation, the concept of **Relative Biological Effectiveness (RBE)** has been introduced. RBE is a numerical value indicating how much greater or lesser the biological effect of a given type of radiation is compared to that of X-rays or gamma radiation under identical conditions (equal absorbed energy by the irradiated object).

Table 6.4 presents the coefficients of relative biological effectiveness, i.e., the quality factors of different ionizing radiations compared to X-rays or gamma radiation. In some literature, this quality factor is denoted by the letter **Q**.

Table 6.4. Relative Biological Effectiveness (RBE) Coefficients

Radiation Type	**Coefficient**	**Radiation Type**	**Coefficient**
Gamma radiation	1.0	Thermal neutrons	3.0
X-rays	1.0	Neutrons, E = 5 keV	2.5
Electrons	1.0	Neutrons, E = 20 keV	2.7
Positrons	1.0	Neutrons, E = 100 keV	9.0
Beta particles	1.0	Neutrons, E = 500 keV	12.0
Alpha particles, $E < 10$ *MeV*	20.0	Neutrons, E = 1 MeV	12.0
Protons, $E < 10$ *MeV*	10.0	Neutrons, E = 5 MeV	7.4
Heavy nuclei	20.0	Neutrons, E = 10 MeV	6.7

Humans may be exposed to radiation both **externally** and **internally**. External exposure occurs only when a person is located within a critical distance from the radiation source. Internal exposure continues for as long as radioactive substances remain inside the body.

Note on Units

All units used above — **curie (Ci), electron volt (eV), roentgen (R), rad (rd), rem (beri)** — were introduced before the establishment of the International System of Units (SI). Therefore, they are **non-SI units**, and each corresponds to SI equivalents. The relationships between these units and SI units are presented in **Table 6.5.**

Table 6.5. Units for Assessing Ionizing Radiation

Particle Rest Mass

SI unit: kilogram (kg)

Non-SI unit: atomic mass unit (amu)

$1\,\text{amu} = 1.66057 \times 10^{-27}\,\text{kg}$

Ionizing Radiation Energy

SI unit: joule (J)

Non-SI units: electron volt (eV), erg (erg)

$1\,\text{eV} = 1.60219 \times 10^{-19}\,\text{J}$

$1\,\text{erg} = 1.0 \times 10^{-7}\,\text{J}$

Absorbed Dose

SI unit: gray (Gy)

Non-SI unit: rad (rd)

$1\,\text{Gy} = 1\,\text{J/kg} = 100\,\text{rad}$

Absorbed Dose Rate

SI unit: gray/s

Non-SI units: rad/second (rd/s), gray/minute (Gy/min)

$1\,\text{rd/s} = 1.0 \times 10^{-2}\,\text{Gy/s}$

$1\,\text{Gy/min} = 1.666 \times 10^{-2}\,\text{Gy/s}$

Exposure Dose

SI unit: coulomb/kilogram (C/kg)

Non-SI unit: roentgen (R)

$1\,\text{R} = 2.57976 \times 10^{-4}\,\text{C/kg}$

Exposure Dose Rate

SI unit: ampere/kilogram (A/kg)

Non-SI unit: roentgen/second (R/s)

$1\,\text{R/s} = 2.57976 \times 10^{-4}\,\text{A/kg}$

Equivalent Dose

SI unit: sievert (Sv)

Non-SI unit: rem (Roentgen Equivalent Man, ‘beri’)

$1\,\text{rem} = 1.0 \times 10^{-2}\,\text{Sv}$

Equivalent Dose Rate

SI unit: sievert/second (Sv/s)

Non-SI unit: rem/second (rem/s)

$1\,\text{rem/s} = 1.0 \times 10^{-2}\,\text{Sv/s}$

Radionuclide Activity
SI unit: becquerel (Bq)
Non-SI unit: curie (Ci)
$1\,\text{Ci} = 3.70 \times 10^{10}\,\text{Bq}$

Specific Activity of Radionuclides
SI unit: becquerel/kilogram (Bq/kg)
Non-SI unit: curie/kilogram (Ci/kg)
$1\,\text{Ci/kg} = 3.70 \times 10^{10}\,\text{Bq/kg}$

Ionizing Radiation Energy Flux
SI unit: watt (W)
Non-SI unit: erg/second (erg/s)
$1\,\text{erg/s} = 1.0 \times 10^{-7}\,\text{W}$

Ionizing Radiation Energy Flux Density
SI unit: watt/m² (W/m²)
Non-SI unit: erg/(s·cm²)
$1\,\text{erg/(s·cm}^2) = 1.0 \times 10^{-3}\,\text{W/m}^2$

Commentary

The introduction of the **International System of Units (SI) in 1961** made it necessary to restrict the use of older non-SI units such as the **roentgen (R)** for exposure dose, **rad (rd)** for absorbed dose, **rem (beri)** for equivalent dose, and **curie (Ci)** for radionuclide activity.

It is noteworthy that the SI unit of energy, the **joule (J)**, is also used to evaluate ionizing radiation and its fields. In parallel, non-SI units such as the **electron volt (eV)** and **atomic mass unit (amu)** remain permissible for practical use.

The SI unit for absorbed dose is the **gray (Gy)**, equivalent to the previously discussed rad. In therapy, the gray is used directly, while in radiobiological research, multiples of the gray are often applied.

The **roentgen** remains in practical use in dosimetric work and instruments, which explains why non-SI units are still referenced in this manual.

ISO 80000-10 establishes internationally recognized quantities and units for atomic and nuclear physics, including radiation measurement. Complementing this, **ISO 4037** defines reference radiation fields used for calibration, ensuring that units applied in research are both standardized and scientifically validated. By linking the discussion of radiation units to these standards, the monograph situates its analysis within a globally harmonized framework. This connection reinforces methodological rigor and guarantees that research outcomes are comparable across international studies.

6.12. Radiation Safety Standards

For the purposes of radiation safety, people are divided into categories. There are three categories: **A, B, and C.**

- **Category A:** Personnel who permanently or temporarily work with sources of ionizing radiation.

- **Category B:** Individuals who, by place of residence or work, may be located near sources of ionizing radiation or radioactive waste.
- **Category C:** The rest of the country's population.

For all categories, three classes of radiation dose norms are established:

1. **Basic dose limits;**
2. **Permissible levels;**
3. **Control levels.**

In addition, the human body is divided into groups of **critical organs**, according to which radiation norms are developed. A critical organ is that part of the human body whose irradiation at a given moment would cause the greatest damage to health or affect the health of future generations.

The established groups of critical organs are:

Group I: Whole body, gonads, red bone marrow;

Group II: Muscles, thyroid gland, adipose tissue, liver, kidneys, spleen, lungs, gastrointestinal system, eye lens, and other organs not included in Groups I or III;

Group III: Skin, bones, extremities, palms and soles, shoulder and neck areas.

Tab. 6.6. Basic Limits of External and Internal Radiation Doses for Categories A and B

N	Category & Type of Dose	Annual Dose Limits by Critical Organ Groups (J/kg or rem)
1	Maximum permissible dose for Category A	I: 0.05 (5 rem) • II: 0.15 (15 rem) • III: 0.3 (30 rem)
2	Dose limit for Category B	I: 0.005 (0.5 rem) • II: 0.015 (1.5 rem) • III: 0.03 (3 rem)

Notes on Table 6.6

1. Except for women under the age of 40, no regulatory limit is set for external radiation dose in Category A.

For **Category A**, the dose norm is defined as the **annual basic dose limits**, while for **Category B**, the dose norm is defined as the **annual permissible levels**, corresponding to Classes 1 and 2 of radiation norms.

The **third class of radiation norms — control levels** — includes the following components:

- Annual intake of radionuclides into the body
- Radionuclide content within the body
- Dose rate or flux density
- Radionuclide concentration in air (for Category B, concentration values must also be specified for water)
- Level of contamination of the earth's surface

Control levels are established separately for Categories A and B. Monitoring these components is carried out to assess the radiation situation or to plan measures that reduce the likelihood of human exposure. For Category A, control levels are determined by the enterprise administration, subject to agreement with the sanitary-epidemiological service. For Category B, control levels are set directly by the sanitary-epidemiological service.

In parallel with the division of people into categories, radioactive substances are classified into **hazard groups**. There are four such groups, designated by letters **A, B, C, and D**. These groups differ by activity levels:

- **Group A:** Very high hazard — activity of 0.1 μCi;
- **Group B:** High hazard — activity of 1 μCi;
- **Group C:** Medium hazard — activity of 10 μCi;
- **Group D:** Low hazard — activity of 100 μCi.

It should be noted that specialized reference materials, sanitary rules and norms, and construction standards contain extensive tables of radionuclides. These tables provide detailed gradations of radionuclides according to all listed characteristics, including: hazard group, critical organ affected, permissible levels of internal and external exposure by category, permissible concentrations in atmospheric air and wastewater, and other important indicators.

Such detailed tables are not included within the scope of this manual.

ISO 15382 and **ISO 7753** establish internationally recognized frameworks for radiation protection and safety standards. ISO 15382 specifies protective measures for workers exposed to ionizing radiation, while ISO 7753 provides guidelines for monitoring and controlling radiation doses in occupational environments. By linking the discussion of radiation safety to these standards, the monograph ensures that research findings are aligned with globally validated practices. This connection reinforces the scientific credibility of safety protocols and highlights their relevance for both laboratory and industrial applications.

6.13. Protection Against Radiation

For the safe use of radioactive isotopes, protective measures must be implemented to safeguard not only those working directly with radioactive substances but also individuals in adjacent buildings and residents in areas near the enterprise. To protect against the harmful effects of radiation, **technical, sanitary-hygienic, and medical-preventive measures** are carried out.

Technical protective means include the installation of stationary and mobile screens made of materials that reflect and absorb radioactive radiation.

Since different types of radiation have different properties, the protective measures vary accordingly:

- **Alpha radiation:** A stream of helium nuclei with a double positive charge. Due to their relatively large mass, alpha particles quickly lose energy when interacting with matter, resulting in low penetration ability but high specific ionization. Protection against alpha radiation is relatively easy — a few centimeters of air or a sheet of paper is sufficient.
- **Beta radiation:** To protect against high-energy beta particles, lead screens are used, lined internally with materials of low atomic mass to reduce the initial energy of electrons and, consequently, the secondary radiation induced in the lead.

- **Gamma and X-ray radiation:** Protection requires materials with high atomic mass and density, such as lead, tungsten, etc. Lighter materials, which are cheaper and less scarce, are also often used — for example, steel, cast iron, and copper alloys. Stationary screens that form part of building structures are preferably made of concrete or barite concrete.
- **Neutron radiation:** Protection requires hydrogen-containing materials (water, paraffin), as well as beryllium, graphite, and others. For combined protection against neutrons and gamma radiation, mixtures of heavy materials with water or hydrogen-containing substances are used, as well as layered screens of heavy and light materials (e.g., lead-polyethylene, iron-water).

Radiation dose is directly proportional to the activity of the source and the duration of exposure, and inversely proportional to the square of the distance between the source and the workplace. Thus, protection against external radiation or reduction of exposure to a minimum can be achieved by the principles of:

- **Protection by quantity** — reducing the activity of the radioactive source;
- **Protection by distance** — increasing the distance from the source;
- **Protection by time** — limiting exposure duration;
- **Protection by shielding** — using special devices (screens, panels, containers, etc.).

Protective devices must be periodically checked with dosimetric instruments, since unnoticed damage over time may partially or completely compromise their protective capacity.

In buildings designed for work with radioactive substances, walls, ceilings, and doors must be smooth, without pores or cracks. Corners should be rounded to facilitate cleaning of radioactive dust. Floors must also be smooth.

Workrooms must be equipped with **air heating and supply-exhaust ventilation** providing at least five air exchanges per hour. Daily wet cleaning and monthly general cleaning are mandatory in such rooms.

ISO 15382 and **ISO 7753** establish internationally recognized requirements for radiation protection, focusing on shielding, monitoring, and personnel safety. ISO 15382 specifies protective measures for workers exposed to ionizing radiation, while ISO 7753 provides guidelines for the design and implementation of radiation monitoring systems. By linking protective strategies to these standards, the monograph ensures that research findings are not only theoretically rigorous but also embedded in globally validated safety practices. This connection highlights the scientific foundation of radiation protection and reinforces its relevance for both laboratory and industrial applications.

6.14. Disposal of Radioactive Waste

1. The amount of radioactive material present at the workplace must not exceed the daily operational requirement.
2. Gamma-active substances must be stored in **lead containers**.
3. Accounting records of radioactive materials must reflect their actual quantity at any given time.

4. Transportation of radioactive materials must be carried out in specially packaged containers. Within city limits, transport is permitted only in specially equipped vehicles. During transport, protection of both escorts and the surrounding population from radiation must be ensured.

5. Disposal of radioactive waste is complicated by the fact that it cannot be neutralized by physical or chemical methods. Concentrated and diluted liquid wastes must be collected separately, since diluted waste may be discharged directly into the sewage system.

6. Solid wastes must be separated according to activity, half-life, etc.

7. It is prohibited to discharge radioactive wastewater into absorption pits, wells, irrigation fields, or ponds intended for fish or waterfowl breeding.

8. Special disposal sites are designated for radioactive waste, equipped with **concrete repositories** for both solid and liquid wastes.

9. Solid radioactive waste is collected in bags made of plastic materials, while liquid waste is stored in hermetically sealed special containers. Radioactive substances with half-lives up to 15 days are held until their activity decreases to permissible concentration levels. After this, solid waste may be discarded with ordinary refuse, and liquid waste may be discharged into the sewage system.

10. Radioactive waste disposal sites must be located at least **20 km away from cities**, in areas where future construction is not planned, and must include a **1,000-meter sanitary protection zone.**

Short Note

In the preceding paragraphs, the manual discussed radiation types, units, norms, and waste disposal. Here, it is appropriate to reference the **International Atomic Energy Agency (IAEA) standards**, which define the global framework for ionizing radiation safety.

The IAEA safety standards establish international rules for radiation control and waste management. They require that all industrial and scientific facilities using radioactive sources develop clear programs for **dosimetric monitoring, personnel protective equipment, and safe storage/disposal of waste.** The principle described in the manual — **protection by quantity** — directly corresponds to IAEA's requirement that reducing activity and strictly controlling waste are fundamental to radiation safety.

6.15. Some Consequences of the Chernobyl Accident

The information presented is taken from the materials of WHO expert meetings on Chernobyl (2003–2005). The assessment was based on high-quality scientific studies in this field, as well as the 2000 report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The latter report used data provided by the governments of Ukraine, Belarus, and the Russian Federation.

After the Chernobyl accident, the number of registered liquidators was **600,000**, of whom **240,000** worked in 1986–87. In 1986, **116,000 people** were evacuated from the 30 km zone, and another **230,000** in subsequent years. Currently, about **5 million people** live in areas of Ukraine, Belarus, and Russia where radioactive cesium deposition exceeds 37,000 disintegrations per square meter (37 kBq/m²). Of these, 270,000 people live in areas where contamination exceeds 555 kBq/m².

It is noteworthy that the average natural radiation background is such that a person receives an equivalent dose of **2.4 mSv per year**. This average varies greatly; in some regions of the world, people naturally receive up to **20 mSv per year**. There are conflicting assessments among researchers regarding such high natural background radiation, particularly concerning technogenic radiation close to natural levels and the ecological cleanliness of nuclear power plants.

According to these data, the average world citizen receives **48 mSv over 20 years**. The **240,000 liquidators** who worked in 1986–87 received, in addition to natural background, more than **100 mSv**; evacuees in 1986 received more than **33 mSv**; the **270,000 people** living in areas contaminated above 555 kBq/m² received more than **50 mSv** between 1986–2006; and about **5 million people** living in areas contaminated at 37 kBq/m² received about **20 mSv** in the same period. These populations continue to receive doses corresponding to background radiation plus additional exposure. For comparison, a **whole-body CT scan** gives a dose of about **12 mSv**.

The SI unit of absorbed dose is the **gray (Gy)**, while the unit of effective dose is the **sievert (Sv)**, which accounts for absorbed energy, radiation type, and tissue sensitivity. In most cases of the Chernobyl accident, these values can be considered approximately equal.

The UNSCEAR report notes that among the liquidators, **134 people** received particularly high doses and were diagnosed with **acute radiation sickness**. Of these, **28 died in the same year**, while the rest died later.

In the population of the aforementioned **5 million people**, cancer incidence increased by 0.6%, while in other groups it increased by 4–5%.

ISO 14001 and **ISO 45001** provide internationally recognized frameworks for environmental management and occupational health and safety, both of which are directly relevant when analyzing the consequences of the Chernobyl accident. ISO 14001 emphasizes systematic approaches to environmental monitoring and remediation, while ISO 45001 establishes requirements for protecting workers in hazardous conditions. By linking the discussion of Chernobyl's aftermath to these standards, the monograph situates its analysis within globally validated practices. This connection highlights how catastrophic events are studied not only through historical and scientific lenses but also through structured international safety and environmental protocols.

7. Lighting of Workplaces

7.1. Guide Seven – For the Chapter

Theoretical Integration:

Light is an electromagnetic wave with a wavelength visible to humans. Eye adaptation, accommodation, and convergence form the physiological basis of vision, upon which lighting standards are established.

Integration with Standards:

ISO 8995-1 Lighting of Work Places sets minimum illumination levels depending on the type of work and the complexity of visual tasks. Emphasis is placed on uniform distribution of light, avoidance of discomfort glare, and inclusion of both general and combined lighting. The ILO and WHO highlight the hygienic importance of lighting in preventing eye strain, errors, and accidents.

Pedagogical Integration:

Readers should be able to connect light units (lux, lumen, candela) with ISO 8995-1 requirements and solve practical tasks using examples from their own fields (office, workshop, warehouse, construction site).

Brief Note:

ISO 8995-1 provides a relatively broad explanation and application.

- **Purpose:** Ensure minimum illumination suitable for visual tasks, with comfort and safety.
- **Key Requirements:**

  Minimum illumination: typically, 300–500 lux in offices; 500–1000 lux for precise work.

  Uniformity: coefficient often ≥0.7 on work surfaces.

  Glare: direct/indirect glare must be reduced; lamp selection and arrangement are critical.

  Mixed lighting: natural + artificial to eliminate dark zones.
- **Design Steps:**

  Task categorization: define object size (mm) and visual difficulty.

  Norm selection: choose illumination level from ISO 8995-1.

  Method: luminous flux or point method; check flicker coefficient (<20%).

  Layout: general lighting ≥10% in combined systems; local lamps for precise vision.
- **Common Mistakes:**

  Considering only illumination level without uniformity or glare control.

  Ignoring flicker.

  Over-reliance on natural light.

ISO 8995 and **EN 12464** provide internationally recognized frameworks for workplace lighting design and assessment. ISO 8995 specifies general principles for lighting of indoor work environments, ensuring that illumination levels support both safety and productivity. EN 12464 defines detailed requirements for lighting in specific tasks and industrial settings, including criteria for luminance, glare control, and color rendering. By linking the explanatory notes of Chapter VII to these standards, the monograph situates its analysis within a globally harmonized framework. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers' health, efficiency, and comfort through appropriate lighting.

7.2. Light and Its Importance

Physical Basis:

Molecules and atoms emit electromagnetic radiation when the energy state of their outer electrons' changes. Light is the portion of this radiation with wavelengths between 0.4–0.8 µm (4000–8000 Å).

Sensitivity of the Human Eye:

In daylight, the human eye is most sensitive to a wavelength of 0.555 µm (5550 Å). Under artificial lighting, maximum sensitivity shifts to about 5070 Å. Light waves exert pressure on surfaces.

Wave Components:

Electromagnetic waves have electric (E) and magnetic (H) components. For daylight, these are oriented perpendicularly to the direction of the rays and to each other.

Impact on Workplaces:

Rational lighting in industrial buildings and workplaces improves sanitary and hygienic conditions, reduces accidents, enhances productivity, and raises the culture of production.

Risks of Poor Lighting:

Insufficient lighting causes constant eye strain, leading to fatigue, reduced attention, and accidents. Excessive lighting can also weaken orientation ability and increase accident risk.

Adaptation and Accommodation:

The human eye adapts to different light levels through pupil dilation and contraction. Accommodation allows clear vision of objects at varying distances. Fluctuations in light intensity disrupt adaptation. Prolonged work under unsuitable lighting can lead to cataracts, myopia, headaches, and other disorders.

ISO 8995 and **EN 12464** provide internationally recognized frameworks for understanding the importance of light in workplaces. ISO 8995 specifies general principles for indoor lighting, emphasizing that adequate illumination is essential for safety, efficiency, and the prevention of accidents. EN 12464 defines detailed requirements for task lighting, glare control, and color rendering, ensuring that workers can perform their duties with precision and comfort. By linking the discussion of light and its importance to these standards, the monograph ensures that both theoretical perspectives and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the role of standardized lighting in safeguarding health, productivity, and well-being.

7.3. Characteristic Units of Light

Luminous Intensity:

Luminous intensity is the light flux emitted by a point source within a unit solid angle (1 steradian).

$$I = \frac{F}{\omega} \tag{7.1}$$

where I is luminous intensity, candela, cd; F is luminous flux, lumen, lm; and ω is solid angle, steradian.

Candela Definition:

A candela is the luminous intensity emitted in a given direction by a monochromatic source of frequency 540×10^{12} Hz, with radiant intensity of (1/683) W/steradian.

Lumen:

The lumen is the unit of luminous flux. It corresponds to the flux produced by a luminous intensity of 1 candela within a solid angle of 1 steradian.

- A 60 W incandescent lamp produces about 710 lumens.
- A 100 W incandescent lamp produces about 1350 lumens.

Illuminance:

Illuminance is the density of luminous flux incident on a surface

$$E = \frac{F}{S} \tag{7.2}$$

where E is illuminance, lux, lx; F is luminous flux, lm; and S is surface area, m^2.

Thus, 1 lux = 1 lumen uniformly distributed over 1 m^2.

Point Source on a Surface:

Illuminance from a point source on a tilted surface is calculated as

$$E = \frac{F \cos \alpha}{r^2} \tag{7.3}$$

where α is the angle between the flux direction and the surface normal, and r is the distance from source to surface.

Brightness (Luminance):

Brightness is the measure of luminous intensity per unit area of a visible surface

$$B = \frac{I}{S} \tag{7.4}$$

where B is brightness, cd/m^2; I is luminous intensity, and S is the visible surface area.

Light Intensity (Radiant Intensity):

Light intensity refers to the electromagnetic wave flux passing through a plane perpendicular to its direction of propagation per unit time. It is proportional to the square of the wave amplitude.

ISO 80000-7 and **CIE** standards provide internationally recognized frameworks for defining characteristic units of light. ISO 80000-7 specifies quantities and units related to optics, including luminous flux, illuminance, and luminance, ensuring consistency in scientific and technical communication. The CIE (International Commission on Illumination) standards establish methodologies for measuring and applying these units in workplace lighting design. By linking the discussion of characteristic units of light to these standards, the monograph ensures that both theoretical definitions and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in workplace illumination.

7.4. Structure of the Human Eye

Optical System:

The eye is a complex optical system. Its optical part consists of a biconvex lens (the crystalline lens) and a diaphragm-like opening (the pupil).

Retina:

The retina is the light-sensitive layer at the back of the eye, where the lens projects a reduced, inverted image of objects. It is composed of photoreceptor rods, cones, and nerve cells. Incoming light breaks down photochemical substances in the retina, and the resulting products stimulate nerve endings in rods and cones.

Visual Processing:

Generated impulses travel through the optic nerve to the brain's visual center, allowing perception of color, shape, and size. The retina contains about 130 million rods and 7 million cones. Cones are responsible for color vision, while rods do not perceive color.

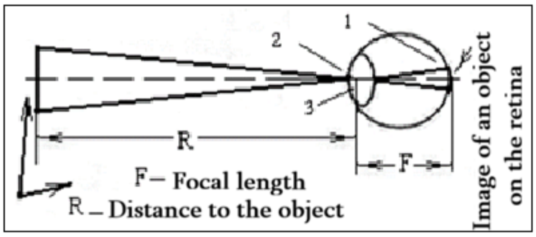

Fig. 7.1. The eye as an optical system: 1 – retina; 2 – pupil; 3 – lens

Mechanisms of Adaptation:

The eye adapts to objects in three ways:

1. **Accommodation:** Changing the curvature of the lens so the image falls on the retina.
2. **Convergence:** Turning both eyes' axes so they intersect at the viewed object.
3. **Adaptation:** Adjusting to the level of illumination, linked to changes in pupil size.

Simple Experiments:

- *Accommodation:* Look at a distant object (tree branch, mast) for 1–2 minutes, then quickly shift gaze to text.
- *Adaptation:* While reading, reduce or switch off artificial light. After a short time, reading becomes possible again. The adaptation time depends on the degree of change in illumination. When brightness changes 5–10 times, adaptation occurs almost instantly.

ISO 8596 and **ISO 10938** provide internationally recognized frameworks for evaluating the structure and function of the human eye in relation to vision and workplace safety. ISO 8596 specifies test methods for visual acuity, ensuring that lighting conditions support accurate perception. ISO 10938 defines requirements for ophthalmic instruments used to assess eye structure and performance. By linking the discussion of the human eye's structure to these standards, the monograph ensures that both physiological explanations and practical safety considerations are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in designing workplace lighting that protects and supports human vision.

7.5. Types of Lighting in Premises

General Classification:

Lighting in all buildings, including industrial facilities, can be natural, artificial, or combined.

Natural Lighting:

This is illumination of interior spaces by direct or reflected sunlight entering through windows or other openings, which must be designed specifically for lighting purposes. Buildings may be lit naturally from the roof, walls, or both.

Artificial Lighting:

Used at night or when daylight is insufficient. It is applied in all types of buildings or open areas where work, movement of people, or transport occurs. Artificial lighting uses electric lamps—incandescent, gas-discharge, or mercury lamps. Beyond production purposes, it can also serve emergency, evacuation, or security needs.

Combined Lighting:

Applied when daylight is insufficient, supplemented by artificial lighting directly at workplaces.

Emergency Lighting:

Installed to prevent interruptions when production lighting fails, ensuring continued operation. It is required where shutdowns could release toxic, explosive, or harmful substances, or risk fire or explosion. Essential facilities include power plants, broadcasting and communication centers, dispatch points, and critical water, sewage, or ventilation systems.

Evacuation Lighting:

Used during failure of production lighting to enable safe evacuation. It is installed on stairways and hazardous passageways. Required when more than 50 people are present, with minimum illuminance of 20 lux.

Security Lighting:

Provides illumination of industrial buildings or premises at night during non-working hours for surveillance. It must be arranged along the boundaries of the protected site.

ISO 8995 and **EN 12464** provide internationally recognized frameworks for defining types of lighting in premises. ISO 8995 specifies general principles for workplace illumination, distinguishing between ambient, task, and emergency lighting to ensure safety and efficiency. EN 12464 establishes detailed requirements for lighting in offices, industrial facilities, and educational environments, including criteria for luminance distribution, glare control, and color rendering. By linking the discussion of types of lighting in premises to these standards, the monograph ensures that both theoretical classifications and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in designing effective lighting systems.

7.6. Natural Lighting in Premises

Coefficient of Natural Illumination (CNI):

The quality of natural lighting at a point in a room is measured by the coefficient of natural illumination (CNI), expressed as a percentage

$$e = 100 \cdot \frac{E_i}{E_o} \quad (7.5)$$

where e is the CNI, %; E_i - illuminance on a surface inside the room, lux; and E_o - illuminance on an equivalent surface outdoors under open sky, lux.

Differences from Artificial Lighting:

Natural light differs significantly from artificial light due to its diffusion, which supports normal working conditions. It also contains ultraviolet rays beneficial to human health. Natural lighting can be arranged as side lighting, top lighting, or a combination of both.

Norms for Side Lighting:

For one-sided side lighting, the average CNI is measured at a point located 1 m from the wall opposite the windows. This point is marked on the vertical section of the building at floor or work surface level.

Norms for Two-Sided Lighting:

For two-sided lighting, the minimum CNI is measured at the midpoint of the building, again marked on the vertical section at floor or work surface level.

Urban Considerations:

In cities, street and square lighting design must follow norms of average surface luminance. Determining these norms is complex, as natural lighting depends on latitude, season, sky conditions (clear or cloudy), and time of day. Therefore, calculations are based on the area of light openings.

Combined Natural Lighting:

When both side and top lighting are used, calculations differ. In such cases, the average CNI is applied, with evaluation points marked along the intersection of the building's vertical section and the floor. The first and last points are taken 1 m from the walls.

Note on Standards:

- ISO 8995-1 defines luminance (cd/m²) as the key parameter for surface brightness.
- Both ISO and WHO emphasize that excessive or insufficient luminance causes eye fatigue and increases accident risk.
- ISO sets quantitative limits (e.g., ≤200 cd/m² on work surfaces), while WHO focuses on health outcomes (cataracts, headaches).
- Practically, specialists must connect ISO's numerical norms (e.g., 300–500 lux in offices, 500–1000 lux for precise work) with WHO's health recommendations to ensure safe working environments.

ISO 8995 and **EN 17037** provide internationally recognized frameworks for natural lighting in premises. ISO 8995 specifies general principles for workplace illumination, emphasizing the integration of daylight to support safety, efficiency, and well-being. EN 17037 defines detailed requirements for daylight in buildings, including criteria for access to sunlight, view quality, and glare control. By linking the discussion of natural lighting in premises to these standards, the monograph ensures that both theoretical perspectives and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in designing healthy, comfortable, and energy-efficient workplaces

7.7. Artificial Sources of Light

Types of Lamps:

Artificial lighting uses electric lamps, which may be incandescent, fluorescent, or mercury-based.

Incandescent Lamps:

- Tungsten filament lamps produce a continuous spectrum.
- Except for mirror-type lamps, their performance is not significantly affected by ambient temperature or humidity.

Fluorescent Lamps:

- Provide more intense light transmission, yielding higher illumination at equal power.
- Service life is about 10,000 hours, compared to 1,000 hours for incandescent lamps.
- They emit lower brightness, operate within +5–150 °C, and perform best at 20–30 °C.
- Advantages: stronger light flux, longer lifespan, lower brightness.
- Disadvantages: light flux decreases by up to 60% near end of life, flicker (causing stroboscopic effect and accident risk), sensitivity to ambient temperature, disposal issues, higher starting voltage requiring complex control devices, and higher cost compared to incandescent lamps.

Luminaires (Fixtures):

Used to distribute light onto surfaces, protect eyes from glare, shield lamps from dirt or damage, ensure fire safety, and secure lamp installation.

Types of Luminaires by Light Distribution:

- Direct
- Diffusing
- Reflecting

Selection depends on the nature of work and surface reflectance.

Types by Construction:

- Open
- Protected
- Dustproof
- Dust-resistant
- Explosion-proof

They may serve general or local lighting purposes.

Examples:

For incandescent lamps, direct luminaires are most common, including open, protected, and universal types.

In hazardous areas, explosion-proof luminaires (e.g., type 4D-100) are used, designed to localize explosions inside the fixture.

Choice of Luminaires:

- In areas with low dust and normal humidity, open-type luminaires are used with fluorescent lamps.
- In dusty or humid environments, closed-type luminaires are required.

Preference for Fluorescent Lamps:

Although incandescent lamps are permitted by standards, fluorescent lamps are preferable due to higher efficiency and better economy. Incandescent lamps may be used only when fluorescent sources are unavailable or technical conditions prevent their use.

Economic Considerations:

Incandescent lamps can be more economical for short-term lighting, such as in machine yards, material warehouses, open parking areas, cranes, and other places where lighting is used for limited periods.

Lamp Characteristics:

Both fluorescent and incandescent lamps are characterized by:

- Power (P)
- Luminous flux (F)
- Distribution of luminous intensity in space
- Light output ratio (η)

Table 7.1. Incandescent Lamp Parameters

Options	Lamp parameter values							
Power, W	15	25	40	60	100	150	200	300
Flux, lm	105	210	380	650	1000	2000	2920	4500
Efficiency, lm/W	7.0	8.4	9.5	10.8	11.6	13.3	14.6	15.0

Formula for Efficiency:

$$\eta = \frac{F}{P} \tag{7.6}$$

Efficiency increases with higher lamp power.

Table 7.2. Fluorescent Lamp Parameters

Lamp Type	**Parameter**	**Parameter values depending on lamp power, W**					
		15	20	30	40	65	80
ЛДЦ	lm	500	820	1450	2100	3050	3560
	lm/W	33.4	41.0	48.5	52.5	47.0	44.5
ЛД	lm	590	920	1640	2340	3570	4070
	lm/W	39.4	46.0	54.8	58.5	55.0	51.0
ЛХБ	lm	675	935	1720	2600	3820	4440
	lm/W	45.0	46.7	57.4	65.0	58.7	5.6
ЛБ	lm	760	1180	2100	3000	4550	5220
	lm/W	50.7	59.0	70.0	75.0	70.0	65.3

Different types (ЛДЦ, ЛД, ЛХБ, ЛБ) show luminous flux values ranging from 500–5220 lm and efficiencies from ~33 to 75 lm/W, depending on power and phosphor color.

Comparison:

Fluorescent lamps have significantly higher efficiency than incandescent lamps. Their performance depends on lamp power and phosphor type.

ISO 8995 and **IEC 60598** provide internationally recognized frameworks for artificial sources of light in workplaces and industrial premises. ISO 8995 specifies general principles for workplace illumination, ensuring that artificial lighting systems meet safety, efficiency, and comfort requirements. IEC 60598 defines standards for luminaires, including design, performance, and testing criteria, guaranteeing that artificial light sources are reliable and suitable for diverse environments. By linking the discussion of artificial sources of light to these standards, the monograph ensures that both theoretical classifications and practical applications are scientifically validated and internationally comparable.

7.8. Artificial Lighting

Types of Lighting in Industrial Buildings:

Artificial lighting in production facilities can be general, local, or combined.

General Lighting:

Designed to illuminate the entire building. Fixtures are usually placed on the ceiling or at a considerable distance from workstations. Illumination is uniform across the workspace, with equal spacing between lamps. Recommended for facilities where similar tasks are performed throughout the area (e.g., electrical repair, carpentry, assembly).

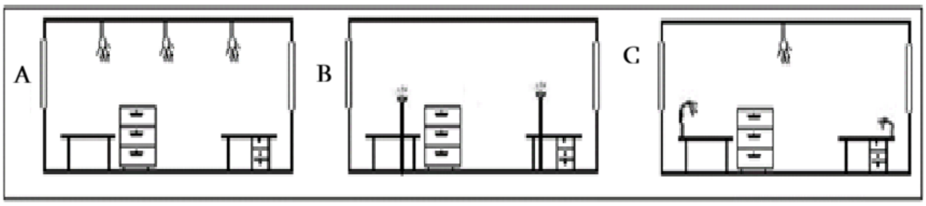

Fig. 7.2. Illustration of lighting in industrial buildings:
A - general; B - local (local); C - combined

Local Lighting:

Provides additional illumination directly at workstations. Fixtures are placed close to the working area. Used when specific tasks require extra light, or when large surfaces or materials are being processed.

Combined Lighting:

Consists of general lighting fixtures for overall illumination and local fixtures positioned directly above workstations. Suitable for precise visual tasks and for surfaces that are vertical or inclined. Examples include machine shops with additional lighting for equipment, or diagnostic lines with localized illumination

Distribution Requirement:

In combined systems, general lighting must provide at least 10% of the normalized illuminance at workstations.

Minimum Illuminance:

The minimum lighting level depends on the size of the object to be distinguished. The object is defined as the part of a subject that must be clearly visible during detailed work (see Table 7.3).

Table 7.3. Natural and Artificial Lighting Norms

Dimensions of the distinguished object, mm	**CNI value, %**		**Artificial lighting, lux**	
	Top lighting	**In side lighting**	**General**	**Combined**
< 0.15	10	3.5	400-1500	1500-5000
0.15-0.30	7	2.5	300-1250	1000-4000
0.30-0.50	5	2.0	200-500	400-2000
0.5-1.0	4	1.5	150-300	300-750
1.0-5.0	3	1.0	100-200	200-300
> 5.0	2	0.5	150	_
Constant monitoring of the production process	1	0.3	75	-
Periodic observation of the production process*	0.5-0.7	0.1-0.2	30-50	-

Note to the Table 7.3 - The smallest values are taken if the storage room does not require constant presence of people.

The table shows coefficients of natural illumination (CNI) and artificial lighting norms depending on the size of the object to be distinguished.

- For very small objects (<0.15 mm), CNI is 10% (top lighting) or 3.5% (side lighting), with artificial illuminance of 400–1500 lux (general) or 1500–5000 lux (combined).
- As object size increases, required CNI and illuminance decrease.
- For permanent observation of production processes, minimum illuminance is 75 lux; for periodic observation, 30–50 lux.

Notes:

- Minimum values apply when continuous human presence is not required.
- Lighting should be increased by one level for prolonged visual work (more than half a day) or when accident risk is high.

Flicker in Fluorescent Lamps:

Fluorescent lamps produce time-dependent pulsation of light flux, measured by the flicker coefficient (K_p, %)

$$K_p = \frac{E_{max} - E_{min}}{2E_{avg}} \cdot 100 \tag{7.7}$$

where E_{max} and E_{min} are maximum and minimum illuminance, and E_{avg} is average illuminance.

Excessive flicker causes eye fatigue and distorts perception of moving or rotating objects, which is especially dangerous in industrial settings. Norms require K_p < 20% for most workplaces.

Calculation Methods:

Lighting calculations are divided into two groups:

1. **Coefficient of luminous flux / specific power method:** Used for evenly lit horizontal surfaces.
2. **Point method:** Applied for unevenly lit surfaces, vertical or inclined surfaces.

Both methods are accurate and simple, but the point method is often used for verification, as it allows analysis of light distribution across building areas.

ISO 8995 and **EN 12464** provide internationally recognized frameworks for artificial lighting in workplaces and industrial premises. ISO 8995 specifies general principles for artificial illumination, ensuring that lighting systems meet safety, efficiency, and comfort requirements. EN 12464 defines detailed criteria for artificial lighting design, including luminance distribution, glare control, and color rendering, guaranteeing that artificial lighting supports both productivity and well-being. By linking the discussion of artificial lighting to these standards, the monograph ensures that both theoretical perspectives and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in designing effective artificial lighting systems.

7.9. Calculation of Artificial Lighting

Steps in Determining Artificial Lighting:

When designing artificial lighting, it is necessary to select:

- Type of light source
- Lighting system
- Type of luminaire
- Lighting norm
- Arrangement of fixtures

After this, calculations are made to determine the number and placement of luminaires. The type of fixture is chosen according to technological conditions, and its construction must match the environmental conditions of the room.

General Lighting Systems:

Illumination depends on lamp type and suspension height (h), which is the distance from the lamp to the work surface. Suspension height is influenced by room height, lamp type, protective angle, lighting system, lamp power, etc.

- For incandescent lamps up to 200 W: mini mum suspension height H_1 = 2.5–4.0 m.
- For lamps above 200 W: H_1 = 3–6 m.
- For fluorescent lamps:
- Up to 4 lamps: H_0 = 2.6–4.0 m;
- 4 or more lamps: H_1 = 3.2–4.5 m.

Spacing Between Lamps:

- Parallel arrangement: L/h = 1.4–1.8;
- Chessboard arrangement: L/h = 1.8–2.5;
- Near walls: l = 0.25–0.3 m (distance from wall to lamp center).

Geometric Relations:

- H = room height, m;
- H_0 = distance from ceiling to work surface;
- h_1 = distance from ceiling to lamp;
- h_0 = distance from floor to work surface;
- h = suspension height;
- H_1 = distance from lamp to floor.

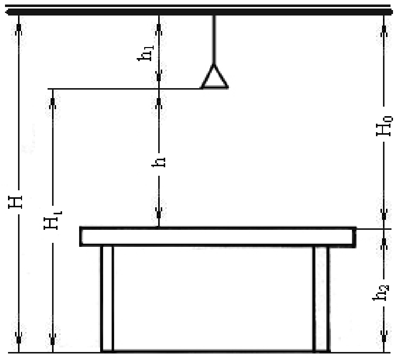

Fig. 7.3. Illustration of artificial lighting

Calculation Methods:

Artificial lighting can be calculated using:

1. Luminous Flux Method: Used for uniform general lighting. Lamp luminous flux (F) is determined by

$$F = E \cdot K \cdot S \cdot Z \cdot N \cdot n \cdot \eta \quad (7.8)$$

where E - normalized minimum illuminance, lux, from Table 7.3; K - maintenance factor (dust conditions; 1.15–1.70 for incandescent, 1.15–1.80 for fluorescent); S - area of the room, m²; Z - minimum illuminance coefficient ($Z = Eavg / Emin$ = 1.10–1.95); N - number of luminaires; n - number of lamps per luminaire; η - utilization factor (0.19–0.74).

Lamp Power Determination:

The luminous flux formula can be used when the number of lamps is known, or conversely, when lamp power is known and the number of lamps must be determined. It is also suitable for verifying lighting calculations.

Utilization Factor:

The utilization factor depends on ceiling, wall, and surface characteristics, as well as the room index (i)

$$i = \frac{S \cdot h}{A + B} \quad (7.9)$$

where S - room area, m²; h - suspension height, m; A - room length, m; B - room width, m.

Actual Illuminance:

Based on luminous flux F from formula (7.8), lamp power is selected. Actual illuminance is calculated as

$$E_f = E \cdot \frac{F_{lamp}}{F} \quad (7.10)$$

Point Method:

Used in workshops (repair, forging, reinforced concrete, etc.) for general, local, or uniform lighting of surfaces in any orientation. It relates illuminance (E) to photometric characteristics

$$E = \frac{J_\alpha \cdot \cos\alpha}{r^2} \quad (7.11)$$

where $J\alpha$ - luminous intensity at a point, cd; α - incidence angle; r - distance from source to surface.

For vertical fixtures illuminating horizontal surfaces, distance is taken as suspension height H_{lamp}

$$E = \frac{J_\alpha Cos^3\alpha}{H_{lamp}K} \quad (7.12)$$

where K - maintenance factor.

Specific Power Method:

Specific power W is the ratio of total lamp power to illuminated area

$$W = \frac{P \cdot n}{S} \quad (7.13)$$

where P - lamp power, W; n - number of lamps per fixture; S – area, m².

Total power of lighting equipment

$$P = S \cdot W \cdot n \quad (7.14)$$

Individual lamp power

$$P_{lamp} = \frac{P}{n} \quad (7.15)$$

Application:

The specific power method is simple but less accurate, so it is mainly used for preliminary or approximate calculations.

ISO 8995 and **CIE 97** provide internationally recognized frameworks for the calculation of artificial lighting in workplaces and industrial premises. ISO 8995 specifies general principles for determining illumination levels, ensuring that calculations meet safety, efficiency, and comfort requirements. CIE 97 establishes methodologies for calculating illuminance, luminance distribution, and glare indices, enabling precise design and verification of artificial lighting systems. By linking the discussion of artificial lighting calculations to these standards, the monograph ensures that both theoretical methods and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in designing effective and reliable lighting systems

7.10. Lighting of Warehouses and Facility Areas

General Requirements:

Territories of facilities, stations, construction sites, warehouses, quarries, and other industrial areas must be illuminated with floodlights or outdoor lamps. Typical stationary or mobile lighting equipment is recommended. For road construction, mobile units are preferable, positioned along roads and work zones.

Types of Lamps:

Lighting devices may use incandescent lamps, high-pressure mercury lamps, xenon lamps, or high-pressure sodium lamps.

Uniform Illumination:

The main requirement is to ensure uniform general lighting across the territory. Fixtures are mounted on special masts or tall buildings.

Lamp Selection by Area Size:

- Up to 20 m: incandescent lamps;
- Up to 150 m: mercury lamps;
- 150–300 m: incandescent floodlights;
- Over 300 m: xenon lamps (must allow 10-fold variation in luminous intensity and be mounted at ≥50 m height).

Floodlight Calculations:

Approximate calculations involve determining the number of floodlights needed, their placement, mounting height, and tilt angle relative to the horizon.

Isolux Curves:

Precise determination uses isolux curves or illuminance diagrams.

- Isolux = curve showing zones of equal illuminance on a plane.
- Each floodlight has its own isolux characteristics.
- Special catalogs provide isolux curves for different tilt angles.
- Curves can also be calculated using tables.

Application:

Floodlight selection is based on isolux curves scaled to match the plan of the illuminated area. Curves are arranged on the plan so the entire area is covered with the minimum number of floodlights.

Installation:

Fixtures may be arranged in rectangular or chessboard patterns. They are mounted on metal masts, temporary wooden supports, or nearby buildings and structures.

ISO 8995 and **EN 12464** provide internationally recognized frameworks for lighting in warehouses and facility areas. ISO 8995 specifies general principles for workplace illumination, ensuring that lighting systems in large storage and operational spaces meet safety and efficiency requirements. EN 12464 defines detailed criteria for lighting in industrial and logistics environments, including minimum illuminance levels, glare control, and uniformity of light distribution. By linking the discussion of warehouse and facility area lighting to these standards, the monograph ensures that both theoretical guidelines and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers, optimizing operations, and maintaining safety in large-scale premises.

7.11. Protective Measures

Engineering Measures:

- Anti-glare luminaires;
- Light diffusers;
- Properly selected protective angles of fixtures;
- Control of local lighting.

Administrative Measures:

- Adjustment and management of work and rest intervals;

- Rotation of visual tasks;
- Periodic inspection of lighting systems.

Individual Measures:

- Use of special glasses or filters when the environment does not meet adequate standards.

Pedagogical Note:

Select a real workplace in your field and compare it with ISO 8995-1 requirements:

- Define minimum illuminance (lux);
- Assess uniformity of lighting;
- Identify glare risks;
- Prepare a short corrective plan for a safe working environment.

Table 7.4. Comparative Standards Analysis

Work Environment	**ISO 8995-1 Min. Illuminance, lux**	**ISO Luminance, cd/m²**	**WHO/ILO Focus**	**Similarity**	**Difference**
Office, documentation	500	≤200 on work surfaces	Eye strain, error prevention	All standards recognize risk of insufficient lighting	ISO → quantitative norms; WHO/ILO → health outcomes
Technical/precise work	750–1000	≤300 on detailed tasks	Accident prevention	All standards emphasize safety	SO → metrics; WHO/ILO → organizational measures
Warehouse/passages	200–300	≤150	Safe movement	All standards recognize need for minimum lighting	ISO → numeric norms; WHO/ILO → practical recommendations

ISO 45001 and **ISO 7010** provide internationally recognized frameworks for protective measures in workplaces. ISO 45001 establishes requirements for occupational health and safety management systems, ensuring that protective strategies are systematically integrated into organizational practices. ISO 7010 defines standardized safety signs and symbols, guaranteeing clear communication of protective measures such as mandatory use of personal protective equipment, emergency exits, and hazard warnings. By linking the discussion of protective measures to these standards, the monograph ensures that both procedural guidelines and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers, facilities, and the environment.

8. Occupational Noise and Vibration

8.1. Guide for Chapter Eight

- **Theoretical integration:** The wave nature of sound and the auditory range form the basis for noise regulation.
- **Integration with standards:** ISO 1999:2013 Acoustics — Determination of Occupational Noise Exposure defines the threshold of 85 dB for an 8-hour period. WHO Occupational Noise Guidelines confirms the same threshold to ensure health protection.
- **Pedagogical integration:** The student must be able to relate noise levels (dB) to ISO/WHO standards and practical examples.
- **Short note:** ISO 1999 Occupational noise exposure sets the threshold of 85 dB for 8 hours, while WHO emphasizes prevention of hearing loss.
- **Similarity:** Both ISO and WHO confirm that ≥85 dB exposure leads to hearing impairment.
- **Difference:** ISO focuses on measurement methodology and dose modeling, WHO on health impacts and prevention.
- **Practical outcome:** The specialist must be able to apply ISO quantitative norms together with WHO recommendations to design a control plan.

Table 8.1. Comparative Analysis of International Standards

Work Environment	ISO 1999 Threshold, dB, 8h	WHO Recommendation	ILO Requirement	Similarity	Difference
Office/Administrative	≤55–65 dB	Comfortable environment, concentration	Monitoring not required	All standards recognize the benefits of low noise	ISO → metrics; WHO → health outcomes
Industrial Workshop	≤85 dB	Hearing tests ≥85 dB	Regular monitoring	All standards confirm the 85 dB threshold	ISO → quantitative; WHO/ILO → organizational
Heavy Industry	≤90–95 dB (short duration)	Prevention, reduction of working hours	Marking of safe zones	All standards recognize high-risk zones	ISO → dose modeling; WHO/ILO → health prevention

Note: ISO 1999 defines quantitative thresholds (85 dB for 8 hours), WHO emphasizes health outcomes, and ILO focuses on organizational measures. The specialist must be able to apply ISO norms together with WHO/ILO recommendations.

ISO 22320 and **ISO 31000** provide internationally recognized frameworks for integrating protective measures and harmonizing risk management in the context of workplace safety. ISO 22320 establishes requirements for emergency management and incident response, ensuring that protective strategies are coordinated and systematically controlled. ISO 31000 defines principles and guidelines for risk management, including hazard identification, consequence analysis, and preventive planning. By linking the explanatory notes of Chapter VIII to these standards, the monograph situates its analysis within a globally harmonized framework. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers, facilities, and the environment.

ISO 1999 and **ISO 2631** provide internationally recognized frameworks for occupational noise and vibration. ISO 1999 specifies methods for assessing occupational noise exposure and its impact on hearing, ensuring that workplace environments are evaluated with scientific precision. ISO 2631 defines criteria for human exposure to whole-body vibration, including measurement techniques and health risk assessment. By linking the guide for Chapter Eight to these standards, the monograph ensures that both theoretical explanations and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers' health and safety against noise and vibration hazards.

8.2. Wave Nature of Sound

Sound propagates in air in the form of waves, which represent pulsating alternations of compression and rarefaction of air under the action of sound pressure along its path of travel.

The human ear distinguishes sound according to its frequency. The unit of frequency is the hertz (Hz), defined as one oscillation per second. A larger unit is the kilohertz (kHz), where 1 kHz = 1000 Hz.

The human ear cannot differentiate all increments of frequency. It can only distinguish neighboring frequencies when their ratio is 1:2. For example, the human ear perceives waves at 16 Hz, but cannot perceive lower frequencies. An increase in frequency is not distinguished until it doubles; thus, only when the frequency reaches 31.5 Hz (nearly double) does the listener recognize a change in the sound characteristic.

The sensitivity of the human ear lies within the range of 16 Hz to 16 kHz. Frequencies lower than 16 Hz in multiples of two (8 Hz, 4 Hz, etc.) are called infrasound. Frequencies higher than 16 kHz in multiples of two (32 kHz, 64 kHz, etc.) are called ultrasound. Each doubling of frequency is referred to as an octave.

The frequency of a wave is inversely proportional to its wavelength: the higher the frequency, the shorter the wave. The wavelength can be approximately calculated using the formula

$$l = \frac{C}{f} \tag{8.1}$$

where: l — wavelength, m; C — speed of sound in air, m/s; f — frequency of sound oscillations, Hz.

It should be noted that the speed of sound varies with temperature. For example, if the speed of sound is 340 m/s, then the wavelength of a wave with frequency f =100 Hz will be l =3.4 m.

The amplitude of a sound wave is the mean value between the maximum and minimum sound pressures (Fig. 8.1), determined by the compression and rarefaction of air under sound pressure.

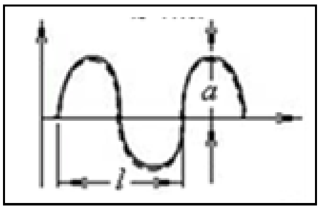

Figure 8.1. Sound wave:
a − amplitude; ℓ - wavelength

To describe the relative temporal properties of two waves, or to evaluate different parts of the same wave, the concept of phase is used. Two waves may coincide in phase, be shifted in phase, or have opposite phase configurations, as illustrated in Fig. 8.2. A person perceives the same sound differently depending on its phase, which is influenced by the position of the ears relative to the sound source.

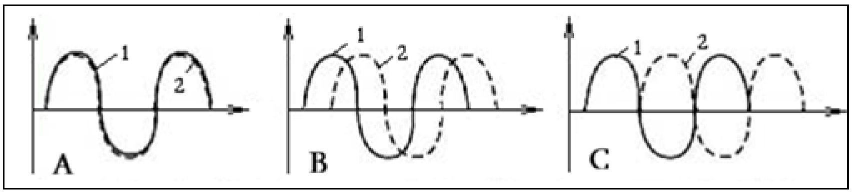

Figure 8.2. Different phase configurations of two sound waves:
A—coinciding phases; B —shifted phases; C —opposite phases; 1,2 — waves

As shown in the figure, in the case of opposite phase configuration, the compression of air caused by one wave coincides with the rarefaction caused by the other, and such waves cancel each other. More often, opposite phase configurations distort the sound.

Sound Pressure and Auditory Thresholds.

Sound pressure is measured in pascals (Pa). To evaluate the intensity of sound waves, the concept of sound power is also used. This represents the flow of acoustic energy passing through one square centimeter of a surface oriented perpendicular to the direction of wave propagation. The unit of measurement is W/cm². Sound power describes the energetic properties of sound and is useful for certain calculations.

For the human ear to perceive sound, it must have a certain minimum power. This level is called the threshold of audibility. If the intensity of sound is below this threshold, it is not perceived, and the listener assumes silence, although air continues to vibrate under the influence of infrasonic waves.

Similarly, in the case of ultrasound (very high-frequency sounds), the human ear does not perceive them as tones. However, there is an important distinction: ultrasound can be sensed as unbearable pain in the ears. Therefore, this limit is referred to as the threshold of painful sensation.

Thus, the human ear can perceive sounds across a very wide range, known as the auditory range, which corresponds to the frequencies between the lower and upper sensitivity thresholds (Fig. 8.3).

- **Lower threshold:**

  Sound pressure: $2 \times 9.8 \times 10^{-6}$ Pa

  Intensity: 10^{-16} W/cm²
- **Upper threshold:**

  Sound pressure: between 5X9,8 and 10X9,8 Pa

  Intensity: 10^{-3} W/cm²

Rounded values are often used:

Lower threshold: 0.00002 Pa

Upper threshold: 100 Pa

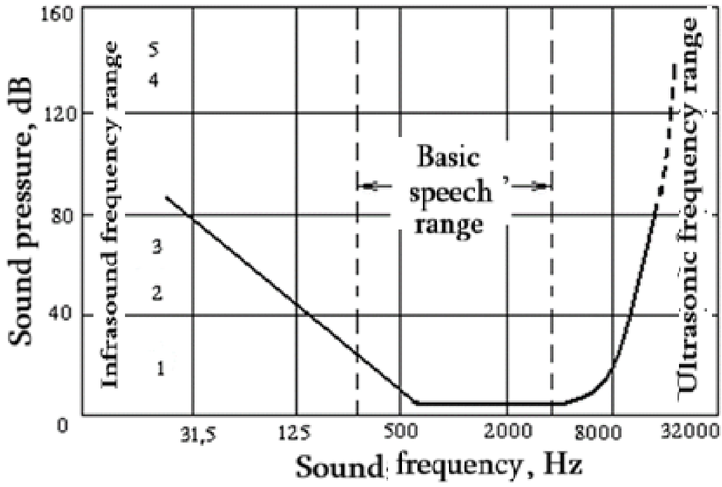

Figure 8.3. Auditory Range (according to Bell):
1-Imperceptible; 2-Range of perceptible tones; 3-Threshold of good perception; 4-Insufficient sensation (discomfort); 5-Threshold of painful sensation

Because of the wide range, it is inconvenient to operate with values expressed in pascals. Therefore, a special unit — the decibel (dB) — is introduced. On the decibel scale, the lower threshold corresponds to 0 dB, while the painful threshold corresponds to 120 dB.

Table 8.2. Logarithmic (Decibel) Scale of Noise Levels

Source of Sound/Noise	**Pressure, dB**
Lower threshold of audibility	0
Whisper at 1 m distance	20
Whisper at 10 cm distance	50
Household noise	40
Quiet conversation at 1 m	50
Applause	60
Acoustic guitar (fingerstyle, 40 cm distance)	70
Acoustic guitar (plectrum, 40 cm distance)	80
Noise in the subway	90
Jet engine operation at 5 m distance	120
Drums and percussion instruments at 3 m	140

The *pitch* and *tonality* of sound vary with frequency. Oscillation frequency determines pitch and also affects the auditory organs. Sounds of equal amplitude are perceived as:

- 300–400 Hz → bass
- 400–800 Hz → baritone
- ≥1000 Hz → tenor

As noted, an *octave* is a frequency range where the upper limit is twice the lower limit. Spectral characterization of sounds means dividing them into octave bands with the following center frequencies: 16, 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16000 Hz. Thus, the entire auditory range consists of 11 octave bands. For safety purposes, the most important frequency range is 31.5–8000 Hz.

ISO 2204 and **ISO 9613** provide internationally recognized frameworks for analyzing the wave nature of sound in occupational environments. ISO 2204 specifies methods for measuring and evaluating noise exposure, emphasizing the physical properties of sound waves such as frequency, amplitude, and propagation. ISO 9613 defines procedures for calculating sound propagation outdoors, including attenuation due to distance, atmospheric absorption, and barriers, which are directly relevant to understanding the behavior of sound waves in workplaces. By linking the discussion of the wave nature of sound to these standards, the monograph ensures that both theoretical explanations and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers against noise hazards.

8.3. The Nature of Industrial Noise

Industrial noise is defined as irregularly varying sounds over time. The classification of industrial noise is based on the following criteria:

By frequency:

- Low-frequency (oscillation frequency < 400 Hz)
- Medium-frequency (oscillation frequency 400–1000 Hz)
- High-frequency (oscillation frequency > 1000 Hz)

By spectral width:

- Broadband — continuous spectrum wider than one octave
- Tonal — spectrum with distinct tones

By temporal characteristics:

- Constant — when the noise background during an 8-hour shift does not vary by more than 5 dB
- Variable — when noise variation during 8 hours exceeds 5 dB

Variable noise may be:

- Pulsating — continuously changing noise level
- Intermittent — noise level suddenly drops to background and rises again to the initial level
- Impulsive — consisting of one or several signals, each lasting no more than 1 second

By origin:

- Mechanical
- Electromagnetic
- Aerodynamic
- Hydrodynamic

Sounds with frequencies between 16 and 16,000 Hz are called audible (acoustic) sounds. As noted earlier, the human ear cannot perceive infra- and ultrasound; however, their effects can be sensed through body tissues.

Harmful effects of noise on the human body:

Noise causes damage to the auditory organs, dizziness, and headaches. Long-term work in noisy environments reduces labor productivity and increases accident rates. Noise often acts in combination with other harmful factors such as vibration and unfavorable meteorological conditions, which intensify its negative impact.

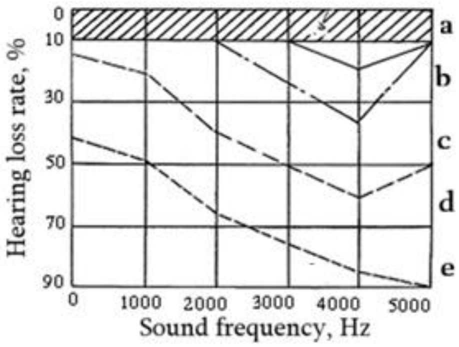

Figure 8.4. Stages of Noise-Induced Hearing Loss:
a — normal hearing; b, c — early stages of hearing loss; d — stage of hearing loss expressed as reduced sensitivity to different frequencies; e — late stage after prolonged exposure

Noise leads to partial or complete hearing loss. In noisy workplaces, hearing impairment develops within 3–5 years. The degree of impairment depends on individual characteristics and overall health. For example, women are more sensitive to noise than men.

Occupational hearing loss is characterized by deterioration in the perception of high tones, particularly at 4000 Hz (Fig. 8.4). An early sign of deafness is poor perception of whispering, which is characterized by high tonality.

Professional deafness is caused not only by high-frequency noise but also by low- and medium-frequency noise of high intensity. Under conditions of intense noise, prolonged work leads to progressive hearing loss (especially in young workers), accompanied by fatigue of the auditory system.

Initially, the human auditory system adapts to noise. This auditory adaptation manifests as temporary hearing loss with rapid and complete recovery after noise ceases. However, under prolonged exposure, the auditory system becomes fatigued, requiring increasingly longer recovery times. This is the main cause of occupational deafness.

ISO 1996 and **ISO 11690** provide internationally recognized frameworks for understanding the nature of industrial noise. ISO 1996 specifies methods for describing, measuring, and assessing environmental noise, including industrial sources, ensuring consistency in evaluation. ISO 11690 defines guidelines for the design of low-noise workplaces, emphasizing noise control strategies such as source reduction, acoustic barriers, and organizational measures. By linking the discussion of industrial noise to these standards, the monograph ensures that both theoretical explanations and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers' health and productivity in noisy industrial environments.

8.4. Causes of Noise Generation

As noted, depending on the source of origin, noise may be mechanical, aerodynamic, hydrodynamic, or electrical. Mechanical noise arises during the operation of technological equipment, machinery, and similar processes. The direct sources of noise in machines include gear transmissions, bearings, static imbalance of rotating and oscillating parts. Rotating and moving components not only generate noise themselves but also transmit it through structurally connected elements.

Table 8.3. Indicative Noise Levels

Noise Source	**Noise Level, dB**
Use of pneumatic equipment	135 and above
Riveting of boiler seams	170
Operation of centrifugal fan	105
Motorcycle without muffler	105
Turbine	105
Boiler nozzle	100
Engine test stand	107-117
Stone crusher	121
Grinding machine	105
Drilling machine	114
Planing machine	97
Lathe	90-96
Forging workshop	98
Turbo-compressor	118
Compressor station	110
Vuvuzela noise	130

Aerodynamic noise is generated by gas flow in air ducts, operation of ventilation and compressor units, jet engines, and also during the release of compressed gas, steam, or air into the atmosphere.

Hydrodynamic noise occurs in pipelines due to stationary and non-stationary processes (hydraulic shock, turbulence of flow, etc.).

Electrical noise is produced during the operation of electrical machines as a result of rotor and stator vibrations caused by alternating electromagnetic forces acting in the air gap between them. The resulting air currents generate noise. Insufficient balancing of the rotor leads to vibration of machine parts and assemblies, which in turn produces noise.

In some enterprises and with certain equipment, indicative noise levels can be assessed using the data in Table 8.3. As shown, the noisiest operations are associated with stone crushers, turbo-compressors, and metal forging and riveting. Additionally, the vuvuzela — widely recognized by the public since the 2010 FIFA World Cup — produces extremely high noise levels.

ISO 11690 and **ISO 15664** provide internationally recognized frameworks for analyzing the causes of noise generation in industrial and occupational settings. ISO 11690 outlines strategies for noise control in workplaces, emphasizing the identification of primary noise sources such as machinery, ventilation systems, and production processes. ISO 15664 specifies guidelines for noise emission assessment of equipment, ensuring that causes of noise are systematically measured and documented. By linking the discussion of noise generation causes to these standards, the monograph ensures that both theoretical explanations and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in diagnosing and mitigating workplace noise hazards.

8.5. Regulation of Industrial Noise

The components of a sound level meter include a microphone, amplifier, corrective filters, detector, integrator (in the case of an integrating sound level meter), and indicator. The general design of the sound level meter is selected so that its properties approximate those of the human ear. Since ear sensitivity depends on both the frequency and intensity of noise, sound level meters use several sets of filters that perceive different intensities of noise. These filters allow simulation of the ear's amplitude-frequency characteristics (AFR) for a given noise power. The filters are designated as A, B, C, and D:

- Filter A perceives noise up to 55 dB.
- Filter B is used in the range of 55–85 dB.
- Filter C is applied when noise exceeds 85 dB.
- Filter D is designed for evaluating aviation noise.

Integrating sound level meters also have linear averaging functions and measure equivalent noise levels, sound exposure levels, various types of noise doses, etc.

The hygienic basis of noise regulation is the physiological response of the human body to its effects. Regulation is based on limiting sound pressure intensity within octave bands, depending on the nature of noise and the specifics of work.

At the workplace, constant noise is characterized by sound pressure level in decibels for the following geometric mean frequencies: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. It is determined by the formula

$$L = 20\log\frac{P}{P_o} \tag{8.2}$$

where P — root mean square sound pressure, Pa; P_o — reference root means square sound pressure, Pa.

Noise regulation is carried out by two methods:

1. The first method sets permissible threshold values for nine octave bands when noise levels by octave bands are known (Table 8.4).
2. The second method is used for random noise regulation when the spectrum is unknown. In this case, the regulating parameter is the equivalent level of broadband constant noise, which has the same effect on humans as real continuous noise, measured using the A filter.

Table 8.4. Permissible Noise Levels by Nine Octave Bands

Workplace	Noise Level (Method II), dB	Threshold noise pressure level according to octave bands, dB								
		31,5	63	125	250	500	1000	2000	4000	8000
Scientific, educational	50	86	71	61	54	49	45	42	40	38
Industrial site	80	107	95	87	82	78	75	73	71	69

When regulating noise characteristics, it is permissible to expand the frequency range. For indicative evaluation, constant noise may be characterized by the sound level in decibels, determined by the sound level meter scale and calculated by the formula

$$L_A = 20\ell og\frac{P_A}{P_o} \tag{8.3}$$

where: P_A — root mean square sound pressure, corrected according to the A filter scale.

According to requirements, acoustic calculations must be performed at workplaces to determine octave sound pressure levels L using the following formulas:

For direct sound

$$L = L_b + \ell og X \Phi S \tag{8.4}$$

For reflected sound

$$L = L_b - 10\ell og B + 10\ell og \Psi + G \tag{8.5}$$

where: L_b — octave level of sound power of the noise source, dB; X — coefficient accounting for the influence of the new acoustic field, depending on the distance r from the acoustic center of the source to the calculation point K, m; Φ — dimensionless value; for sources radiating sound uniformly, $\Phi = 1$; ΦS — imaginary area of correct geometric shape surrounded by the noise source, m²; Ψ — coefficient accounting for disturbance of sound diffusivity in a building, m²; B — building constant, defined as $B = B_{1000}.\mu$; B_{1000} — building constant corresponding to the geometric mean frequency of 1000 Hz, depending on building volume V and type; μ — frequency coefficient.

ISO 1996 and **ISO 11690** provide internationally recognized frameworks for the regulation of industrial noise. ISO 1996 specifies methods for measuring and assessing environmental and industrial noise, ensuring that regulatory limits are applied consistently across workplaces. ISO 11690 defines guidelines for noise control strategies, including engineering solutions, administrative measures, and workplace design, to reduce exposure and comply with legal requirements. By linking the discussion of industrial noise regulation to these standards, the monograph ensures that both theoretical principles and practical enforcement mechanisms are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in protecting workers' health and ensuring compliance with occupational safety regulations.

8.6. Regulation of Ultrasound

Ultrasound regulation is carried out separately. At workplaces, regulation of air vibrations caused by sound pressure is based on sound pressure levels. The permissible values are specified in the standards according to ultrasonic frequency bands. For greater reliability of protection, regulation begins not at 16 kHz (the lowest frequency octave band of the ultrasonic range), but at 11–12 kHz.

The permissible level is determined under the condition that an 8-hour workday ensures a high level of safety and practically eliminates the risk of occupational disease among workers and employees. Table 8.5 presents the permissible sound pressure levels in ultrasonic frequency bands for an 8-hour workday.

Table 8.5. Permissible Sound Pressure Levels in Ultrasonic Frequency Bands

Geometric Mean Frequency, kHz	Sound Pressure Level, dB
12,5	75
16	85
20 and above	110

Periodic monitoring of ultrasound levels in the workplace must be conducted once per year. In addition, unscheduled monitoring must be performed whenever equipment is repaired or replaced. Noise level measurements should be taken at the worker's main position, in the space 5 cm from the ears. During such measurements, the instrument scale must be set to fast, and readings should be taken from the C scale.

Reduction of ultrasonic radiation intensity or its harmful effects in workplaces can be achieved by:

1. Lowering the operating frequencies of ultrasonic sources and eliminating parasitic emissions in equipment.
2. Using soundproof casings, shields, and screens.
3. Providing worker training and rationally combining working and resting conditions.

ISO 5349 and **ISO 1683** provide internationally recognized frameworks for the regulation of ultrasound and high-frequency vibration in occupational environments. ISO 5349 specifies methods for measuring and evaluating human exposure to hand-transmitted vibration, including ultrasonic frequencies, ensuring that risks to health are systematically assessed. ISO 1683 defines reference values for sound pressure levels and acoustic signals, establishing standardized approaches for evaluating ultrasound emissions in workplaces. By linking the discussion of ultrasound regulation to these standards, the monograph ensures that both theoretical explanations and practical safety measures are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in protecting workers from the potential hazards of ultrasonic exposure.

8.7. Prevention of Industrial Noise

Proven methods of noise prevention include reducing noise at the point of generation and along its transmission path. The following measures are recommended:

- Replacing noisy processes with quieter alternatives.
- Substituting metallic parts in machinery with materials that generate less noise.
- Installing mufflers on aggregates that produce noise.
- Enclosing individual machines or components in sound-absorbing casings.
- Constructing soundproof or sound-absorbing partitions along the direction of noise propagation.
- Placing all noisy equipment in a single room and isolating it from other areas with green belts.
- Automating technological processes and implementing remote control.

Periodic medical examinations and protection of workers' health are also of great importance. If a worker is found to have deteriorated health, they must be reassigned to tasks not characterized by high noise levels.

Most of the above methods are based on the absorption of acoustic energy by construction materials. When a sound wave encounters a wall, it loses a significant portion of its energy due to the vibration of air in the pores of the material. Part of the sound energy is converted into thermal energy, part is reflected, and a small portion passes through the wall, producing significantly weakened waves on the other side.

The magnitude of reflection, absorption, and transmission depends on the frequency of oscillation, the angle of incidence of the sound wave, and the physical properties of the wall material. These properties are characterized by specific coefficients:

Coefficient of sound absorption

$$\alpha = \frac{E_{abs}}{E} \tag{8.6}$$

Coefficient of sound reflection

$$\beta = \frac{E_{ref}}{E} \tag{8.7}$$

Coefficient of sound transmission

$$\tau = \frac{E_{trans}}{E} \tag{8.8}$$

where: E_{abs} — absorbed sound energy, J; E — incident sound energy on the wall, J; E_{ref} — reflected sound energy, J; E_{trans}— transmitted sound energy through the wall, J.

The sum of all coefficients equals unity

$\alpha + \beta + \tau = 1.$

The choice of material for sound-absorbing partitions depends greatly on the frequency of sound. For low-frequency sounds, finishing panels are preferable. Their use is more effective when the frequency of the sound wave coincides with the natural frequency of the panels.

For high-frequency sounds, porous and soft materials are more effective. In this case, resonance phenomena occur, accompanied by maximum absorption of sound energy.

Noise Reduction and Protective Measures

In the calculation point located within the zone of reflected sound, the maximum reduction of sound pressure is determined by the formula

$$\Delta L = 10 \cdot \lg \frac{B_1 \Psi}{B \Psi_1} \quad (8.9)$$

where: B_1 — building constant after installation of partitions, m²; B — building constant, m²; Ψ , Ψ_1 — coefficients defined according to standard norms.

One of the most effective methods of reducing noise within industrial buildings is sound insulation, which involves enclosing noisy aggregates in casings. These casings are made of metal or plastic and lined with sound-absorbing materials. With their use, broadband noise can be reduced by up to 20 dB, while in specific spectral regions the threshold level in octave bands can be reduced by 25–30 dB.

When noise reduction to permissible normative levels is not possible, personal protective equipment must be used. Such equipment includes earplugs, earmuffs, helmets, and pads made of various materials.

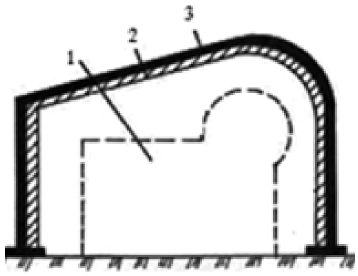

Fig. 8.5. Soundproof Shield:
1 - Noise source; 2 - Sound-absorbing clothing; 3 - Steel plate casing

Requirements for personal protective equipment include:

- Reduction of noise to permissible normative levels
- Ensuring speech perception
- Ensuring perception of warning signals
- Compliance with hygienic requirements

According to standard requirements, all work zones where noise levels exceed 85 dB must be marked with warning signs. During industrial design, sanitary-protective green zones must be established.

The distance from the noise source to residential areas, protected by green zones, is calculated based on permissible sound power levels. The radiation of the noise source is determined by the formula

$$L_{sg} = L_d + 15 \cdot \log \tau - 10 \cdot \log \phi + \beta_{at} \cdot \tau_{1000} + 10 \cdot \log \beta_{at} \quad (8.10)$$

where: L_d — permissible noise level in residential zones, dB; τ — permissible distance from noise source to residential area, m; ϕ — directional factor of the noise source; β_{at} — spatial angle of noise radiation.

Industrial facilities with noise levels exceeding normative limits must be located so that prevailing wind directions carry emissions away from residential areas, not toward them.

ISO 11690 and **ISO 15664** provide internationally recognized frameworks for the prevention of industrial noise. ISO 11690 establishes guidelines for noise control strategies in workplaces, emphasizing preventive measures such as source reduction, acoustic insulation, and optimized workplace design. ISO 15664 specifies procedures for assessing noise emission from machinery, enabling preventive planning by identifying and mitigating noise at its origin. By linking the discussion of industrial noise prevention to these standards, the monograph ensures that both theoretical approaches and practical solutions are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in creating healthier and safer work environments.

8.8. Industrial Vibration

Vibration is the oscillatory motion of machine parts, technological equipment, and devices, caused by dynamic imbalance of rotating components. When a person comes into contact with vibrating parts, individual body parts or the entire body begin to oscillate. Mechanical vibration spreads rapidly throughout the body from the point of contact.

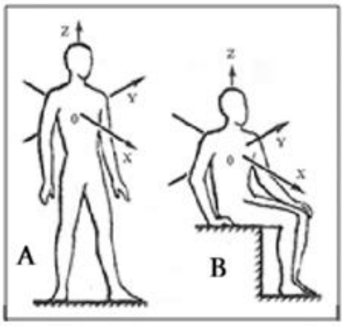

Fig. 8.6. Illustration of Whole-Body Vibration Effects

Depending on the transmission path, vibration affecting the human body may be classified as whole-body or local.

- **Whole-body vibration occurs when:**

1. It is transmitted to a standing person through the feet, affecting the entire body.
2. It is transmitted to a seated person, affecting the entire body.

Whole-body vibration is particularly dangerous when the head is directly involved.

- **Local vibration** is transmitted through the hands. For seated individuals, vibration transmitted only through the feet, without direct impact on the spine, is also considered local.

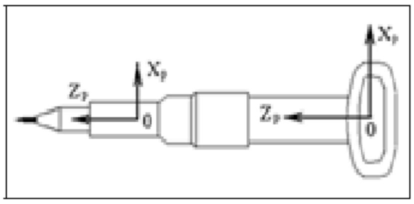

Fig. 8.7. Axes of Vibration Transmission During Local Vibration at Tool Grip Points

As shown in Fig. 8.6, the directions of whole-body vibration propagation are along the X, Y, and Z axes:

- OX axis — from the back toward the chest (for both standing and seated persons).

- OY axis — from the right side toward the left shoulder.
- OZ axis — from the feet toward the head.

Whole-body vibration affects workers operating excavators, bulldozers, various mining machines and complexes, stone crushers, mills, vibration compactors, woodworking and processing equipment, drilling machines, etc.

Local vibration affects workers using pneumatic or electrically powered tools of impact or rotary type, and similar devices (Fig. 8.7). In this case, the axes are directed into the worker's hands from the grip points of the tool, as illustrated by the jackhammer.

By temporal characteristics, vibration is classified as:

- Constant vibration — when a control parameter does not vary by more than a factor of 2.
- Variable vibration — when the parameter increases by a greater magnitude.

ISO 2631 and **ISO 5349** provide internationally recognized frameworks for industrial vibration. ISO 2631 specifies methods for evaluating human exposure to whole-body vibration, including criteria for health risk assessment and comfort levels in workplaces. ISO 5349 defines procedures for measuring and assessing hand-transmitted vibration, ensuring that risks from tools and machinery are systematically evaluated. By linking the discussion of industrial vibration to these standards, the monograph ensures that both theoretical explanations and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in protecting workers from vibration hazards.

8.9. Effects of Vibration on the Human Body

The impact of vibration on the human body, depending on its frequency and amplitude, may be both positive and negative. Short-term exposure to low-intensity vibration can have beneficial effects: it strengthens muscles and reduces fatigue. In certain medical conditions, vibration is even used therapeutically, for example, to improve blood circulation.

However, prolonged exposure causes significant harm. Neurotrophic and geometric disorders develop in the body, and the skin becomes sensitive and painful to vibration and temperature fluctuations.

Long-term work with pneumatic and electrically powered tools can lead to loss of sensation in the fingers and hands. After work, pain may be felt in the wrist, and sometimes deformities occur in the wrist, elbow, and shoulder joints, impairing support and motor functions.

The severity of vibration disease depends on vibration intensity, duration of exposure, the point of transmission to the body, and the direction of wave propagation within the body. In its early stages, vibration disease responds well to treatment if exposure ceases. Severe forms require prolonged therapy and complete isolation from vibration. Neglect may result in partial or total loss of work capacity.

General symptoms include: rapid fatigue, headaches, dizziness, abdominal and chest pain, and insomnia.

The human body is conditionally considered a vibratory system, since vibration causes relative displacement of body parts depending on the source of oscillation and the mass of organs. Relative displacement leads to joint strain and heavy loading.

Prolonged exposure to oscillations with frequency $f =$ 3-5 Hz adversely affects the vestibular apparatus and cardiovascular system, causing motion sickness syndrome. Oscillations with $f =$ 5-11 Hz negatively affect the head, stomach, intestines, and other organs. At $f =$ 11-45 Hz, nausea, vomiting, impaired vision, and disruption of normal organ function occur. Frequencies above 45 Hz damage cerebral blood vessels, impair circulation and higher nervous activity, leading to the development of vibration disease.

The human body, considered as a viscoelastic mechanical system, has its own natural frequencies and pronounced resonance properties. Resonance frequency ranges of different body parts are as follows:

- Head: 2–27 Hz;
- Neck: 6–27 Hz;
- Chest: 2–12 Hz;
- Legs and arms: 2–8 Hz;
- Lumbar spine: 4–14 Hz;
- Abdomen: 4–12 Hz.

ISO 2631 and **ISO 5349** provide internationally recognized frameworks for assessing the effects of vibration on the human body. ISO 2631 establishes criteria for evaluating whole-body vibration, including thresholds for discomfort, fatigue, and long-term health risks such as musculoskeletal disorders. ISO 5349 specifies methods for assessing hand-arm vibration exposure, identifying risks such as vascular and neurological damage. By linking the discussion of vibration effects on the human body to these standards, the monograph ensures that both theoretical perspectives and practical health assessments are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers' health against vibration hazards.

8.10. Regulation of Industrial Vibration

Regulation of vibration is carried out according to special documents — sanitary norms and rules. Regulation is based on the type of vibration (whole-body or local) and its direction (vertical or horizontal) within octave bands. Regulation also applies to infrasonic oscillations up to 16 Hz (8, 4, 2, 1 Hz), which are not perceived by the human ear but are sensed by the body.

In octave bands, the regulatory parameters are:

- Root mean square vibration velocity (m/s);
- Logarithmic level of vibration velocity (dB).

Table 8.6. Hygienic Norms for Whole-Body Vibration

N	Frequencies, Hz	Values (Root Mean Square Vibration Velocity ×100, 10^{-2} m/s / Logarithmic Level, dB)
1	Transport-induced vibration	Vertical vibration along OZ axis (see Fig. 8.7); Horizontal vibration along OX and OY axes
2	Transport-technological vibration	Along all three axes
3	Technological vibration	I — in industrial premises; II — in warehouses and similar premises; III — in educational institutions and similar premises

Detailed values are presented in the original table, showing permissible vibration velocities and levels for octave bands at 1, 2, 4, 8, 16, 31.5, and 63 Hz.

Explanation of Table 8.6:

1. The first column refers to transport-induced whole-body vibration:
- Row I show vertical vibration along the OZ axis.
- Row II shows horizontal vibration along the OX and OY axes.
2. The second column refers to transport-technological vibration along all three axes.
3. The third column refers to technological vibration along all three axes:
- Row I — vibration in industrial premises.
- Row II — vibration in warehouses and similar premises.
- Row III — vibration in educational institutions and similar premises.

When establishing hygienic norms, it is assumed that vibration affects the worker's body only during an 8-hour work shift. Compliance with these norms ensures that vibration disease will not develop throughout the entire working career.

Hygienic norms for local vibration not caused by hand-held tools are presented in Table 8.7.

Table 8.7. Hygienic Norms for Local Vibration

N	Frequencies (Hz)	Values (Root Mean Square Vibration Velocity ×100, 10^{-2} m/s / Logarithmic Level, dB)
1	8	5.0 / 120
2	16	5.0 / 120
3	31.5	3.5 / 117
4	63	2.5 / 114
5	125	1.8 / 111
6	250	1.3 / 108
7	500	0.9 / 105
8	1000	0.65 / 102

Explanation of Table 8.7:

The first column presents values for both axes of direction.

For hand-held machines, the regulated parameters of local vibration are:

1. Root mean square vibration velocity (m/s) and logarithmic level of vibration velocity (dB) in octave bands, similar to whole-body vibration, but starting from 8 Hz.

2. Grip force on the tool, which must not exceed 200 N.

3. Weight of the tool or its part held in the worker's hand, which must not exceed 100 N (equivalent to 9.8 kg).

Additionally, the thermal conductivity of the tool's surface at grip points is regulated. The material must have a thermal conductivity coefficient of 0.5 W/(m·°C) or less.

Table 8.8. Hygienic Norms for Local Vibration in Hand-Held Machines

Octave Band Center Frequency, Hz	**Lower Limit, Hz**	**Upper Limit, Hz**	**Permissible Vibration Velocity, 10^{-2} m/s**	**Permissible Level, dB**
8	5.6	11.2	5.00	120
16	11.2	22.4	5.00	120
31.5	22.4	25	3.50	117
63	45	90	2.50	114
125	90	180	1.80	111
250	180	355	1.20	108
500	355	710	0.90	105
1000	710	1400	0.63	102
2000	1400	2800	0.45	99

Explanation of Table 8.8:

As seen from the fourth column (10^{-2} m/s), the values presented are 100 times magnified root mean square vibration velocities.

ISO 2631 and **ISO 5349** provide internationally recognized frameworks for the regulation of industrial vibration. ISO 2631 specifies criteria for evaluating whole-body vibration, including exposure limits, measurement techniques, and health risk thresholds, ensuring that workplace environments comply with international safety standards. ISO 5349 defines procedures for assessing hand-arm vibration exposure, establishing regulatory benchmarks to prevent long-term health effects such as vascular and neurological disorders. By linking the discussion of industrial vibration regulation to these standards, the monograph ensures that both theoretical principles and practical enforcement mechanisms are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in protecting workers' health and ensuring compliance with occupational safety regulations.

8.11. Measurement and Prevention of Vibration

The rules for vibration measurement, the nomenclature of measuring instruments, and methods and means of protection against vibration are regulated by sanitary norms. The instrument used for vibration measurement is called a vibrometer. Vibrometers can measure both whole-body and local vibration.

Modern vibrometers are digital and may be combined with other devices such as sound level meters, thermometers, anemometers, etc. Instruments designed solely for vibration measurement may provide data in terms of acceleration (m/s²), velocity (m/s), or displacement (mm) within octave bands.

Fig. 8.8A. Digital instrument Octave 1018 for measuring whole-body and local vibration. Fig. 8.10B. Modern instrument TV-110, manufactured by TIMEGroup, designed for high-precision measurement of periodic rotational and translational vibrations.

Fig. 8.10. Digital vibration measuring devices:
A - Octave 1018; B – TV − 110

Means of protection against vibration are divided into collective (vibration isolation, vibration absorption) and individual means. The main requirement for protecting humans from vibration is the creation of safe zones or working conditions where vibration does not affect the body.

Creation of vibration-safe working conditions includes:

- Use of vibration-safe machines.
- Architectural and technological design of industrial buildings and processes to ensure compliance with hygienic norms at workplaces.
- Organizational and technical measures aimed at maintaining and improving the technical condition of machinery.
- Use of additional dampers integrated into machine structures.
- Passive or active vibration isolation (using additional energy sources), dynamic vibration suppression.
- Use of metallic, polymeric, fibrous, pneumatic, or electromagnetic damping.
- Application of individual damping or vibration isolation for the operator's hands, feet, and body.

This list represents only part of the technical measures used to protect humans from vibration disease. These must be combined with organizational-technical and medical-preventive measures.

Organizational-technical measures include:

- Periodic inspection of machinery according to normative documentation, with vibration parameters checked at least once per year for whole-body vibration and at least twice per year for local vibration.
- Inspection of vibration characteristics after acquisition of new machines or after scheduled repairs.
- Control and enforcement of rules and conditions for machine operation.

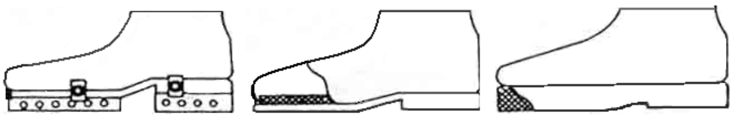

Fig. 8.9. Special vibration-damping and vibration-isolating footwear

Medical and Preventive Measures

Among medical-preventive measures, periodic medical examinations of workers engaged in vibration-related tasks are essential. These examinations must be conducted at least once per year.

When designing vibration-safe machines, methods are applied to reduce vibration parameters at the point of generation. For vibration-hazardous machines, technological processes are designed to reduce vibration along its transmission path.

During the design of technological processes, industrial buildings, and structures, measures must be implemented that can be considered collective means of protection against vibration or prerequisites for their installation. These measures include:

1. Performing calculations to determine expected vibration levels at workplaces.
2. Identifying workplaces with increased vibration.
3. Selecting machines with low vibration characteristics.
4. Developing layouts of machinery to minimize vibration levels at workplaces.
5. Choosing foundations or casings for machinery that ensure compliance with hygienic vibration norms at workplaces.

Protective Measures:

Engineering: mufflers, soundproof partitions, vibration-resistant supports.

Administrative: management of working hours, hearing tests, marking of safe zones.

Individual: earplugs, earmuffs, anti-vibration gloves, footwear, chest protectors, knee pads, belts, suits.

ISO 2631 and **ISO 5349** provide internationally recognized frameworks for the measurement and prevention of vibration in occupational environments. ISO 2631 specifies methods for evaluating whole-body vibration, including measurement techniques, exposure limits, and preventive strategies to reduce health risks. ISO 5349 defines procedures for assessing hand-arm vibration, establishing preventive measures such as tool design improvements, exposure time reduction, and protective equipment. By linking the discussion of vibration measurement and prevention to these standards, the monograph ensures that both theoretical approaches and practical solutions are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers' health and preventing vibration-related disorders.

9. Electrical safety

9.1. Guide for the Ninth Section

Theoretical integration

The impact of electric current on human tissues includes thermal, electrolytic, mechanical, and biological effects. These effects form the basis for the classification of electrical injuries and the methods of prevention.

Integration with standards

ISO 45001 – Occupational health and safety management system.

IEC 60364 – Safety requirements for electrical installations.

IEC 60479 – Effects of electric current on humans and animals.

WHO recommendations – International practices for health protection.

ISO 45001, **IEC 60364**, and **IEC 60479**, together with **WHO** recommendations, provide internationally recognized frameworks for electrical safety. ISO 45001 ensures that occupational health and safety management systems incorporate preventive measures against electrical hazards. IEC 60364 defines safety requirements for electrical installations, guaranteeing that design and operation meet global standards. IEC 60479 specifies the physiological effects of electric current on humans and animals, forming the scientific basis for injury classification. WHO recommendations reinforce health protection practices, ensuring that electrical safety is harmonized with international public health guidelines. By linking the guide for the ninth section to these standards, the monograph situates its theoretical and pedagogical integration within a globally validated framework.

9.2. Effect of Electric Current on Living Tissues

Electric current flowing through the human body produces **thermal, electrolytic, mechanical, and biological** effects. Consequently, the passage of current causes changes in the physical–chemical processes characteristic of both living and non-living matter.

Short note — This corresponds to **IEC 60479 standard**, which defines the effects of electric current on the human body.

- **Thermal effect:** Current causes heating of blood vessels, nerves, the heart, brain, and other organs to high temperatures, leading to functional disorders or burns. Lymphatic fluid and blood may become intensely heated.
- **Electrolytic effect:** Current leads to decomposition of blood and other organic fluids (ion formation), significantly disturbing their physical–chemical composition.
- **Mechanical effect:** Current can tear and rupture tissues (skin, muscles, vessel walls, etc.), producing damage similar to electrodynamic shock or sudden explosive effects.
- **Biological effect:** Current excites and irritates living tissues, disrupting internal bioelectrical processes directly linked to vital functions. In living tissues (including the heart muscle and nervous system), bio-potentials are constantly generated. External current interferes with these small bio-currents, suppressing their normal activity, causing specific disorders, and often leading to death.

The multifaceted action of electric current on the human body results in various **electrical injuries**, which can be divided into two groups:

- **Local electrical injuries;**
- **Electrical shock.**

These two types often occur together but differ significantly in their effects, so they are considered separately.

Statistical data:

- Local electrical injuries — 20% of total cases;
- Electrical shock — 25%;
- Mixed injuries — 55%.

IEC 60479 provides the internationally recognized framework for defining the effects of electric current on living tissues. It specifies thresholds and physiological responses to thermal, electrolytic, mechanical, and biological impacts, ensuring that the classification of electrical injuries is scientifically validated. By linking the discussion of current effects to IEC 60479, the monograph guarantees that theoretical explanations and practical safety measures are internationally comparable and methodologically rigorous.

9.3. Local Electrical Injuries

The following groups of local electrical injuries are distinguished: **electrical burns; electrical marks; skin metallization; mechanical damage; and electro-ophthalmia.**

Short note — Regarding local electrical injuries, **ISO 45001** requires preventive measures, including the use of protective clothing.

a) Electrical burns

Electrical burns are the most common type of electrical injury. **63% of injured persons** present burns, and among them, **23% also have other injuries** such as electrical marks, metallization, or ophthalmia. Burns may be **contact burns** or **arc burns**.

- **Contact burns** occur through direct contact with conductive parts.
- **Arc burns** are caused by the action of an electrical arc.

Contact burns usually occur in electrical installations with relatively low voltage (up to 2 kV). At higher voltages, electrical arcs or sparks appear, producing corresponding burns. Contact burns are typically burns of the skin. Only in rare cases, when large current passes through the body, can subcutaneous tissues be damaged. Severe internal tissue damage is also possible under the influence of high-frequency current.

Contact burns are mainly **first- and second-degree** (skin redness and blister formation under the skin). At voltages above 380 V, more severe burns occur: **third- and fourth-degree**, meaning tissue charring and carbonization.

Arc burns occur in installations of various voltages. In systems up to 6 kV, they are usually caused by short circuits. At higher voltages, arcs can arise when approaching conductive parts at inadmissible distances; when insulating devices (rods, voltage indicators, etc.) are damaged, leading to contact with conductive parts; or during operations on switching equipment. In all these cases, powerful arcs are generated, causing severe burns and large currents (up to tens of amperes) to pass through the body. Such injuries are extremely severe and usually fatal.

An electrical arc can cause deep burns over large areas of the body, carbonization, and sometimes complete incineration. Death in such cases occurs due to respiratory paralysis or extensive burns over a large portion of the body.

b) Electrical marks

Electrical marks on the skin appear as distinct **gray or light-yellow spots**. They usually have a circular or oval shape, 1–5 mm in size, with a depression in the center. They may also appear as subcutaneous scratches, small wounds, warts, or bruises.

The damaged skin area hardens like a callus; its upper layer dies, becoming dry, without accompanying inflammatory processes.

Typically, electrical marks are painless, and their treatment ends without complications — over time, the upper skin layer peels off and is replaced by normal skin with usual color, elasticity, and sensitivity. Electrical marks are observed in about **10% of persons injured by electric current.** In most cases, it is accompanied by arc burns, which are far more severe than metallization.

In the case of direct current, skin metallization may occur through **electrolysis**, involving prolonged and close contact with conductive parts. Here, metal particles penetrate the skin via electric current, which simultaneously decomposes organic fluids in tissues and produces basic and acidic ions. The metal reacts with acidic ions to form salts, giving the skin a specific coloration. For example:

- Green — copper ions under the skin
- Blue-green — zinc ions
- Grayish-yellow — lead ions

This form of metallization disappears completely after treatment.

d) Mechanical damage

Mechanical damage results from sharp involuntary convulsive contractions of muscles caused by current passing through the body. This may tear skin, tendons, and blood vessels, and can also cause dislocations and fractures.

Mechanical injuries occur in electrical installations up to 1000 V under prolonged current exposure. These injuries are severe, require serious treatment, and are rare — found in about **1% of injured persons.** They always accompany electrical shock and sometimes occur together with contact burns.

e) Electro-ophthalmia

It is known that an electrical arc is a strong source of visible, ultraviolet, and infrared radiation. A strong flow of ultraviolet rays damages the eye, causing inflammation of the cornea and conjunctiva. Ultraviolet rays are absorbed by eye cells and trigger chemical reactions.

Infrared rays are also harmful to the eyes, but only at close distances or with prolonged exposure.

Electro-ophthalmia develops **4–8 hours after irradiation.** Its symptoms include: eye redness, inflammation, tearing, purulent discharge, eyelid spasms, and partial loss of vision. The injured person experiences headache and severe eye pain, which intensifies in sunlight (so-called photophobia). In severe cases, corneal transparency is impaired and the pupil narrows.

Typically, the disease lasts several days. Corneal damage requires more complex and prolonged treatment.

Electro-ophthalmia is observed in about 3% of persons injured by electric current. Its prevention is the use of protective goggles, which shield the eyes from ultraviolet and infrared rays as well as from tiny molten metal particles.

ISO 45001 establishes preventive measures for occupational health and safety, requiring protective clothing, safe work practices, and hazard control to minimize local electrical injuries. **IEC 60479** complements this by defining the physiological mechanisms behind burns, metallization, and electro-ophthalmia, ensuring that injury prevention strategies are scientifically grounded. By linking the discussion of local electrical injuries to these standards, the monograph reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers against localized electrical hazards.

9.4. Electrical Shock

Short note — Regarding electrical shock, WHO emphasizes the importance of first aid, which must be integrated into workplace instructions.

Electrical shock is the excitation of living tissues caused by the passage of current through the human body, manifested by involuntary convulsive contractions of muscles. During this process, the normal functioning of the heart, lungs, and nervous system is disrupted.

- The weakest electrical shock produces slight convulsive contractions at the points of current entry and exit.
- In more severe cases, it causes disturbances in the functioning of the heart and lungs, sometimes their complete cessation, leading to death. External injuries may not always be visible.

It should be noted that industrial frequency current (50–60 Hz) passing through the body is the most dangerous. At higher frequencies, current spreads over the skin surface, causing severe burns but not electrical shock.

It must be remembered that the human body is harmed not by voltage itself, but by the current flowing through it. The passage of 100 milliamperes (0.1 A) through the body is incompatible with life. According to Ohm's Law, the corresponding voltage can be calculated

$$U = I \cdot R \tag{9.1}$$

where: U — voltage across the body, V; I — current, A; here $I = 100\ mA = 0.1\ A$; R — average electrical resistance of the human body, Ω, here R=1000 Ω.

Substituting values into formula (9.1)

$$U = 0.1 \cdot 1000 = 100\ V$$

Thus, the passage of **100 V** through the human body is fatal.

Even electrical shocks that do not cause immediate death can lead to serious changes in the body, which may manifest later. Possible conditions include arrhythmia, angina pectoris, hypertension, neurosis, endocrine disorders, etc. Victims often experience distraction, weakened memory, and reduced attention. Even without visible symptoms, electrical shock lowers the body's resistance to diseases, especially cardiovascular and nervous disorders.

Electrical shock is received by **80% of persons injured by electric current**. Among them, the majority (**55%**) also suffer local electrical injuries, primarily burns.

Electrical shock is considered a major hazard for the victim. **85–87% of fatal cases** are caused by electrical shock. In **60–62% of cases**, injuries are mixed, but death is mainly due to electrical shock.

a) Fatal cases

Death is the complete cessation of the body's interaction with the external environment: loss of physiological processes (thinking, breathing, heartbeat) and absence of reaction to external stimuli. In other words, death is the irreversible cessation of metabolism accompanied by protein decomposition.

Death has two main stages: **clinical** and **biological**.

Clinical death

Clinical death is a short transitional state between life and death, beginning with the cessation of heart and lung function.

During clinical death, vital signs are absent: no breathing, no heartbeat, no reaction to painful stimuli, pupils are markedly dilated and unresponsive to light. Since tissues are not yet decomposed and remain alive, the organism continues to exist for a short time. Organ functions gradually fade; at the initial moment, metabolism still proceeds slowly, allowing the possibility of survival.

Due to lack of oxygen, brain cells (neurons) die first, leading to loss of consciousness and thought. Even then, restarting the heart and saving the person is sometimes possible, though survivors may remain psychologically impaired.

The duration of clinical death is defined as the time from cessation of heart and lung function until death of the cerebral cortex cells. For most people, this period is 4–6 minutes; in healthy individuals accidentally injured by current, it may last 7–8 minutes. In sick individuals with heart or lung disease, clinical death may last only a few seconds. Theoretically, survival is still possible.

Biological (true) death

Biological death is an irreversible event characterized by cessation of biological processes in cells and tissues and decomposition of protein structures. It occurs immediately after the period of clinical death ends.

In cases of electrical injury, causes of biological death may include cessation of heart function, cessation of breathing, electrical shock, or their combination.

Cessation of heart function is especially dangerous, as restoring life is far more difficult compared to cessation of breathing or shock.

The effect of current on the heart muscle may be:

- **Direct**, if current flows through the heart.
- **Reflexive**, if current passes through other parts of the body and affects the heart via the central nervous system.

In both cases, the heart may stop or undergo fibrillation. In electrical injuries, fibrillation occurs more often than complete stoppage.

b) Heart fibrillation

Heart fibrillation is the chaotic, unequal contractions of the heart muscle fibers (fibrils), preventing the heart from pumping blood into vessels.

Normally, the heart works rhythmically: it fills with blood, contracts, and ejects blood into arteries. This rhythm is ensured by muscle relaxation followed by simultaneous contraction of all fibrils. Each nerve impulse corresponds to one contraction, maintaining rhythm.

When an additional stimulus is applied, the heart responds with an irregular contraction. Fibrillation is the collective irregular and arrhythmic contraction of fibrils caused by electric impulses.

During fibrillation, breathing continues for **2–3 minutes.** The person may still speak a few words. However, as time passes, the condition worsens: fibrillation persists, the heart no longer functions as a pump, circulation is disrupted, oxygen starvation develops, breathing ceases, and clinical death occurs.

c) Electrical shock (in the strict sense)

Electrical shock is a severe neuro-reflex reaction of the body to excessive irritation by electric current, accompanied by disturbances in circulation, respiration, metabolism, and other functions.

Shock begins with a brief **excitation phase**, when the victim reacts to stimuli, feels pain, and blood pressure rises. This is followed by the **inhibition phase**, with nervous system exhaustion: blood pressure falls, pulse accelerates, breathing becomes rare, depression develops, and complete insensitivity to the environment occurs, though consciousness remains.

Shock may last from fractions of a second to a full day. Afterwards, the person may die due to cessation of vital functions, or recover through active medical treatment.

IEC 60479 provides the internationally recognized framework for defining the physiological effects of electrical shock on humans and animals. It specifies current thresholds, exposure durations, and resulting health outcomes, ensuring that the classification of electrical shock is scientifically validated. **ISO 45001** complements this by requiring preventive measures within occupational health and safety management systems, including protective equipment, safe work practices, and emergency response planning. By linking the discussion of electrical shock to these standards, the monograph ensures that both theoretical explanations and practical safety measures are internationally comparable and methodologically rigorous. This connection highlights the importance of standardized approaches in safeguarding workers against the severe risks of electrical shock.

9.5. Electrical Resistance of the Human Body

The human body conducts electric current, but its conductivity differs from that of ordinary conductors due to the specific **physical, biochemical, and biophysical processes** characteristic of living matter. As a result, the electrical resistance of the human body is a **variable quantity**, nonlinearly dependent on many factors, including the condition of the skin, parameters of the electrical network, physiological factors, and environmental conditions.

Living tissues do not contain free electrons, so they cannot behave like metallic conductors, where current is the orderly movement of free electrons.

Human tissues contain water (about **65% of body mass**). Therefore, in living tissue, charge transfer occurs not through free electrons (as in metals) but through **ions**, similar to electrolytes. Consequently, when current passes through living tissue, all fluids within it undergo chemical decomposition.

Living tissue also exhibits **cellular–hole conductivity**, characteristic of semiconductors, where charge transfer occurs via electrons and holes. Thus, the human body can be considered a special conductor with **variable resistance** and properties of both a semiconductor and an electrolyte.

Different tissues of the human body have different electrical resistance. For alternating current at **50 Hz frequency**, the resistance of dry skin ranges between **40,000–100,000 Ω.** The resistance of the skin, and therefore the whole body, decreases sharply when the corneal layer is damaged, when the skin is moist, heavily perspiring, or dirty.

Damage to the corneal layer (cuts, scratches, microtraumas) reduces body resistance to the level of inner tissues (**500–700 Ω**), increasing the risk of injury.

Moisture also significantly reduces skin resistance. Wetting the hands with saline water decreases resistance by **30–50%**, while distilled water reduces it by **15–35%.**

Sweating and skin contamination can be compared to wetting with saline water, also reducing resistance. Conductive contamination with metallic or carbon dust reduces resistance especially sharply.

The numerical value of human electrical resistance depends greatly on factors such as the location of electrode contact, current magnitude, applied voltage, type and frequency of current, electrode area, duration of current exposure, and other conditions.

The location of electrode contact is important because skin resistance varies across the body: the corneal layer is not of uniform thickness everywhere, sweat glands are unevenly distributed, and blood vessels supply different areas differently. The lowest resistance is found in the **skin of the face and neck, wrist, upper side of the hand, armpits**, etc.

Electrode area directly affects human electrical resistance — increasing the area decreases resistance. However, with increasing current frequency to **10–20 kHz and above**, electrode area practically loses significance.

An increase in current magnitude causes **heating and irritation of the skin**. This, in turn, reflexively triggers a rapid response from the brain — dilation of skin blood vessels, increased blood supply, enhanced sweating, and reduction of electrical resistance in those areas.

An increase in voltage sharply reduces electrical resistance. In this case, **Ohm's Law is violated** — the reduction is much greater than the formula (9.1) would suggest. According to studies conducted in the United States at the beginning of the 20th century on persons executed by the electric chair:

- At a few volts, human resistance was about **40 kΩ**
- At **110 V**, resistance dropped to **10 kΩ**
- At **2000 V**, resistance was only **200 Ω**

The **International Electrotechnical Commission (IEC)** recommends the values shown in **Table 9.1** (frequency 50 Hz, circuit hand–feet).

Table 9.1. Dependence of human resistance on voltage

Voltage, V	**25**	**50**	**250**	**> 250**
Resistance, Ω	2500	2000	1000	650

In our country, it is accepted that the **average electrical resistance of the human body** for practical calculations is **1000 Ω at voltages above 50 V.**

Influence of current type:

Experiments show that human body resistance is greater under **direct current (DC)** than under **alternating current (AC).**

Influence of current duration:

The duration of current flow is a very important parameter for resistance variability. Experiments show that under small voltages (20–30 V) applied for **1–2 minutes**, resistance decreases by **10–40%**, on average **25%.**

At high voltages and correspondingly large currents, resistance decreases very rapidly. For example, measurements in the United States on the electric chair showed that at **1600 V**, resistance was **800 Ω.** After **50 seconds**, this value decreased to **516 Ω.**

Other influencing factors

- **Sex and age:** Women generally have lower resistance than men; children lower than adolescents; young people lower than middle-aged adults. This is explained by thinner, more delicate skin in some individuals compared to thicker, rougher skin in others.
- **Physical irritation:** Pricking, striking, light rays, sound, and other sudden stimuli reduce body resistance by **20–30%.**
- **Partial oxygen pressure:** Human resistance varies proportionally with oxygen partial pressure. In closed spaces with lower oxygen levels, the danger of electrical injury is greater than in open air, since resistance is lower.
- **Ambient temperature:** Raising the temperature by **30–40°C** reduces resistance even if exposure is brief (a few minutes) and without excessive sweating. One reason may be dilation of skin blood vessels due to increased blood supply, which is the body's reflex response to thermal influence.

IEC 60479 provides the internationally recognized framework for defining the electrical resistance of the human body. It specifies resistance values under different conditions, including dry and wet skin, contact area, and current pathways, ensuring that risk assessments are scientifically validated. **ISO 45001** complements this by requiring occupational health and safety management systems to account for variations in human resistance when designing preventive measures and protective equipment. By linking the discussion of electrical resistance to these standards, the monograph ensures that both theoretical explanations and practical safety strategies are internationally comparable and methodologically rigorous. This connection highlights the importance of standardized approaches in safeguarding workers against electrical hazards.

9.6. Influence of Current Magnitude on Injury Outcome

The main damaging factor for humans, as noted, is the **magnitude of current flowing through the body**. The greater the current, the stronger its negative effects.

Safe currents, when flowing for long periods (several hours), do not cause complications and are even used in medicine. Their magnitude is:

- **50–75 μA** for alternating current at 50 Hz;
- **100–125 μA** for direct current.

Perception current

For alternating current at 50 Hz, perception begins at **0.6 mA**; for direct current, at **5 mA**. This produces mild sensations: tingling or itching for AC, and skin heating for DC.

Table 9.2. Probability of perception depending on current magnitude

Probability of perception, %	**99.9**	**50**	**10**	**5**	**1**	**0.1**
Threshold perception current, mA	1.50	1.10	0.90	0.85	0.70	0.60

As seen, only **1 in 1000** people perceives 0.60 mA, while **999 out of 1000** perceive 1.50 mA. These thresholds apply only when current paths are hand–hand or hand–feet; in other cases, values differ.

Perception current does not injure humans. It is considered safe, though prolonged exposure can affect health: victims may lose confidence, make mistakes, and create risks for themselves and colleagues working with conductive parts.

Holding and fibrillating currents

Currents are also classified as **holding currents** and **fibrillating currents**.

- Direct current is not classically holding: instead of gripping, it causes severe pain when releasing a conductor, so the person does not let go voluntarily.
- Heart fibrillation requires significantly higher DC magnitudes compared to AC.

Table 9.3. Effects of current magnitude on the human body

Current magnitude (mA)	**AC at 50 Hz**	**DC**
0.6-1.5	Beginning of sensation, mild tingling	Not perceived
2-4	Involuntary hand movement	Not perceived
5-7	Pain and cramps in hand muscles, slight pain in arm	Beginning of sensation, skin heating at electrode contact
8-10	Strong pain throughout hand, possible release from electrode	Heating sensation increases
10-15	Unbearable pain, release impossible (holding current)	Heating felt beyond electrode contact
20-25	Instant paralysis of hands, breathing difficulty, severe pain	Strong internal heating, involuntary muscle movements
25-50	Severe chest pain, extreme breathing difficulty, possible respiratory paralysis or weakened heart	Heating increases, pain and cramps in hand, painful release due to muscle contraction
50-80	Respiratory paralysis within seconds, heart rhythm disturbed, fibrillation possible	Strong heating, chest pain, release impossible due to pain
100	Heart fibrillation in 2–3 s, respiratory paralysis soon after	Respiratory paralysis with prolonged exposure
300	Faster fibrillation and respiratory paralysis	Heart fibrillation in 2–3 s, respiratory paralysis soon after
5000+	Instant respiratory paralysis, heart cannot fibrillate, tissue damage after several seconds	Same effect

Threshold holding current

The threshold magnitude of holding current varies among individuals. Conventionally, the values in Table 9.4 are accepted.

Table 9.4. Threshold holding current for AC at 50 Hz

Probability of holding effect, %	**99.9**	**50**	**10**	**5**	**1**	**0.1**
Threshold holding current, mA	24.6	14.9	10.9	9.8	7.7	5.3

For men, women, and children, the threshold holding current decreases in that order.

IEC 60479 provides the internationally recognized framework for defining the influence of current magnitude on injury outcomes. It specifies threshold values for different current intensities, exposure durations, and pathways through the human body, ensuring that the severity of injuries is scientifically classified. **ISO 45001** complements this by requiring preventive measures within occupational health and safety management systems, including risk assessment and control strategies to minimize exposure to dangerous current levels. By linking the discussion of current magnitude and injury outcomes to these standards, the monograph ensures that both theoretical explanations and practical safety measures are internationally validated and comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers against electrical hazards.

9.7. Influence of Current Duration on Injury Outcome

Analysis of accidents and observations on animals show that the severity of injury increases with the duration of current flow. This is explained by two main factors:

1. Human body resistance decreases over time.
2. The probability increases that current will coincide with the most vulnerable phase of the cardiac cycle (see Fig. 9.1).

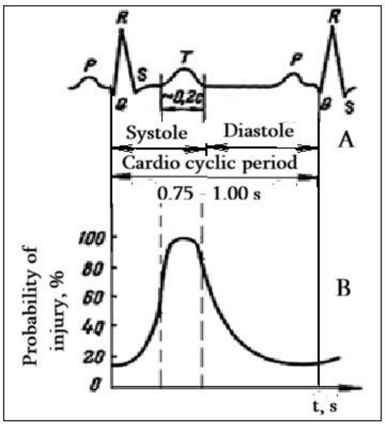

Fig. 9.1. Coincidence of current passage through the heart with the T phase of the cardiac cycle:
A - Electrocardiogram of a healthy person;
B - General character of danger from electrical injury

The harmful effects of prolonged current exposure include:

- Disturbance of central nervous system function
- Changes in blood composition
- Tissue damage due to heating
- Disruption of heart and lung function

As exposure time increases, these negative factors accumulate, and their combined effect on the body intensifies.

On the electrocardiogram:

- **P phase** corresponds to atrial contraction, when relaxed ventricles fill with blood.
- **QRS peak** corresponds to ventricular contraction, ejecting blood into the aorta.
- **T phase** is the period when ventricular contraction ends and relaxation begins.

It has been established that the heart's sensitivity to electric current varies across phases. The heart is most vulnerable during the **T phase**, which lasts about **0.2 seconds**. If current passes through the heart exactly during the **T phase**, the fibrillating current threshold is much lower than the values given in Table 9.3.

Experiments on animals revealed:

- Industrial-frequency current up to **10 A** for **0.2 seconds** usually does not cause fibrillation if coinciding with the **P or QRS phases**.
- The same current coinciding with the **T phase** causes death even at much lower magnitudes **(0.6–0.7 A)** during the same time.
- If current exposure coincides with the entire cardiac cycle **(0.75–1 second)**, the danger increases, since it inevitably overlaps with the **T phase**.

IEC 60479 provides the internationally recognized framework for defining the influence of current flow duration on injury outcomes. It specifies exposure time thresholds that determine the severity of physiological effects, including fibrillation, burns, and nervous system disruption. **ISO 45001** complements this by requiring occupational health and safety management systems to incorporate time-based risk assessments, ensuring that preventive measures account for both current magnitude and duration. By linking the discussion of current flow duration to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers against electrical hazards.

9.8. Influence of Current Path on Injury Outcome

Practice and experiments show that the **path of current through the human body** largely determines the severity of injury. If vital organs such as the **heart, lungs, or brain** lie along the current path, the danger increases because the current acts directly on them. If current flows in other directions, vital organs are affected indirectly — reflexively — and the danger is relatively reduced.

There are various current paths in the human body. In practice, about **15 directions** are observed, also called **current loops** (see Fig. 9.2).

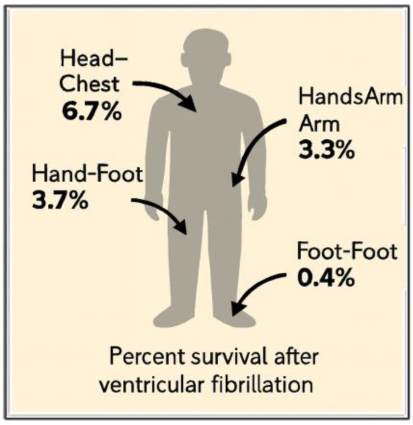

Fig. 9.2. Current paths (loops) in the human body

The most common paths are:

- Right hand–feet;
- Left hand–feet;
- Hand–hand;
- Foot–foot.

The danger of each path is reflected in the severity of injury, mainly determined by the amount of current passing through the heart. Statistical data show:

- In accidents where victims lost consciousness for 3 or more days, **87%** occurred with the right hand–feet path.
- Left hand–feet — **80%**
- Hand–hand — **83%**
- Foot–foot — **15%**

Thus, the most dangerous loop is **right hand–feet**, where **6.7%** of the total body current flows through the heart. For other loops:

- Left hand–feet — **3.7%**
- Hand–hand — **3.3%**
- Foot–foot — **0.4%**

The most hazardous loops are considered head–hands and head–feet, where current passes through the brain and spinal cord. Fortunately, these loops are rare. The least dangerous is the foot–foot loop, caused by step voltage, where only negligible current flows through the heart. Experiments on animals confirmed this path as the least dangerous.

However, outcomes can worsen unexpectedly. For example, **step voltage of 80 V** can cause involuntary convulsive contractions of leg muscles, leading to a fall. In such cases, current flows through more dangerous paths, mainly from hands to feet, and the effective voltage is much higher than the original step voltage.

IEC 60479 provides the internationally recognized framework for defining the influence of current path on injury outcomes. It specifies how the route of current through the human body—such as hand-to-hand, hand-to-foot, or head-to-torso pathways—determines the severity of physiological effects, including fibrillation, respiratory arrest, and burns. **ISO 45001** complements this by requiring occupational health and safety management systems to incorporate risk assessments that account for current pathways, ensuring preventive measures such as insulation, protective equipment, and safe installation practices. By linking the discussion of current path influence to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers against electrical hazards.

9.9. Influence of Individual Human Characteristics on Injury Outcome

Healthy and physically strong individuals endure electrical shock more easily than sick or weak persons. Those suffering from cardiovascular, endocrine, pulmonary, or nervous system diseases are especially sensitive to current.

A person's mental state at the moment of injury is as important as their electrical resistance. Individuals with alcoholism, neurasthenia, epilepsy, or tendencies toward hysteria and melancholy may die from currents that are safe for healthy people.

Psychological preparedness for possible electrical injury is also significant. A sudden, unexpected shock is far more dangerous than an anticipated one, even at small magnitudes. Moral condition, attentiveness, concentration, fatigue, and similar factors also play a role.

For these reasons, technical safety regulations require special medical examinations for personnel working with live electrical installations before employment and follow-up checks once or twice a year. This is done not only for their own safety but also for the safety of others. For example, a person with impaired vision may fail to distinguish colored signals, or one with speech difficulties may be unable to give precise commands.

Table 9.5. Permissible current magnitudes in the human body at 50 Hz sinusoidal frequency, depending on duration (τ), resistance (R), and applied voltage (U)

Duration τ, s	**0.2**	**0.5**	**0.7**	**1.0**	**3.0-30.0**	**> 30.0**
Current I, mA	250	100	75	65	6	1
Resistance R, Ω	700	1000	1065	1150	3000	6000
Voltage U, V	175	100	80	75	18	6

Human qualification also greatly influences injury outcomes. In general, inexperienced individuals suffer more severely than trained electricians.

IEC 60479 provides the internationally recognized framework for assessing how individual human characteristics influence injury outcomes from electric current. It specifies how factors such as age, sex, body mass, skin condition, and health status affect resistance values and physiological responses to current exposure. **ISO 45001** complements this by requiring occupational health and safety management systems to account for individual variability in risk assessments, ensuring that protective measures are adapted to diverse worker populations. By linking the discussion of human characteristics to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers with differing physiological profiles against electrical hazards.

9.10. Electrical Safety Standards

Household electrical installations are defined as devices used in residential apartments and all types of public buildings (cinemas, clubs, schools, kindergartens, shops, hospitals, theaters). For these, the current paths considered are hand–hand or hand–feet. International electrical safety standards (IEC 60479-1; IEC 60364-4-41; IEEE Std. 80) define the permissible touch voltage and the maximum allowable current through the human body. These standards emphasize that both the magnitude of current and its duration are critical: even small currents can be dangerous if they act for a long time. Protective grounding, neutralization, and automatic disconnection are required to ensure that accidental short contacts remain harmless.

Short note — International electrical safety standards **IEC 60364-4-41** define the rules for protective grounding, neutralization, and automatic disconnection.

Table 9.6. Maximum permissible touch voltage and current in the human body for household electrical installations

Type of current and frequency	**Maximum permissible values**	
	Touch voltage, V	Current in body, mA
AC, 50 Hz	2	0.3
AC, 400 Hz	3	0.4
DC	8	1.0

At high temperature **(above 30°C)** and humidity **(above 75%)**, these norms are reduced by approximately **three times**.

Table 9.7. Maximum permissible touch voltage (U_{touch}) and body current (I_body) for emergency operation in networks with grounded neutral up to 1000 V, isolated neutral up to 1000 V, and isolated neutral above 1000 V

Duration of current action, s	**0.1**	**0.2**	**0.5**	**0.7**	**1.0**	**1-5**
Permissible touch voltage, V	500	400	200	130	100	65

Touch voltage control is carried out by measuring in places where accidental human contact with the network may occur.

In addition, premises are classified according to the risk of electrical injury, as shown in **Table 9.8:**

- **Safe premises:** dry rooms with wooden floors, no dust emission, normal temperature regime, and no grounded equipment. Examples: residential apartments, educational institutions, cultural facilities.

- **Increased danger premises:** stairwells and workshops with conductive floors, or non-conductive floors containing grounded equipment. In such places, simultaneous contact with grounding and motor housings is possible.
- **Especially dangerous premises:** most industrial workshops, machine-building, chemical and metallurgical plants, mines, quarries, power stations. Outdoor workplaces are considered equivalent to especially dangerous premises.

Table 9.8. Classification of premises according to risk of electrical injury

N	Class of premises	Description
1	Safe	Premises without conditions defined below as increased danger or especially dangerous.
2	Increased danger	Premises with one of the following: 1. High humidity; 2. Conductive dust; 3. Conductive floors (metal, concrete, brick, soil); 4. High temperature; 5. Risk of simultaneous contact with grounded structures and motor housings.
3	Especially dangerous	Premises with one of the following: 1. Extremely high humidity; 2. Chemically active environment; 3. Two or more increased danger conditions simultaneously.

Table 9.9. Classification of premises according to ecological indicators

N	Class of premises	Description
1	Normal	Dry premises without high temperature, dust generation, or chemically active substances.
2	Dry	Relative humidity not exceeding 60%.
3	Humid	Relative humidity between 60–75%.
4	Damp	Relative humidity above 75% most of the time.
5	Especially damp	Relative humidity at or near 100%, with condensation on walls, floors, ceilings, and objects.
6	Hot	Temperature above 30°C most of the time.
7	Dusty	Dust generated by production, settling on surfaces, penetrating machinery and equipment. Dust may be conductive or neutral.
8	Chemically active	Chemically active vapors or deposits released, damaging insulation of conductive parts.

Table 9.10. Classification of electrotechnical equipment according to risk of electrical injury

N	Class	Description
1	0	Must have working insulation; grounding not provided (no grounding element).
2	0I	Must have working insulation and a grounding element; supply cable does not include a grounding conductor.
3	I	Must have at least working insulation and a grounding element.
4	II	Must have double insulation; grounding not provided (no grounding element).

5	III	Equipment without internal or external electrical networks

Notes to Table 9.10:

1. For Class I equipment: if accompanied by a supply cable, it must include a grounding conductor and a properly designed plug.
2. For Class III equipment: devices powered from external sources may belong to Class III if the supply voltage does not exceed 42 V (50 V in no-load conditions). If powered by a transformer, its primary and secondary windings must not be electrically connected, and insulation between them must be double or reinforced.

ISO 45001, **IEC 60364**, **and IEC 60479** together provide the internationally recognized framework for electrical safety standards. ISO 45001 ensures that occupational health and safety management systems integrate preventive measures against electrical hazards. IEC 60364 specifies requirements for electrical installations, guaranteeing that design, construction, and maintenance practices meet global safety benchmarks. IEC 60479 defines the physiological effects of electric current on humans and animals, establishing scientific criteria for injury classification and risk assessment. By linking the discussion of electrical safety standards to these frameworks, the monograph ensures that theoretical principles and practical applications are scientifically validated and internationally comparable. This connection reinforces methodological rigor and highlights the importance of standardized approaches in safeguarding workers and the public against electrical risks.

9.11. Release of a Person from the Action of Electric Current

First aid for persons injured by electric current consists of two stages:

1. **Releasing the victim from the action of current;**
2. **Providing primary medical assistance until the doctor arrives.**

Often, the victim cannot free themselves due to involuntary muscle contractions, paralysis of limbs or other organs, and nervous system damage. Release can be achieved in several ways, the first being **rapid disconnection of the electrical installation.**

Disconnection is performed by switching off the nearest breaker, unscrewing fuses, turning off switches, etc. It must be considered that if the victim is at a height, they may fall when power is cut, or lighting may go out. Therefore, a light source should be available, or emergency lighting should be switched on.

If rapid disconnection is impossible due to distance or inaccessibility, the circuit can be interrupted by cutting the conductor or removing the victim from contact. The method depends on voltage, disconnection conditions, available tools, and especially the rescuer’s qualification. In all cases, the victim must be freed quickly, while ensuring the rescuer does not suffer electric shock.

In networks up to **1000 V**, conductors may sometimes be cut with a dry-handled axe or insulated tool. Non-insulated tools may also be used if the rescuer wears **rubber gloves and shoes.** To avoid short circuits or arc formation, each conductor must be cut separately to prevent burns or eye injury.

The victim may be pulled away by grasping **dry clothing**. Direct contact with the body or grounded objects must be avoided. The rescuer should act with one hand only, keeping the other in a pocket or behind the back.

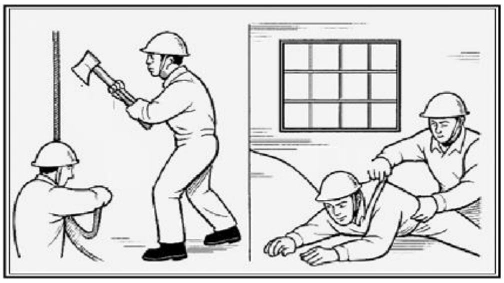

Fig. 9.3. Illustration of releasing a victim from electric voltage: Cutting the conductor with a dry-handled axe; Pulling the victim away by grasping dry clothing

If clothing is wet and contact is unavoidable, the rescuer must wear **dielectric gloves.** If unavailable, hands should be wrapped in dry fabric (jacket, coat, rubber mat). Rubber boots or standing on dry insulating objects are also required.

If the victim grips a conductor due to convulsive contractions, each finger must be pried open separately. The rescuer must wear dielectric gloves, rubber boots, and stand on an insulating platform. Conductors can be pushed away from the victim's body using a dry stick or other non-conductive object.

In high-voltage installations, dielectric gloves and rubber boots are mandatory, and actions must be performed with special **insulating rods and tongs.** Rubber boots protect against step voltage. Automatic disconnection of equipment may be achieved by creating a short circuit or grounding a phase. This is convenient at high voltage, since such installations are equipped with fast-acting relay protection. However, these actions are dangerous and should be used only in extreme cases, e.g., on overhead lines when the victim cannot be quickly freed due to distance.

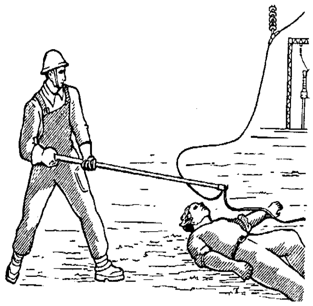

Fig. 9.4. Release of a victim in networks above 1000 V

Short circuiting and grounding on overhead lines can be done by throwing a grounding conductor over them. Preferably, a flexible uninsulated copper wire of sufficient cross-section should be used:

- Up to 1000 V — **16 mm²**
- Above 1000 V — **25 mm²**

Before throwing, one end of the conductor must be securely grounded, and a small weight attached to the other end. Throwing must be done so that the conductor does not touch people, including the victim and rescuer. If the victim is in contact with a single conductor, often grounding only that conductor is sufficient.

IEC 60479 provides the internationally recognized framework for defining safe procedures when releasing a person from electric current. It specifies the physiological risks associated with contact interruption, including muscle contraction and involuntary grip, and outlines methods for minimizing secondary injuries during rescue. **ISO 45001** complements this by requiring occupational health and safety management systems to incorporate emergency response protocols, training, and protective equipment to ensure safe intervention. WHO recommendations further reinforce international practices for health protection, emphasizing immediate medical evaluation and standardized first-aid procedures. By linking the discussion of releasing a person from electric current to these standards, the monograph ensures that both theoretical explanations and practical rescue strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers and rescuers during electrical emergencies.

9.12. Current Flow into the Ground

Current flows into the ground only through a conductor in contact with it. Such contact may be **accidental or intentional.**

A conductor or group of conductors electrically connected to the ground is called a **grounding electrode.**

- A single conductor in contact with the ground is called a **single grounding electrode** or simply an **electrode.**
- A grounding system consisting of several electrodes connected in parallel is called a **group (complex) grounding electrode.**

Causes of current flow into the ground:

- Short circuit of live parts to the grounded housing of electrical equipment;
- Falling of a conductor onto the ground;
- Use of the ground itself as a conductor.

In all these cases, the potential (voltage relative to ground) decreases sharply. This is beneficial for safety, but negative phenomena also occur:

- Potential appears on the grounding electrode, which is connected to metallic parts;
- Potential arises around the point of current flow on the ground surface, which may reach significant values.

The difference in potentials, variability, and resulting danger depend on many factors:

- Magnitude of current flowing into the ground;
- Configuration, size, number, and arrangement of electrodes;
- Specific resistance of the soil.

By adjusting these factors, potential can be reduced to safe levels.

Types of single grounding electrodes

Single electrodes may be of various types: **spherical, rod-shaped, ring-shaped, circular,** etc. Their electrical resistances differ. The most common are **rod electrodes of various cross-sections.**

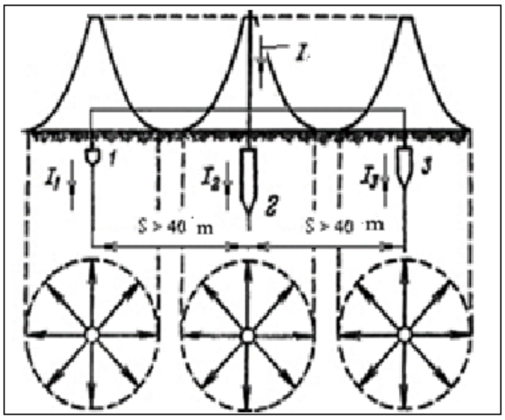

Fig. 9.5. Curves of potential and current dispersion fields of a group grounding device, when the distance between electrodes is greater than 40 m.Group grounding electrodes

It should be noted that the earth's potential at a distance of **20 m from any electrode** is practically equal to zero.

Resistance of grounding electrodes

Current flowing into the ground encounters resistance called **grounding resistance.** It consists of three components:

1. Resistance of the electrode itself
2. Transition resistance between electrode and soil
3. Soil resistance

The first two are negligible compared to soil resistance, so the latter is considered the main factor. If the grounding system is extensive, its resistance must also be taken into account.

Electrical safety requirements demand low resistance of grounding systems. This is achieved by:

- Increasing the geometric dimensions of single electrodes
- Using several electrodes connected in parallel (group grounding)

Group grounding is more economical in terms of metal consumption and other parameters. Moreover, multiple electrodes help **flatten the potential curve** in the area of current flow, which is very important for safety. Therefore, group grounding is commonly used in practice.

- If the distance between electrodes is **greater than 40 m**, each electrode has its own independent potential curve; they do not overlap, and all electrodes share the same potential even if currents differ (see Fig. 9.5).
- If the distance is **less than 40 m**, current fields overlap, potential curves intersect, and a combined potential curve is formed. Since electrodes are interconnected, they share a common potential, called the **group grounding potential** (see Fig. 9.6).

Formulas for calculating resistance and potential of group electrodes differ depending on whether electrodes are identical or of different sizes, and whether their spacing is greater or less than 40 m.

As shown in Fig. 9.6, the combined potential curves in the area of current flow have **lower amplitude** compared to the individual potential curves of single electrodes. Flattening the potential curve — reducing amplitude variation — is crucial for safety.

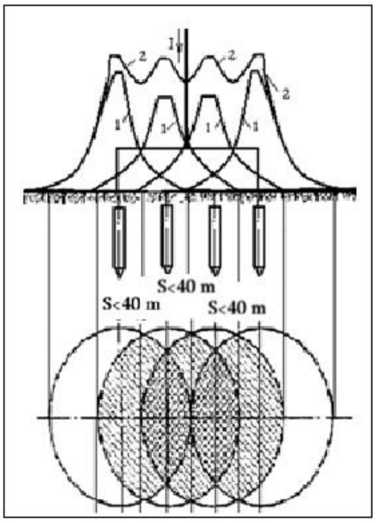

Fig. 9.6. Curves of potential and current dispersion fields of a group grounding device, when the distance between electrodes is less than 40 m: 1-Curves of the individual electrode's own potential; 2-Curves of the total potential

Complex grounding electrodes

In complex grounding systems (square grids, rectangular meshes, etc.), calculation formulas consider grid configuration, electrode shape, number, spacing, and other factors through a **utilization coefficient**, with numerical values taken from special tables.

IEC 60364 provides the internationally recognized framework for electrical installations, including grounding systems that safely direct current flow into the earth. It specifies design principles, protective measures, and testing procedures to ensure that fault currents are effectively discharged, minimizing risks of electric shock and fire. **ISO 45001** complements this by requiring occupational health and safety management systems to incorporate grounding practices into workplace safety protocols. WHO recommendations further reinforce international health protection measures, emphasizing the importance of reliable grounding in reducing electrical hazards. By linking the discussion of current flow into the ground to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers and installations against electrical current.

9.13. Touch Voltage

Touch voltage (U_{touch}) is defined as the voltage between two points of an electrical circuit simultaneously touched by a person. It is calculated by the formula

$$U_{\text{touch}} = I_{\text{body}} \cdot R_{\text{body}} \quad (9.2)$$

where I_{body} — current flowing through the human body via the hand–feet path, A; R_{body} — electrical resistance of the human body, Ω.

In the zone of protective grounding or neutralization, one point touched by a person has the **grounding potential** (φ_g), while the other point (foundation where the person stands) has the **foundation potential** (φ_f). The touch voltage between hand and feet is then

$$U_{\text{touch}} = \varphi_g - \varphi_f \tag{9.3}$$

Or alternatively

$$U_{\text{touch}} = \varphi_g \cdot \alpha_1 \tag{9.4}$$

where α_1 is the **touch coefficient**, which accounts for the shape of the potential curve and is always less than 1.

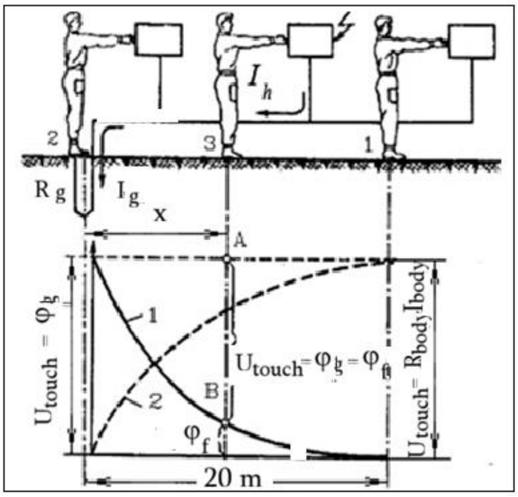

Fig. 9.7. Touch voltage for a single grounding electrode:
1 - potential curve; 2 -touch voltage variation curve depending on distance X

For a single electrode, the casing of equipment near the electrode has the same potential as the electrode (φ_g). The farther a person is from the electrode, the greater the touch voltage, and vice versa. At a distance of **20 m**, touch voltage reaches its maximum and equals the grounding potential ($U_{\text{touch}} = \varphi_g$), with $\alpha_1 = 1$. This is the most dangerous case. When standing directly on the electrode, $U_{\text{touch}} = 0$ and $\alpha_1 = 0$, the safest case. Although the person is under the influence of grounding potential, they are not affected by touch voltage. At distances between 0–20 m, touch voltage increases from 0 to φ_g, while α_1 rises from 0 to 1.

For **group grounding electrodes**, current fields overlap, so the ground potential at any point differs from zero, but:

$$U_{\text{touch}} < 1,\ \alpha_1 < 1.$$

As with single electrodes, touch voltage is zero when a person touches grounded equipment and stands directly on one of the electrodes. Maximum touch voltage occurs at some distance from the electrodes, depending on their shape and arrangement. Touch coefficients are taken from reference tables.

Transitional resistance

Current flowing through the human body also encounters the resistance of the surface on which the person stands (soil, floor, foundation). This is called **transitional resistance**. It is not zero and can sometimes be significant.

Taking transitional resistance into account, touch voltage is calculated as

$$U_{\text{touch}} = \varphi_g \cdot \alpha_1 \cdot \alpha_2 \quad (9.5)$$

where: α_1 — touch coefficient; α_2 — coefficient accounting for voltage drops in transitional resistance.

$$\alpha_2 = \frac{R_{\text{body}}}{R_{\text{body}} + 1.5\rho} \quad (9.6)$$

Here ρ is the **specific electrical resistance of soil**.

IEC 60364 provides the internationally recognized framework for defining safe limits of touch voltage in electrical installations. It specifies protective measures, grounding systems, and insulation requirements to ensure that contact voltages remain below hazardous thresholds. **IEC 60479** complements this by detailing the physiological effects of touch voltage on humans and animals, establishing scientifically validated criteria for risk assessment. **ISO 45001** further reinforces occupational health and safety management systems by requiring preventive strategies, protective equipment, and monitoring practices to minimize exposure to dangerous touch voltages. By linking the discussion of touch voltage to these standards, the monograph ensures that theoretical explanations and practical safety measures are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers and the public against electrical hazards.

9.14. Step Voltage

During the operation of electrical installations, if insulation is damaged or a bare conductor touches the ground, current begins to flow into the soil and spreads radially (see Fig. 9.8). If a person is near the point of current flow into the ground, they may be exposed to **step voltage**.

This occurs because, within the zone of current flow, the points of soil touched simultaneously by a person’s feet have **different potentials**, creating a potential difference between the feet.

The area of soil where significant voltage is observed due to current flow is called the **discharge zone**.

On the ground surface, voltage decreases with distance from the support or short-circuit point. Near the axis, the voltage distribution curve has a steep drop. Current flow is often represented graphically, with voltage values measured in volts or as relative (dimensionless) values. In the latter case, the voltage at a given point is divided by the total voltage at the support or short-circuit location.

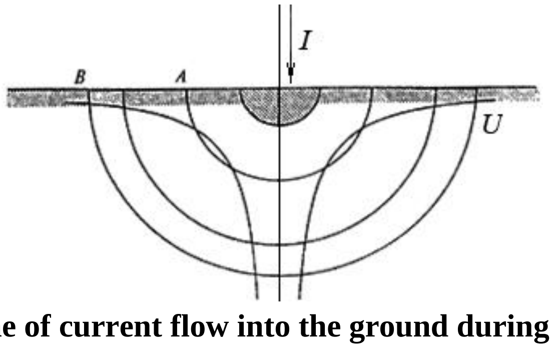

Fig. 9.8. Scheme of current flow into the ground during a short circuit

When current flows into the soil (foundation), an **electric potential field (φ)** is created on the surface. The farther the short-circuit point is, the smaller the potential values. Within the discharge zone, potential is distributed according to a **hyperbolic law**

$$\varphi = \frac{k}{x} \quad (9.7)$$

where k — constant depending on soil resistance and magnitude of short-circuit current; x — distance from the short-circuit point to the point of interest (see Fig. 9.9)

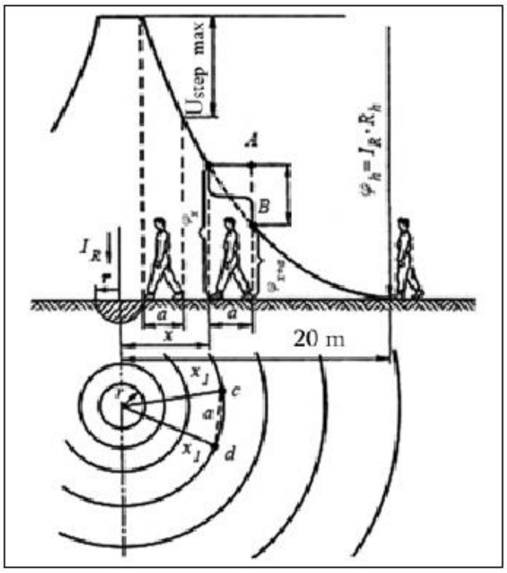

Fig. 9.9. Step voltage in the case of a single grounding electrode

The discharge zone usually extends about **20 m**, beyond which potentials are negligible and can be considered zero.

The potential difference between two points simultaneously touched by a person's feet is called **step voltage**. It is the voltage drop across the human body and is defined as

$$U_{\text{step}} = I_{\text{body}} \cdot R_{\text{body}} \quad (9.8)$$

where U_{step}— step voltage, V; I_{body} — current flowing through the body via the foot–foot path, A; R_{body} — electrical resistance of the human body, Ω.

Near a grounding electrode or bare conductor on the ground, the potential at one foot is higher than at the other. The distance between the feet — the **step** — creates this potential difference, called step voltage.

The most dangerous situation is standing close to the grounding electrode. The farther one moves from the point of current flow, the smaller the step voltage, becoming practically zero at **20 m**. For calculations, the step length is taken as **0.8 m**.

Although the foot–foot path is relatively safer, step voltages above **80 V** cause involuntary convulsive contractions of leg muscles, leading to falls. This increases the applied voltage across the body and thus the danger.

Therefore, it is prohibited to approach a bare conductor lying on the ground within a radius of **4–5 m indoors** and **8–10 m outdoors**.

IEC 60364 provides the internationally recognized framework for defining safe limits of step voltage in electrical installations. It specifies grounding systems, protective measures, and installation practices to ensure that potential differences between two points on the ground remain below hazardous thresholds. **IEC 60479** complements this by detailing the physiological effects of step voltage on humans and animals, establishing scientifically validated criteria for risk assessment. **ISO 45001** further reinforces occupational health and safety management systems by requiring preventive strategies, protective footwear, and monitoring practices to minimize exposure to dangerous step voltages. By linking the discussion of step voltage to these standards, the monograph ensures that theoretical explanations and practical safety measures are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers and the public against electrical hazards.

9.15. Soil Electrical Resistance

Soil is a poor conductor of electricity. Compared to metals such as copper, soil conductivity is **5.7 billion times lower**. However, because the discharge surface is very large, soil offers only minor resistance to current flow.

Soil is a **dispersed porous body** consisting of solid, liquid, and gaseous components.

The electrical resistance of soil is characterized by its **specific resistance** (ρ), defined as the resistance of a cube with 1 m sides. Its unit of measurement is Ω·m.

Variability of soil resistance

Soil specific resistance varies widely — from tens to thousands of Ω·m — depending on many factors:

- Soil moisture;
- Temperature;
- Type of soil;
- Degree of compaction;
- Season of the year.

Dry soil of any composition has very high specific resistance ($\geq (10^4)$Ω·m), meaning it practically does not conduct electricity. Moisture drastically reduces resistance because water dissolves salts in the soil, and salt solutions conduct electricity.

Increasing moisture up to **15–20% (by mass)** sharply reduces resistance. Further increases have less effect. At **70–80% moisture,** resistance slightly increases again due to reduced salt concentration in excess water.

Moist soil behaves like an **electrolyte.** Raising its temperature decreases specific resistance because higher temperature increases dissociation of molecules in water, producing more ions and improving conductivity. This holds until **intensive evaporation** begins, which occurs when large currents heat the soil near grounding electrodes. Dried soil has high resistance.

At 0°C, specific resistance changes abruptly: ice has much higher resistance than water at the same temperature. Ice in soil is not conductive. Further cooling below 0°C increases resistance only gradually.

Influence of soil type

Soil may be clay, loam, sand, sandy loam, black earth, peat, etc. The content of soluble substances (acids, salts, bases) directly affects resistance: the more such substances, the lower the specific resistance .

Dispersion (degree of fragmentation) also matters. Finely dispersed soils have greater pore surface area, stronger sorption forces, more bound water, and therefore higher resistance.

- **Clay soils:** retain water well, are dense, have relatively low resistance, and are good for grounding.
- **Sandy soils:** retain water poorly, have high resistance, and are unsuitable for grounding.

Soil compaction

Compaction directly reduces soil resistance: the denser the soil, the lower its resistance. Therefore, during grounding installation, soil is well compacted, saving metal. Black earth and clay compact well; sand compacts poorly.

Seasonal variation

Due to temperature and atmospheric phenomena, soil specific resistance changes with the seasons. It is considered that soil resistance decreases sharply in **spring and autumn**, when melting snow and rainfall increase moisture. Resistance increases in **winter** (when soil freezes) and in **summer** (when water evaporates). In grounding calculations, this is accounted for by a seasonal coefficient.

Measurement of soil resistance

When designing grounding devices, it is necessary to know the soil resistance at the specific location. Therefore, it must be measured.

For homogeneous soil, specific resistance is measured by **single probing.** A control probe — a rod-shaped electrode 4–5 cm in diameter with a pointed end — is driven vertically into the recommended depth, and resistance is measured at the other end. Then, using a formula, specific resistance is calculated. For greater accuracy, the probe is inserted at **3–4 different points,** and the average resistance is taken to calculate specific resistance. Other measurement methods also exist.

Multilayer soil resistance

In theory, soil is often assumed homogeneous, i.e., having the same specific resistance everywhere. In reality, soil is **multilayered,** with layers differing in composition, structure, porosity, density, temperature, moisture, etc., and therefore in specific resistance. Typically, upper layers have higher resistance than lower ones, though sometimes the opposite occurs.

For simplification, soil is considered as having **two layers** with specific resistances $\rho_1$and ρ_2.

The resistance of a grounding electrode in multilayer soil depends on its geometric dimensions, construction, depth, and the **equivalent specific resistance** of the soil. This is determined using a special test electrode.

For two-layer soil, the equivalent specific resistance is calculated by

$$\rho_{eq} = \frac{l_1 \cdot \rho_1 + l_2 \cdot \rho_2}{l} \tag{9.9}$$

where ρ_{eq} — equivalent specific resistance of two-layer soil, $\Omega\cdot$m; l — total length of electrode, m; l_1, l_2 — lengths of electrode sections in upper and lower layers, m; ρ_1, ρ_2 — specific resistances of upper and lower soil layers, $\Omega\cdot$m

Using values from special tables, the **calculated resistance of various types of grounding electrodes in two-layer soil** can be determined.

IEC 60364 provides the internationally recognized framework for evaluating the electrical resistance of soil in grounding systems. It specifies measurement techniques, acceptable resistance values, and installation practices to ensure that fault currents are safely discharged into the earth. **ISO 45001** complements this by requiring occupational health and safety management systems to incorporate soil resistance assessments into risk management, ensuring that protective measures are adapted to local geological conditions. **WHO** recommendations further reinforce international health protection practices, emphasizing the importance of reliable grounding systems in reducing electrical hazards. By linking the discussion of soil resistance to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers and installations against electrical risks.

9.16. Danger of Electrical Injury in Networks

All cases of electrical injury are determined by factors such as:

- The scheme of human connection to the network;
- The network's own configuration;
- Its voltage and neutral regime;
- The degree of insulation of conductive parts from the ground;
- The capacitance of conductive parts relative to the ground.

Single-phase AC networks

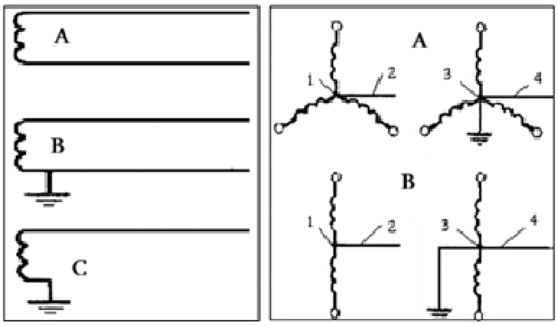

Fig. 9.10. Single-phase networks:
A - Two-wire isolated from ground; B - Two-wire with grounded conductor; C - Single-wire system. Right side: 1 — neutral point; 2 — neutral conductor; 3 — zero point; 4 — zero conductor

Single-phase networks are relatively rare (see Fig. 9.10, left side).
Single-phase networks are mainly used at **low voltages:** 12, 24, 36, and 42 V. Their applications include portable lamps, electrified tools, and similar devices. In such cases, a two-wire network is used.

At higher voltages — 127, 220, 380 V and above — single-phase networks are used for welding transformers, test equipment, and other consumers. Single-wire single-phase networks are also used in **electrified transport.**

Three-phase AC networks

Three-phase networks are widely used. They are classified as **isolated-neutral** or **grounded-neutral** (see Fig. 9.11).

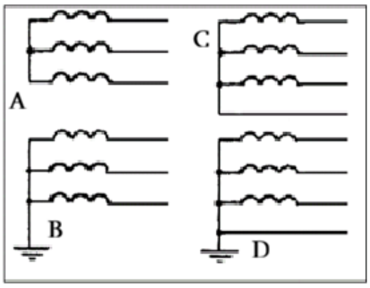

Fig. 9.11. Three-phase network schemes:
A - Three-wire with isolated neutral; B - Three-wire with grounded neutral; C - Four-wire with isolated neutral; D - Four-wire with grounded neutral

The **neutral** is the point with equal voltage in all directions of the winding.

- A grounded neutral point is called the **zero point.**
- The conductor connected to the neutral point is the **neutral conductor.**

Human connection schemes in three-phase networks

There are two main ways a person may connect to a three-phase network:

1. Between two phases (**two-pole contact**);
2. Between one phase and the ground.

Two-pole contact is rarer but more dangerous, because the person is subjected to the **full line voltage,** which is three times the phase voltage. In such cases, isolation from the ground (rubber boots, dielectric mats, etc.) does not protect the person.

In single-phase isolated networks under normal operating conditions, the safer the insulation of conductors relative to the ground, the lower the danger of touching them. However, in emergency conditions (short circuit of a conductor to ground), the higher the insulation resistance, the more dangerous it becomes. When a person touches a conductor, they are subjected to nearly the full voltage regardless of insulation resistance. Thus, the danger is much greater in emergency conditions than in normal operation.

In a **single-phase network with a grounded conductor**, touching the ungrounded conductor exposes a person to the **full voltage**, and the current through the body is maximal. In this case, insulating floors and footwear play an important protective role.

Touching the grounded conductor is generally considered safe, since its voltage relative to earth is negligible. In reality, this is not always true. Under normal conditions, touch voltage is small — about **5% of network voltage**. But during a short circuit between conductors, current rises sharply, and voltage across conductors approaches **100% of network voltage**. Consequently, touch voltage also increases proportionally and may reach dangerous levels.

In a **grounded-neutral three-phase network**, when a person touches a phase conductor (single-pole contact), the circuit is closed as follows:

Human body → footwear → floor → ground → neutral grounding electrode → neutral (see Fig. 9.12 B, C).

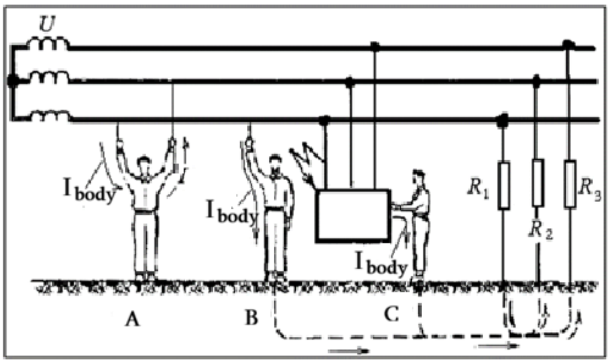

Fig. 9.12. Contact with conductors of a three-phase network:
A - Two-pole contact; B, C - Single-pole contact; R_1, R_2, R_3 — total insulation resistances of conductors relative to ground

The current through the human body is given by

$$I_{\text{body}} = \frac{U_{\varphi}}{R_{\text{body}}+R_{\text{floor}}+R_{\text{shoe}}+r_g} \tag{9.10}$$

where U_{φ} — phase voltage of the network, V; $R_{\text{body}}, R_{\text{floor}}, R_{\text{shoe}}$ — resistances of body, floor, and footwear, Ω; r_g — resistance of neutral grounding, Ω.

The greater the total resistance in formula (9.10), the smaller the current through the body. In this case, body current does not depend on network capacitance or insulation resistance relative to ground, since these are bypassed by the neutral conductor and low-resistance grounding.

In an **isolated-neutral unexpended network**, phase capacitances are so small they can be neglected. If one phase is broken, the circuit closes through the human body and the insulation of the other two phases relative to ground (see Fig. 9.13 D).

Here, phase insulation resistances and body resistance form a star-connected asymmetric load, with the ground as the neutral point. The vector diagram (Fig. 9.13 B) shows that if insulation resistances R_1, R_2, R_3 are symmetrical, the ground potential coincides with the neutral potential. When a person touches one phase, symmetry is broken, and the diagram changes (Fig. 9.13 C).

In this case, body current is

$$I_{\text{body}} = \frac{3U_{\varphi}}{2(R_{\text{body}}+r)} \tag{9.11}$$

where $r = R_1 + R_2 + R_3$.

Thus, in single-phase contact, body current depends on the insulation resistance of the other two phases. As this resistance increases, body current decreases.

Single-pole contact is also dangerous when insulation resistance is high but phases have significant **capacitance relative to ground.**

Capacitance magnitude depends on network construction (cable or overhead) and length. Cable networks and overhead networks above **1000 V** have large capacitance. Increased capacitance significantly raises the danger of injury.

Conclusion

Analysis shows that in single-pole contact, less current flows through the body in **isolated-neutral networks**. However, if a person touches one phase while another phase is shorted to ground, the danger is greater in isolated-neutral networks, because the person is subjected to **line voltage**, not phase voltage.

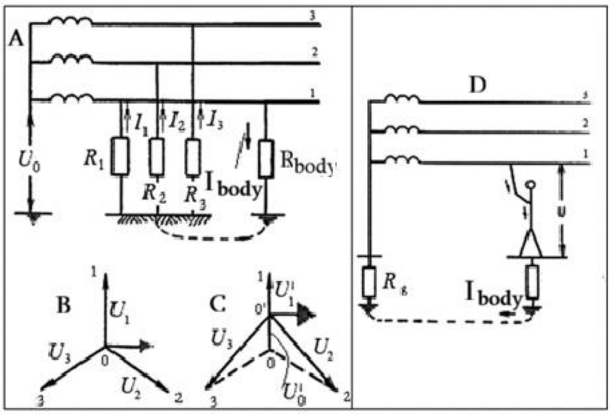

Fig. 9.13. Single-pole contact illustration in three-phase grounded-neutral (a, b, c) and isolated-neutral unexpended (D) networks

IEC 60364 provides the internationally recognized framework for electrical installations, specifying protective measures against network faults that may cause electric injury. It defines grounding, insulation, and circuit protection requirements to ensure that electrical networks operate safely under both normal and fault conditions. **IEC 60479** complements this by detailing the physiological effects of current exposure, establishing scientifically validated thresholds for injury risk. **ISO 45001** further reinforces occupational health and safety management systems by requiring hazard identification, risk assessment, and preventive strategies to minimize dangers in electrical networks. By linking the discussion of electric injury risks in networks to these standards, the monograph ensures that theoretical explanations and practical safety measures are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers and the public against electrical hazards in complex network environments.

9.17. Selection of Network Scheme and Neutral Regime

The choice of network scheme and, accordingly, the neutral regime is determined by **technological requirements** and **safety conditions.**

In our country, for networks up to **1000 V**, two types of schemes are mainly used:

- **Three-wire network with isolated neutral;**
- **Four-wire network with grounded neutral.**

Technological requirements

Preference is given to the **four-wire network**, since it allows the use of two working voltages — **line voltage** and **phase voltage.**

- Power loads can be connected between phase conductors at **380 V line voltage.**
- Lighting devices can be connected between phase and neutral conductors at **220 V phase voltage.**

Safety requirements

Under normal operating conditions, **isolated-neutral networks** are safer. Therefore, in facilities where high insulation levels can be maintained and conductor capacitance relative to ground is negligible, isolated-neutral networks should be used. Examples include relatively short networks without aggressive environments, monitored by specialized personnel (e.g., portable equipment, mining operations).

Grounded-neutral networks are used where insulation control is difficult (due to capacitance, aggressive environments, or long lengths), where insulation damage is hard to detect, or where capacitive currents during ground faults may reach dangerous levels. Examples include large industrial facilities, urban and rural distribution networks.

Networks above 1000 V

For voltages above **1000 V**, the choice of neutral regime is based on both technological and safety considerations. In such networks, **grounded neutral** is preferred, i.e., grounding through low resistance.

This is because in high-voltage networks, conductor capacitance relative to ground is large, so insulation loses its protective role. Contact with conductors is equally dangerous in both isolated-neutral and grounded-neutral networks.

To reduce danger during phase-to-ground faults, standards require **rapid detection of ground faults** in isolated-neutral networks above 1000 V. In facilities with high probability of ground faults, lines are equipped with **protective disconnection devices** that operate when a ground fault occurs.

IEC 60364 provides the internationally recognized framework for selecting network schemes and neutral modes in electrical installations. It specifies protective measures, grounding arrangements, and system configurations (such as TN, TT, and IT systems) to ensure safe operation under both normal and fault conditions. **IEC 60479** complements this by detailing the physiological effects of current exposure, reinforcing the importance of selecting schemes that minimize risks of electric shock. **ISO 45001** further strengthens occupational health and safety management systems by requiring risk assessments and preventive strategies that account for network design and neutral mode selection. By linking the discussion of network schemes and neutral modes to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers and installations against electrical hazards.

9.18. Protective Grounding, Neutralization, and Protective Disconnection

During the operation of electrical installations, due to insulation damage, voltage may appear on their casings and other metallic non-conductive parts. For safety, **protective devices** must be used, including:

- **Protective grounding;**
- **Neutralization;**
- **Protective disconnection.**

Protective grounding

Protective grounding is the **intentional connection of non-conductive parts of electrical equipment to the ground** using grounding conductors and electrodes. Electrodes are metallic rods placed in the soil and must have **low resistance to current flow into the ground.** Natural equivalents of grounding may include river or sea water, coal layers, etc. Protective grounding differs from working grounding and lightning protection.

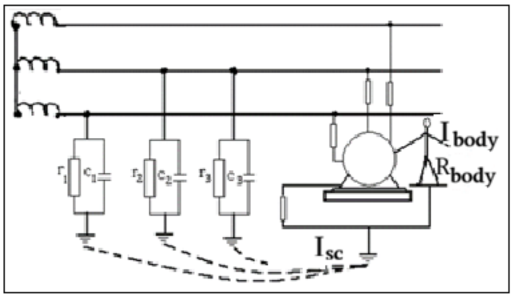

Fig. 9.14. Protective grounding scheme

If voltage appears on metallic parts due to a short circuit or other reasons, protective grounding eliminates the danger of injury by reducing **touch voltage** and **step voltage** to safe values. This is achieved by lowering the potential of the grounding device and equalizing the potentials of the grounded equipment and the foundation where a person stands.

Protective grounding is mainly used in:

- **Isolated-neutral AC networks up to 1000 V;**
- **Grounded-neutral AC networks above 1000 V.**

Without grounding, the casing has **phase voltage relative to earth,** and touching it is as dangerous as touching live parts. Connecting the casing to ground redistributes voltages, giving the casing a potential

$$U_{\text{ground}} = I_{\text{sc}} \cdot r_g$$

where U_{ground} — casing voltage, V; I_{sc} — short-circuit current, A; r_g — grounding resistance, Ω.

The current through the human body is then

$$I_{\text{body}} = \frac{I_{\text{sc}} \cdot r_g}{R_{\text{body}}} \quad (9.12)$$

This formula shows that to reduce body current I_{body}, the **grounding resistance $\boldsymbol{r_g}$** must be minimized, since other parameters cannot be altered.

When a person and the grounding resistance are connected in parallel, the current flowing into the ground divides into two branches: one through the person and the other through the grounding resistance. If the grounding resistance is sufficiently low (as required by standards), only a **safe current** flow through the human body.

Norms for grounding resistance

According to the *Rules for Electrical Installations:*

- In networks up to **1000 V,** protective grounding resistance must satisfy:

$$r_g \leq 4$$

- In installations above **1000 V:**

If short-circuit current $I_{sc} > 500$ A:

$$r_g \leq \frac{250}{I_{sc}} \quad \text{but not exceeding } 10\ \Omega.$$

If $I_{sc} > 500$ A:

$$r_g \leq 0.5\ \Omega.$$

Construction of grounding devices

Grounding devices consist of:

- **Grounding electrodes** placed vertically in the soil;
- **Connecting strips** joining them together.

Electrodes are typically steel pipes, steel angles, or steel rods.

Grounding electrodes may be **natural** or **artificial:**

- **Natural electrodes:** underground metal pipes and structures, building reinforcement, cable sheaths.
- **Prohibited:** pipelines for flammable liquids or gases, sewage pipes, or pipes covered with anti-corrosion insulation.

Typical resistance values:

- Branched water supply networks: ≤ 2 Ω
- Vertical pipelines (artesian wells, shafts): ≤ 1 Ω

If natural grounding resistance meets standards, artificial grounding is not required for installations up to 1000 V.

Grounding design and calculation

Protective grounding consists of:

- A group of electrodes;
- Connecting strips;
- A grounding bus connected in parallel to equipment casings via conductors (see Fig. 9.15).

Artificial electrodes typically use:

- Steel angles (40×40 to 60×60 mm);
- Steel pipes (diameter ≥ 35 mm);
- Steel strips (cross-section ≥ 100 mm²);
- Vertical electrodes length: 2.5–3.0 m.

Strip steel is used to connect vertical electrodes or as independent horizontal electrodes. Minimum dimensions: 4×12 mm. Steel rods must have diameter ≥ 6 mm.

Calculation procedure

Design calculations must determine:

- Grounding device resistance;
- Soil specific resistance;
- Type and arrangement of electrodes;
- Number of vertical electrodes and length of connecting strips.

The total grounding resistance must not exceed the permissible standard. Exact resistance is measured after installation; if insufficient, additional vertical electrodes are added.

Factors affecting grounding resistance

Grounding resistance depends on:

1. **Soil properties and condition** at the location of electrodes
2. **Type of elements** used for electrodes and their depth of burial
3. **Number and arrangement** of grounding elements

If an electrical installation has **no protective grounding**, then under insulation failure, touching metallic parts is equivalent to touching a phase conductor. If protective grounding is installed, the potentials of soil and metallic parts are equalized, reducing the voltage difference between them. Thus, touching grounded metallic parts results in a **safe current** for human health and life.

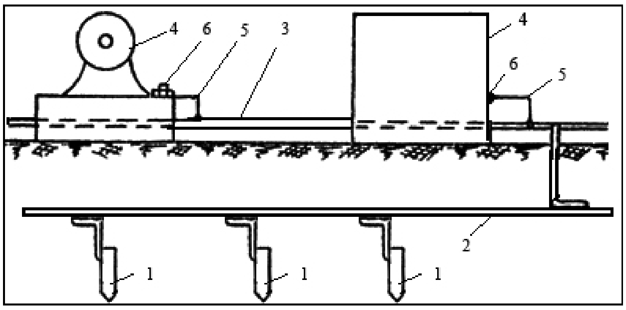

Fig. 9.15. Grounding arrangement:
1-Electrodes; 2-Strip steel; 3-Grounding bus; 4-Equipment casings;
5-Connecting conductors; 6-Bolted or welded joints

When a phase fault occurs, the casing voltage is

$$U_g = I_f \cdot r_g \tag{9.13}$$

where U_g— casing voltage, V; I_f — fault current, A; r_g — grounding resistance, Ω.

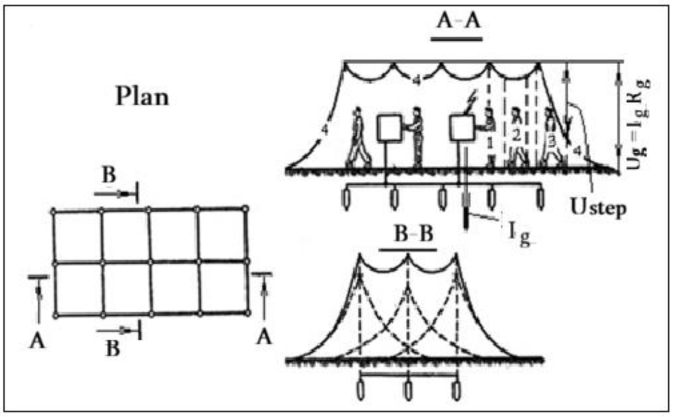

Fig. 9.16. Contour grounding device:
1-Touch voltage = 0 (step voltage also 0, feet together); 2-Step voltage = 0 (potentials equal at foot positions); 3-Step voltage maximum (potential difference between feet greatest); 4-Combined potential curves; I_f- Current flowing into soil; U_s - Step voltage

The touch voltage experienced by a person is:

$$U_{\text{touch}} = \alpha \cdot U_g \tag{9.14}$$

where α is the **touch coefficient**, varying with distance from the grounding point, ranging between 0 and 1.

Thus, body current can be expressed as

$$I_{\text{body}} = \frac{U_{\text{touch}}}{R_{\text{body}}} = \frac{\alpha \cdot U_g}{R_{\text{body}}} \tag{9.15}$$

This shows that touch voltage and body current can be significantly reduced by using **low-resistance grounding** and minimizing the touch coefficient.

Types of protective grounding layouts

- **Remote grounding**: electrodes are installed at some distance from the installation.
- **Contour grounding**: electrodes are interconnected in a closed loop around the installation.

Calculation procedure for protective grounding (up to 1000 V)

Grounding device design must follow these steps:

1. Determine permissible grounding resistance r_g, considering operating voltage, neutral regime, and other factors.
2. Determine soil specific resistance at the site, considering climatic zone.
3. Select grounding type and preliminarily arrange electrodes on the plan.
4. Calculate the number of vertical electrodes and length of connecting strips.

This sequence is illustrated in **Fig. 9.17 and Fig. 9.18**:

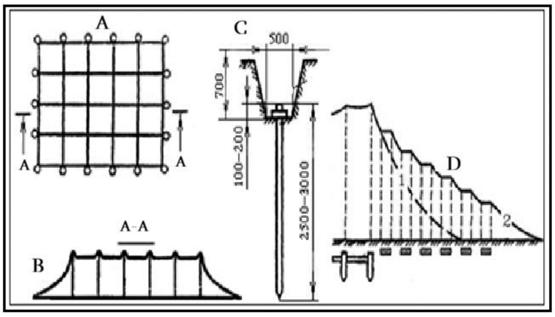

Fig. 9.17. Calculation of grounding devices:
A-Vertical electrodes; B-Potential equalization curve inside the contour; C-Potential variation outside the contour: 1 — without equalization; 2 — with equalization; D-Layout scheme of vertical electrodes

Normative values of grounding resistance

According to sanitary design standards, the maximum **permissible grounding resistance** is:

- **2, 4, and 8 Ω** for three-phase sources at **660 V, 380 V, and 220 V** respectively;
- For single-phase sources at **380 V, 220 V, and 127 V** respectively;
- In grounded-neutral installations below **1000 V**, resistance must not exceed **0.5 Ω**;
- In isolated-neutral installations below **1000 V**:
- **≤ 10 Ω** for capacities under 100 kVA
- **≤ 40 Ω** for all other cases

Limitation of protective grounding in grounded-neutral networks

In grounded-neutral networks below 1000 V, protective grounding is **ineffective,** because during a single-phase ground fault, the short-circuit current is insufficient to activate protective devices (fuses, automatic breakers). Thus, automatic disconnection of the damaged section is not ensured.

In such installations, when a short circuit occurs on the casing, the ground fault current is

$$I_{sc} = \frac{U}{R_0 + r_g} \tag{9.16}$$

where U — phase voltage, V; R_0 — resistance of neutral grounding, Ω; r_g — resistance of protective grounding, Ω.

If this current flows for a long time, the potential on the grounded casing is

$$U_g = I_f \cdot r_g \tag{9.17}$$

When $r_g = R_0$, casing potential equals **half the phase voltage**. If $r_g > R_0$, casing potential is even higher. Thus, in such networks, protective grounding cannot reliably protect against electrical injury.

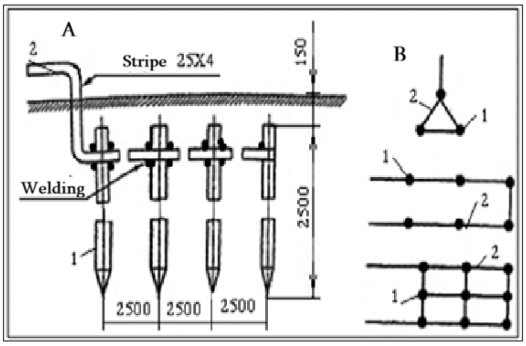

Fig. 9.18. Grounding device calculation:
A-Contour grounding arrangement; B-Variants of horizontal steel strip arrangement:
1 — Vertical electrodes; 2 — Steel strips

Neutralization (Protective Neutral Connection)

Neutralization is the **intentional connection of metallic casings of electrical installations to a repeatedly grounded neutral protective conductor**. It is used in **grounded-neutral networks up to 1000 V** and ensures **automatic disconnection of the damaged section** and reliable protection of personnel.

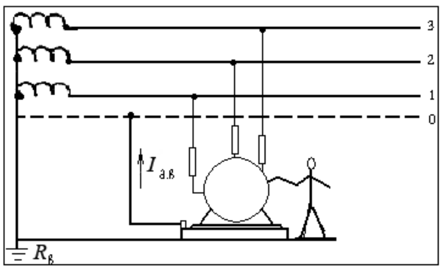

Fig. 9.19. Neutralization scheme

When voltage appears on the neutralized casing due to insulation failure, it is transformed into an **artificial short circuit**, activating maximum current protection and disconnecting the damaged section (see Fig. 9.19).

The cross-section of the neutral conductor must be chosen so that, wherever the neutral conductor contacts live parts, the short-circuit current is at least:

- **2.5 times** the rated current of the nearest fuse
- **1.5 times** the operating current of the automatic breaker

In this case, the neutral conductor's full conductivity must be at least **50% of the phase conductor's conductivity**.

Simplified calculation of short-circuit current

The short-circuit current is calculated by the simplified formula:

$$I_{sc} = \frac{U_\varphi}{R_\varphi + r_0} \quad (9.18)$$

where U_φ — phase voltage of the network, V; R_φ, r_0 — resistances of phase and neutral conductors, Ω.

If the short-circuit current does not meet the required conditions, protective devices will not operate, and a person touching the casing of the installation will be exposed to dangerous voltage.

Restrictions on neutralization

In grounded-neutral networks, **neutralization must not be used**, because under insulation failure the fault current may be insufficient to melt a fuse or trip a breaker.

In installations where operating conditions may cause **breakage of the neutral conductor** (e.g., overhead lines, construction site power supply), repeated grounding of the neutral conductor is required. Its purpose is to reduce voltage on casings of equipment that may otherwise be left unprotected.

During operation, the integrity of neutral, working, and repeated grounding conductors must be checked.

To reduce cost and simplify neutralization, metallic cable sheaths, building steel structures, and steel conduits of electrical wiring may be used as neutralizing conductors.

Protective disconnection

For reliable disconnection of a faulty section, the short-circuit current must exceed the rated current of the protective device

$$I_f \geq k \cdot I_{rated} \quad (9.19)$$

where k — coefficient ≥ 3 for fuses; 1.4 - for protective breakers up to 100 A; 1.25 - for other breakers.

In all cases, the full conductivity of the neutral conductor must not be less than **50% of the phase conductor's conductivity**.

Detailed calculation of short-circuit current

The calculated value of short-circuit current is

$$I = \frac{U_1}{Z/3 + R_1 + R_0} \quad (9.20)$$

where Z/3 — transformer winding resistance, Ω; taken from Table 9.11; R_1 — active resistance of phase conductor, Ω; R_0 — active resistance of neutral conductor, Ω.

The active resistance of conductors is

$$R = \rho \cdot \frac{l}{s} \quad (9.21)$$

where ρ — specific resistance of conductor material, Ω·mm²; Copper: ρ =0.0184, Aluminum: ρ =0.0285; l — conductor length, m; s — conductor cross-section, mm².

Table 9.11. Transformer winding resistance depending on transformer power

Transformer power, kVA	**25**	**40**	**63**	**100**	**160**	**250**	**400**	**630**	**1000**

Z/3, Ω	1.040	0.650	0.413	0.260	0.164	0.104	0.095	0.043	0.027

Resistance of steel strips used as neutralizing conductors

If a steel strip is used as a neutralizing conductor, its resistance is

$$R_{\varphi} = R_{\varphi-0} \cdot L \qquad (9.22)$$

where $R_{\varphi-0}$ — specific resistance of 1 km steel strip, Ω/km; taken from Table 9.12; L — length of strip, km.

Mutual inductance resistance is not considered.

Table 9.12. Specific resistance of steel strips under AC (Ω/km)

Strip size, mm	Cross-section, mm²	Current density, A/mm²	0.5	1.0	1.5	2.0
20×4, 30×4, 30×5, 40×4, 50×4, 50×5, 60×4, 60×5	80–300	Values vary from 5.24 to 1.04 depending on current density				

Verification of protective neutralization

After determining the short-circuit current, the **coefficient** k must be calculated as the ratio

$$k = \frac{I}{I_n} \qquad (9.23)$$

where I — short-circuit current, A; I_n — rated current of the fuse or protective breaker, A.

If the result satisfies $k > 3$ for fuses (as required by formula 9.19), then protective neutralization is considered correctly designed.

Purpose of protective disconnection

The purpose of protective disconnection is the **automatic isolation of a damaged electrical installation from the network.** Danger arises from:

- Ground faults;
- Reduction of insulation resistance;
- Imperfect grounding or neutralization.

Schemes of protective disconnection

The main element in protective disconnection schemes is a **sensitive relay,** which responds to:

- Voltage between casing and ground;
- Zero-sequence voltage;
- Ground fault current in phases.

Thus, different protective disconnection schemes exist.

Simplest scheme: responds to voltage between casing and ground (Fig. 9.20a).

- The relay is connected between the casing and an auxiliary grounding electrode.

• When voltage reaches a dangerous level, the relay operates, opening its normally closed contact, de-energizing the contactor coil, and disconnecting the casing from dangerous voltage.

Disadvantage: requires an auxiliary grounding electrode and does not protect against direct contact with bare conductors.

Ventil-type scheme (Fig. 9.20b): often used in isolated-neutral networks.

• If a person touches a phase conductor, the current through their body flows via the relay winding.

• When this current reaches a dangerous level, the relay operates and disconnects the network via the automatic breaker.

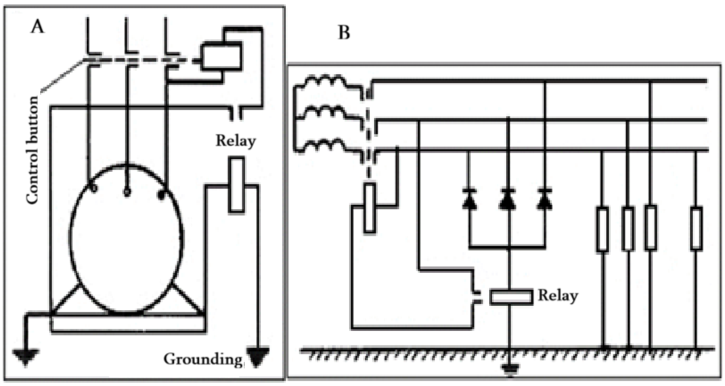

Fig. 9.20. Protective disconnection schemes:
A-Voltage relay between casing and ground; B-Ventil-type disconnection

IEC 60364 provides the internationally recognized framework for protective grounding, neutralization, and protective disconnection in electrical installations. It specifies grounding arrangements, neutral conductor management, and automatic disconnection of supply to ensure that fault currents are safely diverted and hazardous voltages eliminated. **IEC 60479** complements this by defining the physiological effects of current exposure, reinforcing the importance of rapid disconnection and reliable grounding in preventing electric shock. **ISO 45001** further strengthens occupational health and safety management systems by requiring preventive strategies, protective equipment, and emergency protocols that integrate grounding and disconnection practices. By linking the discussion of protective grounding, neutralization, and protective disconnection to these standards, the monograph ensures that theoretical explanations and practical safety measures are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers and installations against electrical hazards.

9.19. Safety in the Operation of Electrical Installations

Most accidents in industrial settings occur during **electric welding,** due to poorly adjusted equipment, faulty switches and protective devices, or contact with exposed conductors. Therefore, to protect workers from electrical injury, various protective measures must be implemented, including:

• **Enclosures;**

- **Interlocks;**
- **Insulation of conductive parts from ground.**

Enclosures and interlocks

- Enclosures and interlocks protect people from contact with live equipment.
- All high-voltage equipment or parts located below 2.5 m from the floor must be enclosed, regardless of insulation.
- Protective screens, boxes, or cabinets are used. These must be locked or equipped with interlocks that prevent opening while equipment is energized.

Types of interlocks:

1. Electrical;
2. Mechanical;
3. Electromechanical — disconnects power when an enclosure or door is opened.

Interlocks are especially important during welding in boilers, tanks, reservoirs, or damp buildings, where welders may be exposed to **75 V** during electrode replacement. In such cases, interlocks ensure **automatic disconnection** during idle operation.

Protective equipment

- **Up to 1000 V installations:** dielectric gloves, insulated tools, current clamps.
- **Above 1000 V installations:** insulating rods, insulating and measuring clamps, voltage indicators.

Additional insulating protective equipment strengthens the effect of basic equipment and is used together with it:

- Dielectric footwear;
- Rubber mats;
- Insulating platforms;
- Rubber boots;
- Overshoes;
- For >1000 V installations: dielectric gloves.

Note: Insulating rods, clamps, measuring clamps, voltage indicators, and rubber mats may be used indoors, but outdoors only in **dry weather.**

- Dielectric gloves are the main protective equipment at **220 V.**
- At higher voltages, insulating rods and clamps are used.
- Gloves must be sized to fit over wool gloves, protecting against frostbite during outdoor winter work.

Measurement of insulation resistance

Insulation of conductors deteriorates over time due to moisture, dust, acidic vapors, and high temperatures.

- Leakage current between insulated conductors must not exceed **0.001 A.**
- Insulation resistance must be at least **1000 Ω** under increased danger conditions.
- Insulating devices must be tested twice a year.

In three-phase equipment with normal insulation, voltmeters show equal **220 V** in all phases.

- A damaged phase shows reduced voltage, while the others show increased voltage.
- In complete short circuit, the damaged phase shows **0 V,** while the others show full operating voltage.

- For easier monitoring, audible, visual, or combined indicators are used.
- Combined testers (sound + light) are convenient and reliable.

Signaling

Signaling devices protect workers from accidental contact with live parts. Safety lamps are placed in boxes near high-voltage equipment.

Safety equipment for working at heights

When working on supports, roofs, or elevated structures, **special belts, ladders, and lifting devices** are used.

- Safety belts must withstand **2.4 kN** force and be tested every 3 months.
- Belts must have high mechanical strength to prevent falls.
- Before work, belts and chains must be inspected.

Protective goggles are used against electric arc radiation, molten metal, and harmful gases.

Insulated tools

Tools with insulated handles are used when working with live equipment.

- Wrenches must have plastic or wooden handles.
- Pliers must be covered with ebonite or plastic.
- All protective equipment must be periodically inspected and marked with the test date.
- Damaged tools must be withdrawn from service.

IEC 60364 provides the internationally recognized framework for ensuring the safe operation of electrical installations. It specifies design principles, protective measures, and maintenance practices that guarantee installations remain safe under both normal and fault conditions. **IEC 60479** complements this by defining the physiological effects of current exposure, reinforcing the importance of protective devices and operational procedures that minimize risks to humans and animals. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, risk assessment, and preventive strategies to ensure safe operation in workplaces. **WHO** recommendations add an international public health perspective, emphasizing the integration of electrical safety with broader health protection practices. By linking the discussion of safe operation of electrical installations to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against electrical hazards.

9.20. Safety of High-Voltage Overhead Lines

In real conditions, continuous power supply is sometimes required, which makes it necessary to perform work on **live overhead lines.**

Features of live-line work

1. During repair, transmission lines remain in operation, so consumers receive uninterrupted energy.
2. Workers are reliably insulated from the ground and can touch live conductors with uninsulated tools or even bare hands.

Currently, live-line work is possible on overhead lines with voltages from **1 to 750 kV,** and in some cases in **open switchgear.** Typical tasks include:

- Replacing insulators and fittings;
- Cleaning conductors;
- Inspecting conductors by opening suspension clamps;
- Replacing or repairing conductors on certain sections;
- Installing measuring and control devices in conductors.

Other tasks performed without line shutdown include:

- Painting metallic or treated wooden supports;
- Straightening supports;
- Replacing individual parts of wooden supports

This method is economical, since energy is continuously supplied to consumers and no losses occur due to shut down. It also requires fewer repair workers, because tasks can be performed at different times on different sections, rather than simultaneously as in de-energized line repairs.

Electrical principle

The method is based on the principle of worker insulation from the ground. Experiments show:

- A person can touch a bare conductor of **50 Hz AC up to 500 V** while standing on a porcelain insulator without discomfort.
- At **1000 V,** contact causes unpleasant sensations.
- At **1000–4000 V,** painful sensations and heating at the contact point occur due to sparking.
- At **8–10 kV,** touching is impossible.

At higher voltages, sparks intensify, pain increases, and injury may result. In such cases, the human body conducts both **conduction current** and **capacitive current** through insulating devices, as well as **human-to-earth capacitive current,** which grows with voltage.

Protective measures

To protect the worker, a **metal sheet** is placed on the insulating device, connected to the line conductor. Thus, the human body is shunted by the conductor, diverting conduction and capacitive currents away from the person.

This scheme allows live-line work, but a drawback remains: the **human-to-earth capacitive current** still flows through the body.

Limiting human-to-earth capacitive current

Experiments show that people do not perceive this current up to **110 kV,** provided its magnitude is **0.5–0.6 A.**

At voltages above 110 kV, the current exceeds the perception threshold, causing unpleasant or painful sensations. This can lead to accidents, as the worker loses orientation and may act incorrectly.

To prevent accidents, capacitive current must be reduced to imperceptible levels. This is achieved by using **resistors of 5–10 MΩ,** which sharply increase circuit resistance and reduce current.

Typically, the resistor is installed in an insulating rod, through which the shunting conductor is connected to the line conductor. After transferring potential to the work area, the resistor is bypassed by a special device, so current no longer flows through it.

IEC 60364 provides the internationally recognized framework for electrical installations, including protective measures for high-voltage overhead lines. It specifies design principles, insulation requirements, and clearance distances to ensure that overhead lines are constructed and maintained in a way that minimizes risks of electric shock, fire, and mechanical failure. **IEC 60479** complements this by detailing the physiological effects of current exposure, reinforcing the importance of strict adherence to clearance and insulation standards to prevent accidental contact. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, risk assessment, and preventive strategies for workers operating near high-voltage lines. By linking the discussion of high-voltage overhead line safety to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against electrical hazards in high-voltage environments.

9.21. Practical Calculation Examples

Readers should note that practical calculation examples here and in other sections are made according to **international standards,** therefore the quantities in formulas are presented in the same form as in the English versions of the relevant literature.

1. Protective Grounding Calculation

Formula:

$$R_A \leq \frac{U_L}{I_a}$$

Definitions:

R_A — grounding resistance, Ω;

U_L — permissible touch voltage, V, usually 50 V according to IEC 60364-4-41;

I_a — operating current of automatic disconnection device, A.

Example:

If the device operates at 30 A:

$$R_A \leq \frac{50}{30} = 1.67\ \Omega$$

Conclusion: Grounding resistance must be ≤ 1.67 Ω.

2. Neutralization (fault loop impedance) calculation

Formula:

$$Z_s \leq \frac{U_0}{I_a}$$

Definitions:

Z_s −Total circuit (fault loop) impedance, Ω.

U_0 − Phase voltage, typically 230 V;

I_a − Operating current of the automatic disconnection device, A.

Example:

$I_a = 100 \text{ A} \Rightarrow Z_s \leq \frac{230}{100} = 2.3$

Conclusion: Circuit impedance must be ≤ 2.3 Ω.

3. Step voltage evaluation

Formula:

$U_{\text{step}} = I_f \cdot \rho \cdot \frac{1}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$

Definitions:

- $\boldsymbol{I_f}$ - Fault current, A;
- **ρ** - Soil resistivity, Ω·m;
- $\boldsymbol{r_1}, \boldsymbol{r_2}$ - Distances of the feet from the fault point, m.

Example:

$I_f = 1000 \text{ A}, \quad \rho = 100\, \Omega \cdot \text{m}, \quad r_1 = 1 \text{ m}, \quad r_2 = 2 \text{ m}$

$U_{\text{step}} \approx 1000 \cdot 100 \cdot \frac{1}{2\pi}(1 - 0.5) \approx 7960$

Conclusion: Step voltage can be extremely high—protective zones are required.

4. Touch voltage evaluation

Formula:

$U_{\text{touch}} = I_f \cdot R_b$

Definitions:

- I_f - Fault current through the body (A)
- R_b - Body resistance, Ω, typically R_b=1000 Ω per IEC 60479

Example:

$I_f = 0.1 \text{ A}, \quad R_b = 1000\, \Omega_{\text{touch}} = 100\, \Omega$

Conclusion: 100 V touch voltage is already incompatible with life.

5. Protective disconnection time

Requirement: In a **230 V** network, automatic disconnection must occur within **≤ 0.4 s** (IEC 60364).

Example:

$Z_s = 2\, \Omega \Rightarrow I = \frac{U}{Z_s} = \frac{230}{2} = 115 \text{ A}$

Conclusion: At **115 A**, disconnection must occur within **≤ 0.4 s**.

6. Grounding Electrode Potential Rise (EPR)

Formula:

$U_{EPR} = I_f \cdot R_A$

where:

I_f — fault current, A;

R_A — grounding resistance, Ω.

Example:

If $I_f = 500$ A, R_A= 2 Ω:

$U_{EPR} = 500 \cdot 2 = 1000\, V$

Conclusion: During a fault, the grounding electrode potential can rise to 1000 V, endangering personnel. Equipotential bonding and protective zones are essential.

Coefficient ranges (for design and evaluation)

- Body resistance : 500–2000 Ω (IEC 60479)
- Soil resistivity : 10–1000 Ω·m (depends on soil type)
- Permissible touch voltage : 50 V (dry), 25 V (wet)
- Automatic disconnection time: ≤ 0.4 s (230 V networks), ≤ 5 s (400 V networks)

Standards used

- **IEC 60364** — Electrical installations
- **IEC 60479** — Effects of current on humans and animals
- **ISO 45001** — Occupational safety

Systematic Summary

Key Topics

Effects of current on the human body: thermal, electrolytic, mechanical, biological.

Protective measures:

- **Collective** — grounding, neutralization, automatic disconnection, protective schemes.
- **Individual** — dielectric gloves, footwear, goggles, insulated tools.

Operational safety: instruction, regular inspection, compliance with ISO 45001 and IEC 60364.

High-voltage lines: live-line working methods, limitation of human-to-earth capacitive current.

Personnel qualification: Groups I–V, periodic medical checks, types of instruction.

Practical calculations:

- Grounding resistance
- Neutralization impedance
- Step voltage
- Touch voltage
- Automatic disconnection time

The examples presented in this section are provided for illustrative and educational purposes only. They demonstrate how theoretical principles and risk assessment methods can be applied in practice, helping students and professionals understand the logic behind calculations. These examples are not intended to replace or supersede the requirements of **IEC 60364**, **IEC 60479**, **ISO 45001**, or other international standards. For actual design, installation, or safety evaluations, practitioners must always rely on the official standards and validated measurement procedures. By including practical calculations alongside theoretical explanations, the monograph enhances accessibility and didactic clarity, while maintaining alignment with internationally recognized safety frameworks.

10. Protection Against Static Electricity

10.1. Guide for Chapter Ten

IEC 61340 provides the internationally recognized framework for protection against static electricity. It specifies design principles, protective measures, and testing procedures to control electrostatic discharge (ESD) in workplaces and installations. **ISO 45001** complements this by requiring occupational health and safety management systems to integrate static electricity risk assessments into preventive strategies, ensuring that workers are protected from both direct shocks and indirect hazards such as fire or equipment damage. **WHO** recommendations further reinforce international health protection practices, emphasizing the importance of reliable grounding, humidity control, and protective clothing in reducing static electricity risks. By linking the discussion of static electricity protection to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and sensitive equipment against electrostatic hazards.

- **Theoretical integration:** Static electricity arises from friction of isolated surfaces and may cause spark discharges. Its consequences range from unpleasant sensations to fire and explosion.
- **Integration with standards:** International standards (IEC 60079, ISO 2878, NFPA 77) emphasize mandatory grounding, humidity control, and use of antistatic materials.

This guide introduces the scope of Chapter 10, outlining the principles of protection against static electricity. It emphasizes that the following sections are aligned with internationally recognized standards, including **IEC 61340** for electrostatic control and **ISO 45001** for occupational safety. By framing the chapter with these standards, the guide ensures that readers understand both the theoretical foundations and the practical measures required for safe and effective management of static electricity.

10.2. Static Electricity and Its Impact

Friction of dielectric and semiconductor surfaces may generate, accumulate, and relax free electric charges, called static electricity. Such currents may arise during transfer of fuels and lubricants with ungrounded equipment, crushing or grinding of insulating solids, aerosol movement, or gas ejection from nozzles.

In fact, atoms and molecules of one substance exert strong attraction, pulling out electrons from another, leading to excess electrons in the first and deficiency in the second. Thus, negative charges appear on the first surface and positive charges on the second.

Static electricity may also arise on rubbing conductors if they are well insulated from ground. Therefore, electrically insulated human bodies may accumulate charges through contact with dielectrics, synthetic or silk clothing, rings, bracelets, etc.

Clouds, isolated from earth and each other, also accumulate charges of different signs. Lightning occurs when air resistance breaks down between oppositely charged clouds or between cloud and earth.

In industry, static potentials may reach:

- 200 kV during free flow of gasoline into ungrounded tanks
- 70–80 kV with belt conveyors at 15 m/s
- 40 kV in machining plastics or wood

- 12 kV in paint spraying
- 1 kV in pumping gasoline through ungrounded pipelines at 0.5 m/s over 25 m

Surfaces form oppositely charged double layers, resembling a capacitor with charge, capacitance, and potential difference.

When potential difference reaches the threshold sufficient to break down the medium's resistance, spark discharge occurs. For air, breakdown voltage is 3 kV/mm.

Discharge energy is defined by the formula

$$E = 0.5 \cdot C \cdot U^2 \quad (10.1)$$

where E is discharge energy, J; C - capacitance, F; U - potential difference, V.

Spark discharge is the most dangerous manifestation of static electricity, since in presence of flammable or explosive substances it may cause fire or explosion.

Human body charges are low, but discharge to grounded structures causes unpleasant sensations. Not dangerous by itself, but in height or extreme conditions may provoke involuntary movements leading to injury.

IEC 61340 provides the internationally recognized framework for understanding and controlling static electricity and its effects. It specifies protective measures, grounding techniques, and testing procedures to minimize electrostatic discharge (ESD) risks. **ISO 45001** complements this by requiring occupational health and safety management systems to integrate static electricity hazards into risk assessments, ensuring that workers are protected from shocks, fires, and equipment damage. **WHO** recommendations further reinforce the importance of environmental controls such as humidity regulation and protective clothing. By linking the discussion of static electricity and its effects to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

10.3. Protection Against Static Electricity

It is clear that the cause of static electricity discharge is the magnitude of the generated potential, more precisely the potential difference. Therefore, protection against static electricity is based on methods of reducing potentials, which are mainly of two types:

1. Elimination or weakening of the causes of potential generation;
2. Neutralization of generated potentials.

Reduction of static charge generation can be achieved by selecting pairs of frictional surfaces so that one develops positive and the other negative charges, which neutralize each other upon formation. For example, combined materials of nylon and Dacron have been created to provide protection against static charges based on this principle.

Attention must be paid to the reliability of soft metallic brushes used to remove static currents in belt drives, conveyors, and other equipment where necessary. Conductive lubricants should be applied, which reduce the possibility of static charge generation and also facilitate neutralization of charges.

Charge generation can also be reduced by lowering operating regimes: reducing processing speed of materials, slowing conveyor movement, decreasing frictional forces, and lowering the intensity of dielectric liquid transfer.

In this respect, the use of relaxation volumes in storage facilities is noteworthy. These are specially grounded sections (expanded parts of pipelines) at the beginning of storage tanks, which absorb the main load of static charge generation and relaxation. From these volumes, loose materials or liquids are transferred into the main storage at such low speeds that increased static charge generation does not occur. The geometric dimensions of relaxation volumes are determined by the flow rate of the material or liquid and the permissible velocity, which varies depending on the type of material.

Neutralization of static electricity is also achieved by ionizing air at the points of charge generation. The sign of the generated charge is known in advance, and ionization produces charges of opposite sign, resulting in mutual neutralization.

The most effective means of neutralizing generated charges is grounding of metallic or other conductive parts of industrial equipment. In this case, grounding resistance must not exceed 100 ohms.

Accordingly, safety rules prohibit working with ungrounded tanks, pipelines, and equipment. Grounding reliability must be periodically checked visually, performed by the shift supervisor or foreman at the beginning of each shift, and after any technical accident or interruption.

Air in rooms where dielectric dust accumulates must be periodically cleaned by wet methods, for example by spraying water. This has a double effect:

a. Dust settles, reducing static charge generation;

b. Relative humidity increases, making air conductive and enabling charge neutralization on grounded surfaces.

At relative humidity above 85%, static charge generation practically does not occur, since the air becomes conductive and charges are neutralized upon formation.

Besides water, air conductivity can also be increased by spraying conductive additives, if circumstances and technology allow.

Workplaces must be equipped with grounded sections, which automatically remove static charges generated by people without the need for discharge.

Individual protective means against static electricity include special clothing and footwear made of conductive rubber, as well as antistatic bracelets.

IEC 61340 provides the internationally recognized framework for protection against static electricity, specifying grounding systems, antistatic materials, and testing procedures to control electrostatic discharge (ESD). It establishes requirements for workplaces, equipment, and protective devices to ensure that static charges are safely dissipated. **ISO 45001** complements this by requiring occupational health and safety management systems to integrate static electricity hazards into risk assessments, preventive strategies, and worker training. **WHO** recommendations further reinforce the importance of environmental controls such as humidity regulation, protective clothing, and safe handling practices to reduce electrostatic risks. By linking the discussion of protection against static electricity to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and sensitive equipment against electrostatic hazards.

10.4 Characteristics of Lightning

The cause of lightning is the presence of atmospheric static charges of opposite signs in clouds and their discharge between clouds, between ground objects and clouds, or between the earth's surface and clouds. Let us consider discharge between the earth's surface and clouds. Lightning formation begins with the appearance of a so-called leader (a luminous channel), in which current reaches hundreds of amperes. Depending on the direction of movement, lightning may be downward or upward. The study of upward lightning began after the construction of tall buildings, revealing that leaders can be initiated from the earth's surface and directed toward clouds.

Downward lightning is triggered by processes within clouds, and its strike on the earth is not dependent on the presence of structures—discharge occurs even without buildings. As the leader initiated in clouds approaches the earth's surface, several counter-leaders are triggered from the surface, and the meeting of one of them causes electrical discharge, determining the strike location on the ground or on a structure.

After formation of a conductive channel, the charge of the downward leader is rapidly neutralized, accompanied by intense brightness and a sharp increase in current. In 50% of cases, current exceeds 30 kA, and in 1–2% it may rise to 200 kA. Current manifests as one or several impulses. The first impulse lasts 3–20 microseconds. Subsequent impulses have decreasing parameters, with average values of about 12 kA and 0.6 microseconds. Despite lower amplitude, later impulses show faster rise times, reaching peak values more quickly. At the same time, channel temperature rises sharply to 30,000 °C, causing instantaneous expansion, perceived acoustically as thunder. The total charge transferred by lightning is about 100 C.

Upward leaders are initiated from tall buildings, where the electric field on rooftops intensifies during thunderstorms. In flat areas, upward lightning affects buildings taller than 150 m, while in mountainous regions it can be triggered from lower structures, cliffs, or irregularities of the earth's surface. For this reason, upward lightning is more frequent in mountainous areas.

When an upward leader reaches clouds, discharge occurs, 80% of which is characterized by negative polarity current. This current appears in two types:

1. Continuous discharge, non-impulsive, with current of several hundred amperes lasting tenths of a second.
2. Superimposed impulses on the continuous background, with amplitudes averaging 10–15 kA and transferred charge about 40 C. These impulses are similar in manifestation and effect to those of downward lightning.

Thus, regardless of type, current in a lightning channel may reach 200 kA or more, voltage 150 MV, overvoltage magnitude 2 MV or more, discharge duration 0.1–1 s, and temperature 30,000 °C or higher.

IEC 62305 provides the internationally recognized framework for understanding and mitigating the effects of lightning. It specifies protective measures, risk assessment methods, and installation practices to safeguard structures, electrical systems, and human life against lightning strikes. **IEC 60364** complements this by integrating lightning protection into electrical installation safety, ensuring that grounding and surge protection devices are properly designed. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification and preventive strategies for workers exposed to lightning risks, particularly in outdoor environments. **WHO** recommendations add a public health perspective, emphasizing the importance of awareness, training, and emergency protocols to reduce lightning-related injuries. By linking the description of lightning to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against lightning hazards.

10.5 Harmful Effects of Lightning

The effects of lightning on buildings and structures can be divided into two main groups:

- **Primary effects,** caused by direct strikes;
- **Secondary effects,** initiated by nearby strikes, with impulses entering the building through ungrounded metal communications.

Secondary harmful effects may lead to sparks within the structure. The scale of danger in both cases depends on lightning discharge parameters and on the structural and technological features of the object (presence of explosive or fire-hazard zones; technologies involving explosive mixtures as intermediate or final products; layout of energy and communication systems; fire resistance of the structure, etc.).

Direct electrical impact is highly significant, as it can harm people (and animals) inside buildings. The severity depends on lightning current amplitude, rise time to peak value, inductance of the structure, and grounding resistance (through which impulse current must flow into the soil). Even with good lightning protection, high current and especially rapid rise times can produce overvoltage of several megavolts.

Without lightning protection, current discharge paths cannot be controlled. Dangerous touch and step voltages may occur everywhere, especially on rooftops.

In conductors of small cross-section (metal parts), lightning current discharge may cause melting and undesirable thermal effects within the structure.

Direct thermal impact is equally important, as it can cause fires. In 95% of cases, energy released in the lightning channel exceeds 5.5 J, which is 2–3 orders of magnitude greater than the minimum ignition energy for industrial gases, vapors, and aerosols. Contact of the lightning channel with such environments leads to fires and explosions.

Lightning also exerts mechanical effects. Heating and expansion of air produce shock waves that damage structures and cause destruction. This mechanical impact lies at the boundary between primary and secondary effects and may be classified as either.

Lightning strikes are also characterized by secondary discharges caused by electrostatic and electromagnetic induction. As a result, sparks occur in communications and buildings, which may initiate secondary fires and explosions in hazardous environments.

Electrostatic induction manifests as overvoltage induced on metal structures. Its magnitude depends on lightning current strength, distance to the strike point, and grounding resistance.

Electromagnetic induction is associated with the generation of electromotive force (EMF) in metal loops. EMF magnitude depends on current rise time to peak value and the area enclosed by the loop. In long communications, EMF may reach tens of kilovolts. At connection points of long communications, sparks may occur with energies of tenths of a joule.

Another dangerous effect is the introduction of high potential into structures via communications (overhead power lines, pipelines, cables). High potential propagates as waves, creating sparks when ungrounded communications contact grounded equipment. Communications may also bring impulse currents into buildings, which are lethal to humans in all cases.

During thunderstorms (especially toward the end), ball lightning may sometimes occur. To avoid it, windows and doors should be closed, and ventilation ducts sealed. Contact with electrical appliances must be avoided. Since smoke is a good conductor, proximity to chimneys or other smoke-emitting heating devices is unsafe during thunderstorms. For safety reasons, one must not remain in the bed of a truck during thunderstorms. Passenger cars, however, are not dangerous in this respect.

IEC 62305 provides the internationally recognized framework for assessing and mitigating the harmful effects of lightning. It specifies risk assessment methods, protective measures, and installation practices to reduce damage to structures, electrical systems, and human life. **IEC 60364** complements this by integrating surge protection and grounding requirements into electrical installations, ensuring that lightning-induced overvoltages are safely managed**. ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and emergency protocols for workers exposed to lightning risks. **WHO** recommendations add a public health perspective, emphasizing awareness campaigns, safe shelter practices, and medical preparedness to minimize lightning-related injuries and fatalities. By linking the discussion of harmful effects of lightning to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against lightning hazards.

10.6 Protective Measures

Lightning protection is a complex of protective measures aimed at safeguarding people, buildings, equipment, and materials from explosions, fires, and destruction. For buildings and structures, static discharge is especially dangerous when discharge current passes through the building itself—that is, in cases of direct lightning strikes.

The probability of a direct strike on a surface object increases with its height and decreases with distance to charged clouds. Geological properties of the soil and the configuration of surrounding buildings also play a role.

Objects requiring protection are divided into three categories:

1. Buildings and structures where technological processes involve or release explosive substances that may detonate from sparks.
2. Buildings and structures where explosive substances are released only in case of accidents, while normal processes do not require them.
3. Buildings and structures without explosive substances.

Protection of first-category buildings must be ensured by separate lightning rods. For second and third categories, either separate or combined lightning rods may be used. In such cases, metal roofing and other metallic parts of the building may serve as lightning receptors (see notes to Table 10.1).

Protection of objects from lightning is achieved through lightning rods. The principle of lightning rod design is to divert discharge away from the protected object and conduct current into the ground through grounding. Structurally, lightning rods may be rod-type, wire (antenna-type), mesh-type, or combined. Schemes of rod and wire lightning rods are shown in Fig. 10.1.

Rod-type receptors may be made of steel or other metals of any profile, with cross-sectional area of 100 mm² or more (see Fig. 10.2). Cross-sectional areas of conductors and other grounding elements are given in Table 10.1.

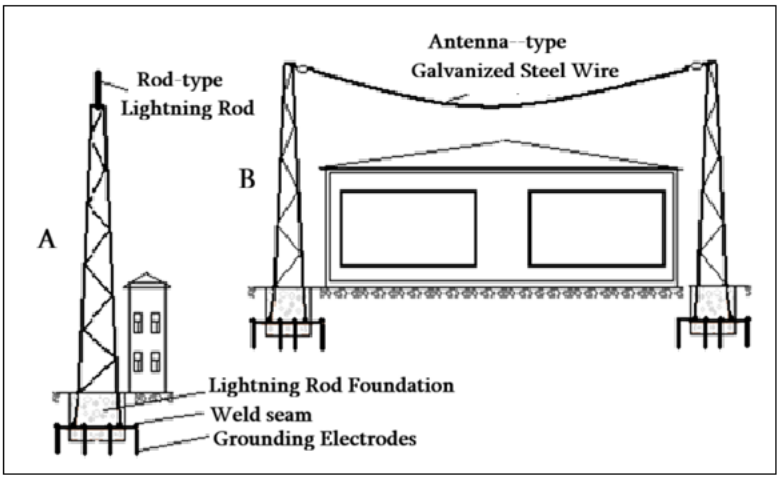

Fig. 10.1. Principle of lightning rod construction:
A – rod-type; B – antenna-type, consisting of one or several wires stretched on conductive supports

Mesh-type lightning rods are installed directly on building roofs as metallic grids, which must be insulated from the building and simultaneously grounded.

Table 10.1 Dimensions of Lightning Receptors, Conductors, and Grounding Electrodes

N	Elements, Forms, and Dimensions	Minimum Size

Lightning Receptors		
1	Rod-type lightning rod – any metal rod: length (mm), cross-sectional area (mm²)	200,100
2	Antenna-type – galvanized steel multi-strand wire: cross-sectional area (mm²)	35
Conductors		
1	Steel round bar diameter (mm)	6
2	Steel strip: cross-sectional area (mm²), thickness (mm)	48, 4
Grounding Electrodes		
1	Steel round bar diameter (mm)	10
2	Steel strip: cross-sectional area (mm²), thickness (mm)	160, 4
3	Steel strip: cross-sectional area (mm²), thickness (mm)	160, 4
4	Steel angle bar: cross-sectional area (mm²), thickness (mm)	12, 3.5

Notes to Table 10.1

1. Lightning receptors must be protected against corrosion by galvanizing, tinning, or painting.
2. Metal structures of protected buildings may serve as receptors: chimneys, deflectors, roofs, meshes, or any metallic part located on or above the roof.
3. Conductors must be protected against corrosion with tin, zinc, or paint, and their length to grounding electrodes should be as short as possible.
4. When sheet-metal roofing is used as a receptor, conductors must be connected to it with bolts and nuts.
5. Wherever possible, welded joints should be preferred. Weld seam length must not be less than twice the width of rectangular elements, or six times the diameter for circular elements.

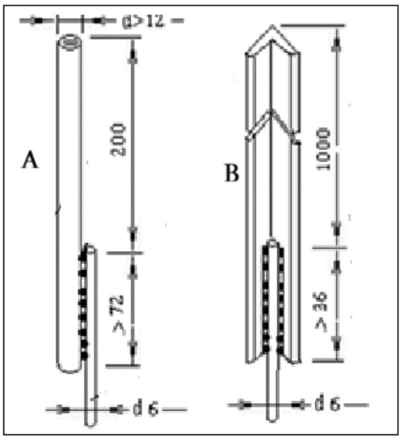

Fig. 10.2. Rod-type lightning receptor:
A – made of pipe; B – made of angle bar

Depending on object size, single, double, or multiple rod-type lightning rods may be used, forming a protective zone around the object. For long structures, one or several wire-type lightning rods are applied.

Buildings and structures of **Category I and II** must be protected against:

1. Direct lightning strikes
2. Electrostatic and electromagnetic induction

3. Introduction of high potentials via overhead or underground communications

Buildings and structures of **Category III** must be protected against:

1. Direct lightning strikes
2. Introduction of high potentials via overhead metallic communications

For buildings and structures wider than 100 m, potential equalization measures must be implemented inside.

IEC 62305 provides the internationally recognized framework for protective measures against lightning and related electrical hazards. It specifies risk assessment methods, grounding systems, surge protection devices, and structural safeguards to minimize damage to installations and ensure human safety. **IEC 60364** complements this by integrating protective measures into electrical installation design, ensuring that grounding, insulation, and disconnection systems are harmonized with lightning protection strategies. **ISO 45001** further strengthens occupational health and safety management systems by requiring preventive strategies, worker training, and emergency protocols that incorporate protective measures against lightning and static electricity. **WHO** recommendations add a public health perspective, emphasizing awareness campaigns, safe shelter practices, and medical preparedness to reduce lightning-related injuries. By linking the discussion of protective measures to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against electrical hazards.

10.7. Lightning Rod Protection Zone

The probable number of direct lightning strikes on buildings and structures per year is determined by the formula

$$N = 10^{-6}(B + 6h_x)(L + 6h_x)n \tag{10.2}$$

where N – expected number of direct lightning strikes per year, units; B – width of the protected building, m; L – length of the building, m; h_x – height of the building including the roof, m; n – coefficient of lightning damage per 1 km² per year, units/km².

The numerical value of the average lightning damage coefficient depends on the number of thunderstorm hours per year in the given area and is taken from Table 10.2. For one square kilometer of earth's surface, thunderstorm hours per year are:

- Eastern Georgia: 80–100 hours;
- Western Georgia (lowlands): 20–40 hours;
- Western Georgia (mountains): 100 hours.

Single Rod-Type Lightning Rod (Height H < 60 m)

Its protection zone is conical. On the ground surface, the radius of the cone base is

$$r = 1.5H$$

At the height of the protected object, the protection zone is a circle of radius r_x.

If the height of the protected object is If the height of the protected object is $h_x = 0.667H$, then the cone height is

$$h = 0.8H$$

and the base radius remains

$$r = 1.5H$$

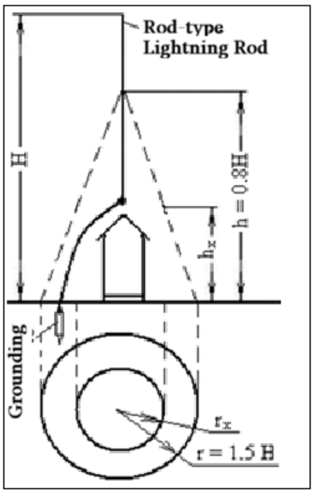

Fig. 10.3. Calculation parameters of the protection zone of a single rod-type lightning rod

Empirical Formulas for Radius of Protection Zone

When $0 \leq h_x \leq 0.667H$:

$$r_x = 1{,}5(H - 1{,}25h_x) \quad (10.3)$$

When $0.667H \leq h_x \leq H$:

$$r_x = 0{,}75(H - h_x) \quad (10.4)$$

Table 10.2 Variation of Average Lightning Damage Coefficient by Thunderstorm Hours per Year

Thunderstorm hours per year	20-40	40-60	60-80	80 +
Damage coefficient, units/km²	3	6	9	12

These empirical formulas (10.3, 10.4) are sufficiently accurate and recommended for lightning rod design calculations. The purpose of such calculations is to determine lightning rod height when building height and required protection radius are known.

Example: For lightning rod height $H = 50$ m and building height including roof $h_x = 33{,}3$ m, both formulas can be applied.

- Formula (10.3) gives $r_x = 12.562$ m;
- Formula (10.4) gives $r_x = 12.525$ m.

The small difference between results confirms the practical accuracy of these formulas.

When the lightning rod height is $H = 60 - 100$ m, then the ground radius is $r = 90$ m. The empirical formulas for calculating the radius of the protection zone at height are:

When $0 \leq h_x \leq 0.667H$:

$$r = 192\left(1 - 1.25\frac{h_x}{H}\right) \quad (10.5)$$

When $0.667H \leq h_x \leq 100$:

$$r = 45\left(1 - \frac{h_x}{H}\right) \quad (10.6)$$

The schematic parameters of the protection zone for a wire-type lightning rod are shown in Fig. 10.4A, and for a double rod-type lightning rod in Fig. 10.4B.

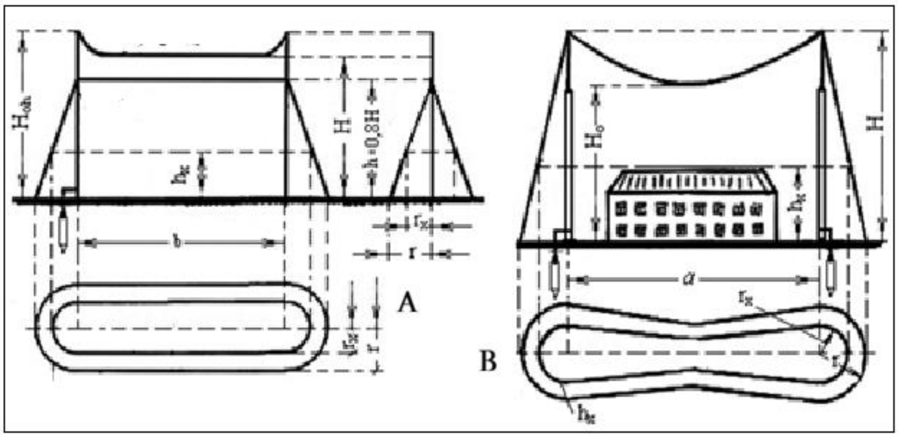

Fig. 10.4. Schemes of protection zone calculation parameters for lightning rods: A – wire-type lightning rod; B – double rod-type lightning rod of equal height

For wire-type lightning rods, the sag of the wire is approximately 2 m, as seen from the height calculation formula

$$H = H_{oh} - 2 \qquad h = 0.85H \quad (10.7)$$

where H_{oh} is the height of the support to which the wire is attached, m.

The radius of the protection zone at height h_x is determined by

$$r_x = (1.35 - 0.0025H)\left(H - \frac{h_x}{0{,}85}\right) \quad (10.8)$$

At ground level, the same value is

$$r_x = (1.35 - 0.0025H)H \quad (10.9)$$

In this case, $H < 120$ m and $H_{oh} < 150$ m.

For double rod-type lightning rods of equal height, the empirical formulas for protection zone parameters are

$$H_0 = 4H - \sqrt{9H^2 + 0.25a^2} \quad (10.10)$$

$$H = 0.517H_0 + \sqrt{0.183H_0^2 + 0.0357a^2} \quad (10.11)$$

where a is the distance between the lightning rods (m).

As noted, during lightning rod design, the geometric dimensions of the protected object provide known values of h_x and r_x, and the required task is to determine H.

IEC 62305 provides the internationally recognized framework for defining and calculating the protection zone of lightning rods. It specifies geometrical methods, rolling sphere models, and risk assessment techniques to determine the areas safeguarded against direct lightning strikes. **IEC 60364** complements this by integrating lightning rod protection into electrical installation safety, ensuring that grounding and surge protection systems are harmonized with the defined protection zones. **ISO 45001** further strengthens occupational health and safety management systems by requiring preventive strategies, worker training, and emergency protocols for those operating within or near lightning protection zones. **WHO** recommendations add a public health perspective, emphasizing awareness campaigns and safe shelter practices to reduce lightning-related injuries. By linking the discussion of lightning rod protection zones to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against lightning hazards.

10.8 Grounding Standardization

For selecting lightning rod grounding systems in buildings and structures, it must be considered that the most effective way to reduce overvoltage in the lightning protection network and in the metallic structures of the object is to install ground electrodes with low electrical resistance. Therefore, the resistance of the grounding system or its components is subject to standardization.

Until recently, in our country, standardization was based on impulse resistance, discussed in the following paragraph. The permissible impulse resistance norms were:

- 10 ohms for Category I and II buildings;
- 20 ohms for Category III buildings.

Additionally, impulse resistance up to 40 ohms was allowed when soil resistivity was 500 ohm·m or more, provided that the lightning rod was sufficiently distant from Category I objects to avoid circuit closure (breakdown) through air or soil.

For outdoor installations, the maximum permissible impulse resistance was set at 50 ohms.

The difficulty lies in the fact that during grounding design, it is impossible to reliably predict lightning current parameters flowing through it, and therefore impossible to determine impulse resistance precisely. Thus, operating with impulse resistance values in standards is associated with certain practical inconveniences. A more rational approach is to preselect ground electrodes capable of functioning across the entire range of lightning currents, based on their inherent electrical resistance.

Accordingly, ground electrodes were defined to meet safety requirements for currents in the range of 5–100 kA.

The most convenient and acceptable type of grounding is reinforced concrete foundations. An additional condition applies: mechanical damage to concrete during current discharge through the foundation must be excluded. It is noteworthy that reinforced concrete structures withstand very high lightning currents due to their impulsive nature, i.e., short duration. Thus, foundations constructed with 5 m reinforced concrete piles or 2 m reinforced concrete steps are optimal for discharging impulse currents up to 100 kA. This approach eliminates the need to calculate grounding resistance during lightning rod installation.

The typical constructions discussed in the next paragraph are applicable only to buildings without reinforced concrete foundations.

Using a building's reinforced concrete foundation as a natural grounding system requires reliable electrical connections between vertical reinforcements, achieved by welding.

IEC 60364 provides the internationally recognized framework for grounding in electrical installations. It specifies design principles, resistance limits, and testing procedures to ensure that grounding systems safely dissipate fault currents and protect both people and equipment. **IEC 62305** complements this by integrating grounding requirements into lightning protection systems, ensuring that surge currents are effectively diverted to earth. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training related to grounding practices. **WHO** recommendations add a public health perspective, emphasizing the importance of reliable grounding in reducing risks of electric shock, fire, and equipment damage. By linking the regulation of grounding to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against electrical hazards.

10.9 Typical Grounding Constructions for Lightning Rods

During atmospheric discharges, the generated current is impulsive, flowing through conductors and soil for a short time. Therefore, the grounding system must be capable of conducting impulse currents. In this context, the resistance is called impulse resistance. Impulse resistance of grounding is a quantitative characteristic of the complex physical process of discharging lightning currents into the soil. Its value differs from the resistance required for grounding industrial-frequency currents. The difference is determined by lightning current amplitude, front duration, rise time to peak value (slope of the peak). All these parameters vary widely. With increasing lightning current magnitude, impulse resistance decreases and may be reduced by a factor of 2–5.

The value of impulse resistance can be determined from the permissible resistance for industrial-frequency current discharge using the formula:

$$R_0 = \propto R_\infty \tag{10.12}$$

where R_0 – required impulse resistance of the lightning rod grounding, Ω; $\propto$ – impulse coefficient, depending not only on lightning current magnitude but also on soil resistivity and grounding construction; R_∞ – permissible resistance for industrial-frequency current discharge, Ω.

Table 10.3 Numerical Values of Impulse Coefficient for Lightning Rod Grounding

N	Soil Resistivity, Ω·m	<100	100	500	1000	2000
1	Impulse coefficient for vertical grounding	0.9	0.7	0.5	0.3	–
2	Impulse coefficient for combined grounding	0.9	0.9	0.7	0.5	0.35

The table is compiled for vertical and combined grounding constructions. For horizontal grounding, the numerical values characteristic of combined grounding may be used. Vertical grounding employs only rod-type electrodes, horizontal grounding uses strips, while combined grounding uses both. Each type of grounding differs in dimensions, which determine their varying resistance to current discharge.

Figure 10.5 shows the structural design of a vertical rod-type grounding electrode. Table 10.4 provides numerical values of characteristic geometric parameters of such constructions depending on the type of metal used, and the corresponding resistance of the grounding electrode for industrial-frequency current discharge. These values also depend on soil resistivity.

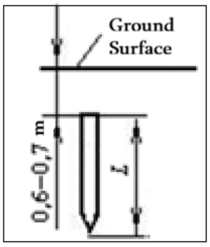

Fig. 10.5. Vertical Rod-Type Grounding Electrode

Table 10.4 Variation of Grounding Resistance for Industrial-Frequency Current Discharge by Soil Resistivity

Material Used for Grounding Electrode	**Resistance (Ω) at Soil Resistivity, Ω·m**	**50**	**100**	**500**
Angle bar 40×40×4 mm, length 2 m	19	38	190	380
Angle bar 40×40×4 mm, length 3 m	14	28	140	280
Pipe diameter 10–20 mm, length 2 m	24	48	240	480
Pipe diameter 10–20 mm, length 3 m	17	34	170	340
Pipe diameter 10–20 mm, length 5 m	14	28	140	280

Other types of grounding electrodes also exist. For example, radial grounding electrodes, which use a vertical rod combined with horizontal strips arranged radially at 120° angles and welded to the vertical rod.

Grounding may also be achieved with piles and connecting beams, known as rostverks. Piles of 0.3 m diameter and 6 m length are made of reinforced concrete, while the rostverk is a steel strip of 4×40 mm welded to the pile in the proper manner. A cross-shaped grounding system made of 36 piles and 9 rostverks forms four equal squares, each side measuring 24 m. Such a grounding system is quite large and its use is naturally subject to certain limitations. This type of grounding is applied when soil resistivity is in the range $\rho = 50 - 500\ \Omega \cdot m$.

IEC 60364 provides the internationally recognized framework for grounding in electrical installations. It specifies design principles, resistance limits, and testing procedures to ensure that grounding systems safely dissipate fault currents and protect both people and equipment. **IEC 62305** complements this by integrating grounding requirements into lightning protection systems, ensuring that surge currents are effectively diverted to earth. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training related to grounding practices. WHO recommendations add a public health perspective, emphasizing the importance of reliable grounding in reducing risks of electric shock, fire, and equipment damage. By linking the regulation of grounding to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against electrical hazards.

10.10 Typical Lightning Rod Constructions

Below are typical lightning rod constructions presented only in drawings, with explanations provided in the captions.

Note: In Figures 10.6–10.10, dimensions are given in meters (with units indicated) or in millimeters (without units).

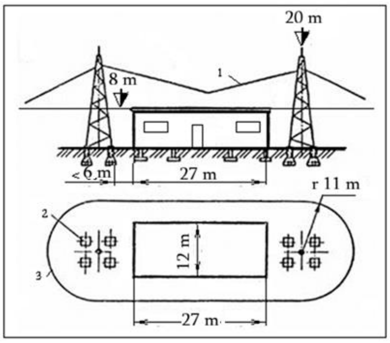

Fig. 10.6. Protection of a Category I building with a separate double rod-type lightning rod (soil resistivity 300 Ω·m):
1 – boundary of protection zone; 2 – grounding electrodes (foundation steps); 3 – protection zone boundaries at 8 m height

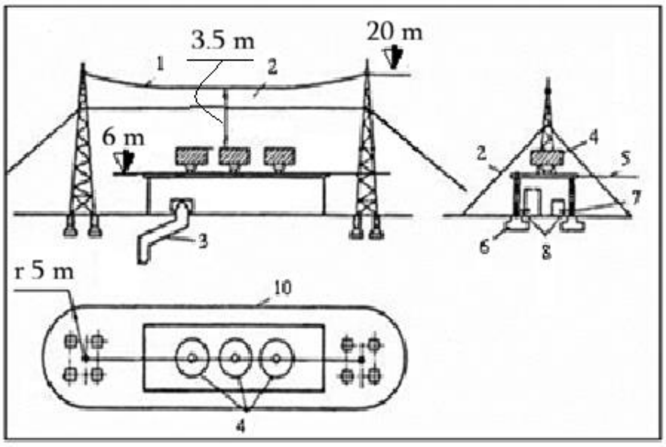

Fig. 10.7. Protection of a Category I building with a separate wire-type lightning rod (soil resistivity 300 Ω·m):
1 – wire; 2 – boundary of protection zone; 3 – inlet of underground pipeline; 4 – boundary of explosive concentration spread; 5 – reinforcement connected by welding; 6 – reinforced concrete foundation; 7 – connecting elements of equipment; 8 – grounding conductor (steel strip 4×40 mm); 9 – grounding electrodes (foundation steps); 10 – protection zone boundary at 10.5 m level

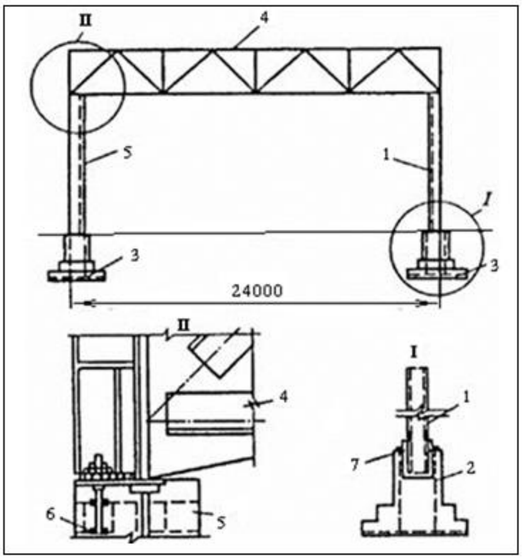

Fig. 10.8. Protection of a Category I building using metal trusses (reinforcement used as conductor and grounding):
1 – column reinforcement; 2 – foundation reinforcement; 3 – grounding electrode; 4 – steel truss; 5 – reinforced concrete column; 6 – anchor bolts welded to reinforcement; 7 – connecting element

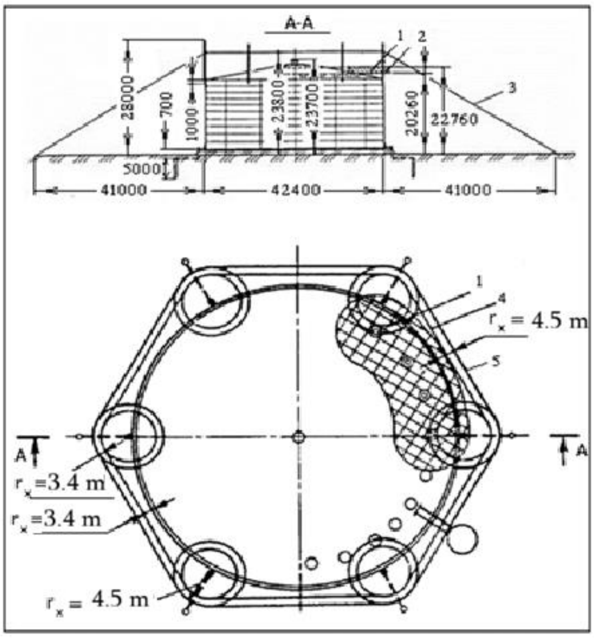

Fig. 10.9. Lightning rod for a metal reservoir with 20,000 m³ capacity:
1 – breathing valve; 2 – nozzle for explosive gas concentrations; 3 – boundary of protection zone; 4 – protection zone boundary at 23.7 m height; 5 – same at 22.76 m height

ISO 11625 and **ISO 9809** provide the internationally recognized framework for the safe design, handling, and storage of compressed and liquefied gas cylinders. These standards specify cylinder construction requirements, testing procedures, and labeling practices to ensure reliability and safety in industrial and laboratory environments. **IEC 60079** complements this by integrating gas cylinder safety into electrical installations, particularly in hazardous areas where explosive atmospheres may occur. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training for handling compressed and liquefied gases. **WHO** recommendations add a public health perspective, emphasizing the importance of ventilation, protective equipment, and emergency protocols to reduce risks of suffocation, fire, or explosion. By linking the discussion of gas cylinders to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable. This connection highlights the importance of standardized approaches in safeguarding workers, installations, and the public against gas-related hazards.

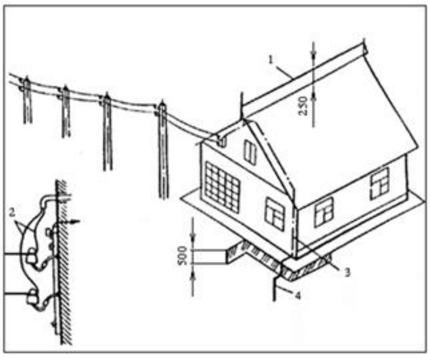

Fig. 10.10. Lightning rod for a rural house:
1 – wire-type receptor; 2 – entry of overhead power lines and metal hooks into the wall for grounding; 3 – conductor; 4 – grounding electrode

10.11. Practical Calculation Examples

Discharge Energy Calculation

Formula: $E=0.5CU^2$

• E – discharge energy, J;

• C – capacitance, F;

• U – potential difference, V.

Example:

C = 100 pF = $100x10^{-12}$ F;

U = 20 kV= 20 $x10^3$ V.

$E = 0.5x100x10^{-12}x(20x10^3)^2 = 0.02$ Ҳ.

Answer: This energy is sufficient to ignite flammable gases.

Grounding Resistance Check

• Example 1: Measured resistance $R = 80$ Ω; Standard requirement ≤100 Ω → **Complies with norm.**

• Example 2: Measured resistance $R = 150$ Ω; Standard requirement ≤100 Ω → **Does not comply,** additional grounding required.

Determining Outlet Cross-Section for Relaxation Volume

Formula: $A = \frac{Q}{v}$

• A – cross-sectional area, m²;

• Q – liquid flow rate, m³/s;

• v – permissible velocity, m/s.

Example:

$Q = 0.5$ m³/s;

v = 0.2 m/s;

$$A = \frac{Q}{v} = \frac{0.5}{0.2} = 2.5 \text{ m}^2$$

Answer: Minimum cross-sectional area must be ≥2.5 m².

Determining Lightning Impulse Current

Formula: $I = \frac{Q}{t}$

• I – current, A;

• Q – charge, C;

• t – time, s.

Example:

Q = 100 C; t = 0.001 s;

$I = \frac{100}{0.001} = 100{,}000\, A = 100\, kA$;

Answer: Lightning impulse current magnitude is 100 kA.

Determining Air Breakdown Voltage

Formula: $\boldsymbol{U = E_{br}d}$

• $\boldsymbol{U}$ – voltage, kV;

• $\boldsymbol{E_{br}}$ – breakdown strength of air = 3 kV/mm;

• $\boldsymbol{d}$ – thickness of air layer, mm.

Example:

$d = 2, mm$

$U = 3 \times 2 = 6, kV$

Answer: Breakdown voltage for a 2 mm air layer is 6 kV.

The examples presented in this section are provided for illustrative and educational purposes only. They demonstrate how theoretical principles and risk assessment methods can be applied in practice, helping students and professionals understand the logic behind calculations. These examples are not intended to replace or supersede the requirements of **IEC 62305**, **IEC 60364**, **ISO 45001**, or other international standards. For actual design, installation, or safety evaluations, practitioners must always rely on the official standards and validated measurement procedures. By including practical calculations alongside theoretical explanations, the monograph enhances accessibility and didactic clarity, while maintaining alignment with internationally recognized safety frameworks.

11. High-Pressure Equipment

11.1. Guide
for Chapter Eleven

- **High-pressure equipment** (tanks, cylinders, boilers, compressors) is used in engineering for the storage and transportation of gases, liquids, and steam.
- **Main hazards:** explosion and fire.
- **Safe operation** requires strict compliance with design, installation, registration, inspection, and maintenance procedures.
- **Materials** must meet mechanical and technological requirements ($\sigma_{flex}, \sigma_{tensile}$).
- **Construction** must avoid stress concentration (circular/elliptical sections).

Table 11.1. Quick Conversion of Pressure Units

Megapascal (MPa)	Pascal (Pa)	Atmosphere (atm)	kg/cm²
0.1	100,000	~0.99	~1.02
0.2	200,000	~1.97	~2.04
0.5	500,000	~4.93	~5.10
1.0	1,000,000	~9.87	~10.20
2.0	2,000,000	~19.74	~20.40
4.0	4,000,000	~39.47	~40.80
6.0	6,000,000	~59.21	~61.20
8.0	8,000,000	~78.95	~81.60
10.0	10,000,000	~98.68	~102.00

Explanation:

- **MPa → Pa:** $1\,\text{MPa} = 10^6\,\text{Pa}$.
- **Pa → atm:** $1\,\text{atm} = 101{,}325\,\text{Pa}$**.**
- **Pa → kg/cm²:** $Pa \to kg/cm^2$: $1\,\text{kg/cm}^2 \approx 9{,}800\,\text{Pa}$**.**

The table shows that $0.1\,\text{MPa} \approx 1\,\text{atm} \approx 1\,\text{kg/cm}^2$**, which provides a convenient starting point for students.**

Applied Standards and Compliance:

- **ISO 4126** → Defines requirements for safety valves and bursting discs. *ISO 4126-3:2020 — Safety devices for protection against excessive pressure — Part 3: Safety valves and bursting disc safety devices in combination.*
- **EN 13445** → European standard for the design of vessels and tanks. *Pressure equipment — CEN-CENELEC.*
- **ASME BPVC Section VIII** → Widely used American code in international practice. *Rules for Construction of Pressure Vessels, Division 1 (2025).*
- **IEC 61508** → Functional safety standard for electronic systems. *IEC 61508-1:2010.*
- **ILO OSH Standards** → International Labour Organization’s safety norms. *ILO Guide to International Labour Standards on Occupational Safety and Health.*

This guide introduces the scope of Chapter XI, outlining the principles of safety for high-pressure equipment. It emphasizes that the following sections are aligned with internationally recognized standards, including **ISO 4126** for safety devices, **ISO 11625** for gas cylinder handling, and **IEC 60079** for electrical safety in hazardous environments. By framing the chapter with these standards, the guide ensures that readers understand both the theoretical foundations and the practical measures required for safe operation, maintenance, and risk management of high-pressure systems.

11.2. Fundamental Requirements for Pressure Equipment

Scope of Application

In engineering practice, high-pressure apparatus and equipment — tanks, cylinders, steam and hot-water boilers, compressors, etc. — are widely used for storing and transporting liquefied, gaseous, and dissolved substances. Their operation requires technical personnel to strictly follow safety rules, norms, and instructions for safe use. Violation of these norms or operating regimes, as well as disorder in control and measuring devices, creates hazardous factors, the most significant being explosion and fire.

Explosion Work During Adiabatic Expansion

The work of an explosion during adiabatic gas expansion is determined by the formula

$$A = \frac{PV}{k-1}\left[(k-1)[1-\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right] \quad (11.1)$$

where: P_1 and P_2 - initial and final gas pressure in the vessel, MPa; V - initial gas volume, m³; k - adiabatic index (for air, approximately $k = 1.41$)

For an ideal gas

$$k = \frac{c_p}{c_v} \quad (11.2)$$

where: c_p - specific heat at constant pressure, J/(kg·K); c_v - specific heat at constant volume, J/(kg·K).

Explosion Power

In case of rupture of a high-pressure vessel, the explosion power is defined as

$$N = \frac{A}{t} \quad (11.3)$$

where: A - work performed by compressed air during expansion until internal pressure equals atmospheric pressure, J; t - time during which the work is performed, s.

For example, at a pressure of 1 MPa, within 0.1 s, the power reaches **10 MW.**

Didactic note: This illustrates how compressed air can release enormous energy almost instantaneously, highlighting why strict safety measures are essential.

Preventive Measures

To avoid explosions, the following are required:

• Proper design, installation, repair, and operation of high-pressure equipment according to instructions.

• Mandatory registration of installed equipment with the State Technical Supervision Inspectorate.

Installation of Equipment

• Registered vessels must be installed in specially designated buildings.

• Partition walls separating them from adjacent industrial buildings must be solid and allow inspection, cleaning, and repair.

• Vessels must be installed securely to prevent overturning.

• Auxiliary structures (stairs, platforms, observation devices) must be provided for safe servicing.

After installation and registration, each vessel must display:

• Registration number

• Permissible pressure

• Date of next inspection and hydraulic test

Types of Vessels Covered by These Rules

1. Vessels operating at excess pressure above 0.07 MPa.
2. Barrels and tanks used for transporting compressed gas, with pressure ≥ 0.04 MPa at +50 °C.
3. Cylinders for storing and transporting compressed, liquefied, or mixed gases at pressures above 0.07 MPa.

ISO 4126 establishes the internationally recognized framework for safety devices used in high-pressure equipment, specifying design principles, performance requirements, and testing procedures to ensure reliability under extreme conditions. **ISO 11625** complements this by defining safe handling and storage practices for gas cylinders, ensuring that equipment meets durability and labeling requirements. **IEC 60079** integrates electrical safety considerations, particularly in hazardous environments where high-pressure systems may interact with explosive atmospheres. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training for the safe use of high-pressure equipment. **WHO** recommendations add a public health perspective, emphasizing ventilation, protective clothing, and emergency preparedness to minimize risks of explosion, suffocation, or mechanical failure. By linking the basic requirements for equipment to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

11.3. Control and Maintenance

For the safe operation of high-pressure vessels, an inspector is appointed by enterprise order. The inspector must belong to the technical staff, be at least 18 years old, have completed industrial training and instruction, and be certified by a qualification commission. Certification is confirmed by a certificate signed by the chairman of the commission.

Every 12 months, the inspector's knowledge is re-examined by a commission within the enterprise. Results must be documented in a protocol. At the workplace, instructions for the operating regime, developed and approved by the administration, must be displayed.

Additional note: The inspector's role is not limited to technical inspection. He is also responsible for informing personnel, explaining safety rules, and strengthening the culture of safety within the enterprise.

Operation of vessels must be stopped in the following cases:

• Excessive pressure beyond permissible limits;
• Malfunction of the safety valve;
• Detection of cracks, significant wall thinning, or leakage in weld seams;
• Fire threatening the vessel;
• Malfunction of the manometer when pressure cannot be measured otherwise;
• Excessive reduction of liquid level in vessels using open flame;
• Malfunction of fastening elements or measuring instruments.

Fig. 11.1. Inspector's duties

It is prohibited to operate cylinders that:

• Have expired inspection periods;
• Have defective valves;
• Have damaged bodies;
• Have improper painting or incorrect labeling.

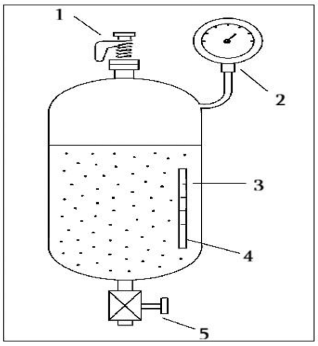

Fig. 11.2. Arrangement of safety devices on a high-pressure vessel:
1 - Safety valve; 2 - Pressure gauge; 3 - Liquid level gauge; 4, 5 - Shut-off device

Diagram Explanation:

Diagram 11.2 illustrates the layout of key safety devices on a high-pressure vessel.

• **Safety valve** is mounted at the top of the vessel and automatically releases gas when pressure exceeds safe limits, preventing explosions.

- **Pressure gauge** displays the internal pressure and allows the operator to detect deviations in time.
- **Liquid level gauge** ensures that the liquid inside the vessel does not drop below critical levels, which is especially important when open flame is used.
- **Shut-off device** is located at the bottom of the vessel and allows the operator to quickly stop the flow of liquid or gas when necessary.

These devices work in coordination, and malfunction of any one of them is a valid reason to immediately cease operation.

Additional note: Stopping operation at critical moments is a preventive measure that averts accidents and protects both personnel and infrastructure.

ISO 4126 establishes the internationally recognized framework for the control and maintenance of safety devices in high-pressure equipment, specifying inspection intervals, testing procedures, and documentation requirements to ensure reliability. **ISO 11625** complements this by defining safe handling and maintenance practices for gas cylinders, including periodic checks, valve inspections, and labeling updates. **IEC 60079** integrates electrical safety considerations, requiring maintenance protocols for equipment operating in hazardous environments where explosive atmospheres may occur. **ISO 45001** further strengthens occupational health and safety management systems by requiring preventive strategies, worker training, and continuous monitoring of maintenance activities. **WHO** recommendations add a public health perspective, emphasizing the importance of ventilation, protective equipment, and emergency preparedness during maintenance operations. By linking the control and maintenance of high-pressure equipment to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

11.4. Causes of Injuries

Enterprises use many devices operating under high pressure: compressors, steam and hot-water boilers, gas cylinders, tanks, steam pipelines, gas pipelines, etc.

Such equipment is dangerous due to the risk of explosion, which almost always causes severe injuries, destroys buildings, and results in major material losses.

Compressor explosions may occur due to ignition of lubricant vapors, overheating of walls, suction of dusty air, and other causes. Explosions may also result from filling a cylinder with the wrong gas. Oxygen cylinder explosions can be triggered by even a small amount of oil entering the valve interior.

Additional note: Explosions under high pressure almost always cause severe injuries — burns, fractures, or internal organ damage.

Figure 11.3 clearly demonstrates that the power of an explosion is inversely proportional to time. An explosion in a pressure vessel is characterized by the following stages:

1. Gas compression – the gas in the vessel is compressed to high pressure.

2. Crack formation – when the structure is damaged, a crack appears, which begins to release pressure and causes a drop in pressure.

3. Adiabatic expansion – the gas expands rapidly, converting almost all of its energy into mechanical work.

4. Rapid energy release – an explosion occurs, followed by injuries and property damage.

Explanation for students:

The diagram shows that an explosion is not an instantaneous event – it begins with minor damage, which quickly escalates into an uncontrolled release of energy. Therefore, prevention (inspection, monitoring, and recording) is not a formality but a necessary condition for protecting life.

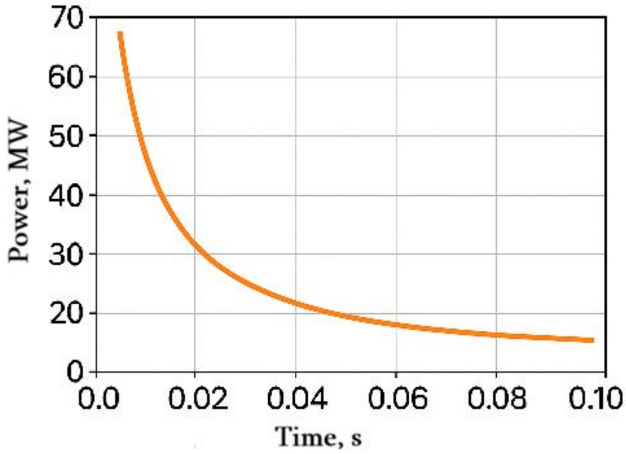

Fig. 11.3. Variation of explosion power over time

Particularly dangerous are primitively manufactured devices, since they are often made from unsuitable materials and usually lack control and safety equipment.

Additional note: Using such primitive devices in enterprises means that even minor defects can escalate into large-scale accidents.

ISO 4126 provides the internationally recognized framework for identifying causes of injuries related to high-pressure equipment, emphasizing failures of safety valves, overpressure events, and inadequate inspection practices. **ISO 11625** complements this by highlighting risks associated with improper handling, storage, or labeling of gas cylinders, which can lead to mechanical failure or chemical exposure. **IEC 60079** integrates electrical safety considerations, noting that sparks or faulty installations in hazardous environments can trigger explosions when combined with high-pressure systems. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training to reduce injury risks. **WHO** recommendations add a public health perspective, emphasizing ventilation, protective clothing, and emergency preparedness to minimize injuries caused by suffocation, burns, or mechanical accidents. By linking the causes of injuries to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

11.5. Requirements for Manufacturing Materials

Materials used for high-pressure equipment and vessels must meet strict requirements in terms of physical, mechanical, and technological properties.

Mechanical properties:

- **Ultimate tensile strength** ($\sigma_{tensile}$);
- **Yield strength** ($\sigma_{0.2'}$);
- **Impact toughness** (a_{impact});
- **Flexural strength** (σ_{flex}).

For equipment operating at high temperatures, properties are tested at different ranges (20–50 °C). A key indicator is the ratio of yield strength to tensile strength:

- For carbon steel ≤ 0.6;
- For alloy steel ≤ 0.7.

Steel testing:

Before welding, steel must be tested for strength, plasticity, and other properties. Additional tests include:

- Elastic modulus;
- Average coefficient of expansion;
- Thermal conductivity coefficient.

Steel must be produced by the open-hearth method or in electric furnaces.

Inspection openings:

If human entry into the vessel is impossible, oval or circular inspection openings of at least 80 mm diameter must be provided. Their number and placement must allow full inspection of internal surfaces exposed to high pressure.

For stationary vessels:

- Rectangular openings of 400×450 mm;
- Or circular openings of at least 450 mm diameter.

Design requirements:

- Incorrect design leads to stress concentration (e.g., rectangular cuts → cracks).
- Openings must be circular or oval.
- Example: for a boiler with 500 mm internal diameter, the entry opening size is 325×400 mm.
- Boiler bottoms must be convex, with height-to-diameter ratio ≥ 0.25, and joints must be rounded.

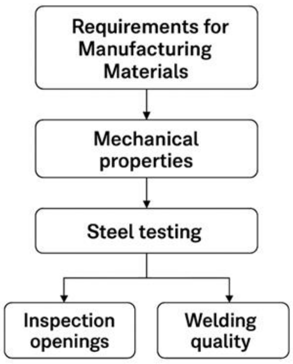

Fig. 11.4. Mechanical properties → Steel testing → Inspection openings → Welding quality

Welding quality:

Weld quality must be verified by:

- Visual inspection;

- Ultrasonic defectoscopy;
- Mechanical testing;
- Metallographic examination;
- Hardness measurement.

Additional note: Proper selection of materials and design ensures not only safety but also reliability during operation and the possibility of effective maintenance.

Detection of welding defects:

Visual inspection reveals:

- Weld shape and size deviations;
- Porosity and slag inclusions;
- Other technological flaws.

Ultrasonic defectoscopy detects:

- Internal porosity;
- Cracks;
- Unwelded areas.

Mechanical testing:

The goal is to determine whether weld strength meets required levels.

Tests include:

- Tension;
- Bending;
- Impact.

Maximum pressure calculation:

Maximum allowable pressure is calculated using

$$[P] = \frac{2(S-C)[\sigma]\varphi}{D+S-C} \quad (11.4)$$

where: S - wall thickness, cm; C - corrosion allowance, cm; $[\sigma]$ - allowable stress, MPa; φ - weld strength coefficient; D - internal diameter, m.

Control and safety instruments:

Equipment must be equipped with:

- Pressure gauge;
- Liquid level indicator;
- Temperature measuring devices.

Pressure gauges:

Indicate pressure of water, steam, and gases

- Can be **control** or **working** type.
- Accuracy class depends on pressure:
  - ≤ 2.3 MPa → ≥ 2.5
  - 2.3–14 MPa → ≥ 1.5
  - 14 MPa → ≥ 1.0
- Must be placed in visible locations.

Safety valves:

- Installed on steam and hot-water boilers;
- Open at set pressure to release excess steam;
- Automatically close after pressure drops;

- Can be **lever** or **spring** typ.
- Schematics shown in Fig. 11.5.

Safety valve discharge formulas:

Saturated steam (0.07–12.0 MPa)

$$(P_2 + 1) \leq 0{,}450(P_1 + 1);\ G_{sat} = 0{,}5aF(P_1 + 1) \qquad (11.5)$$

Superheated steam

$$(P_2 + 1) \leq 0.470(P_1 + 1);\ \ G_{super} = G_{sat}\sqrt{\frac{V_{sat}}{V_{super}}} \qquad (11.6)$$

Above 12 MPa

$$G = 0{,}72aF\sqrt{\frac{P+1}{V}} \qquad (11.7)$$

where: a - steam discharge coefficient; F - minimum flow area, mm²; P, P_1, P_2 – pressures, MPa; $V_{\{sat\}}, V_{\{super\}}, V$ - specific volumes, m³/kg.

Safety valve constructions:

A — **Lever valve:** operates through a weight corresponding to allowable pressure.

B — **Spring valve:** pressure is regulated by spring resistance proportional to allowable

Additional note:

These formulas show that valve discharge capacity depends not only on pressure but also on steam type and volume. Proper selection is critical to prevent explosions.

Safety valve parameters for hot-water boilers

$$ndh = \frac{Q}{KP(i - t_{in.})} \qquad (11.8)$$

where: n - number of valves; d - valve seat diameter, cm; h - valve lift height, cm; K - empirical coefficient:

$K = 1.35$ for low-lift valves ($\frac{h}{d} \leq \frac{1}{20}$);

$K = 70$ for high-lift valves ($\frac{h}{d} \leq \frac{1}{4}$);

P - maximum absolute pressure in the boiler, MPa; i - enthalpy of saturated steam at allowable pressure, J/kg; $t_{in.}$ - inlet water temperature, °C; Q - maximum boiler heat output, W.

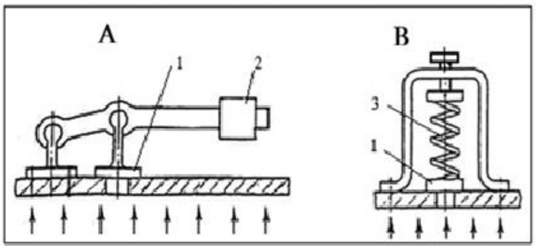

Fig. 11.5. Safety valve designs:
A - lever; B - spring; 1 - cap; 2 – weight; 3 - spring

Membranes as protective devices:

- Made of brittle or plastic materials.
- In case of danger, the membrane ruptures, pressure drops, and main structural elements are preserved.

Membrane calculation:

Brittle material:

$$\delta = 0{,}11r\sqrt{\frac{P}{\sigma_{flex}}} \tag{11.9}$$

Plastic material:

$$\delta = 2\,Pr/\,4\,\sigma_{tensile} \tag{11.10}$$

where: r - membrane radius, mm; P - pressure at which rupture occurs, MPa; σ_{flex} - flexural strength, MPa; $\sigma_{tensile}$ - tensile strength limit, MPa.

Automatic control equipment:

Steam and hot-water boilers are equipped with systems that automatically stop fuel supply in case of:

- Fire extinguishing;
- Emergency drop in air pressure.

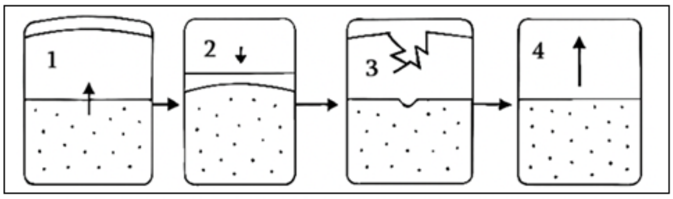

Fig. 11.6. Visual diagram of the membrane operation:
1 - normal state; 2 - pressure increase; 3 - membrane rupture,
4 - pressure drop

Additional note:

This section emphasizes that safety devices are diverse — valves, membranes, and automatic control systems work together to prevent explosions.

ISO 4126 establishes the internationally recognized framework for the selection and testing of materials used in high-pressure equipment, ensuring that safety devices and components maintain integrity under extreme conditions. **ISO 9809** complements this by specifying requirements for steel and composite gas cylinders, including mechanical strength, fracture resistance, and corrosion protection. **IEC 60079** integrates material considerations into electrical equipment design for hazardous environments, requiring non-sparking, durable, and chemically resistant materials to minimize explosion risks. **ISO 45001** further strengthens occupational health and safety management systems by requiring preventive strategies, worker training, and inspection protocols to ensure that materials used in manufacturing meet safety standards. **WHO** recommendations add a public health perspective, emphasizing the importance of safe material selection to reduce risks of toxic exposure, mechanical failure, and fire hazards. By linking the requirements for manufacturing materials to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

11.6. Safe Operation of Compressors

Hazards and Safety Measures

During compressor operation, the main hazard is the potential explosion caused by the decomposition products of oil present in compressed air. This risk is especially high in piston-type compressors. Oil decomposition releases flammable gases — for example, the breakdown of 20 grams of oil can produce approximately 2 cubic meters of explosive air mixture.

If the air contains oil vapor in the range of 6–11%, it may explode at temperatures around 200 °C. These decomposition products and fine oil droplets enter the pneumatic system (air ducts, air receivers, etc.), adhere to internal surfaces, and create explosion risks.

To prevent explosions and ensure safe compressor operation, the following measures must be taken:

- The temperature of compressed air must not exceed the allowable limit.
- Pressure inside the compressor cylinder must not exceed the standard level.
- Generation of explosive mixtures in the cylinder and air ducts must be avoided.

Thus, both stationary and mobile compressor units used for compressed air production can pose explosion risks. Compression processes follow the polytropic law

$$PV^n = const \qquad (11.11)$$

where P - gas pressure, MPa; V - specific volume, m³/kg; n - polytropic index.

As gas is compressed, its temperature increases proportionally to pressure. The final temperature is determined by the formula

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \qquad (11.12)$$

where T_1, T_2 - absolute gas temperature before and after compression, K; P_1, P_2 - absolute pressure before and after compression, MPa.

To prevent overheating in compressors, air or water cooling is used:

- **Air cooling —** for low-pressure compressors (up to 0.7 MPa);
- **Water cooling —** for high-pressure compressors.

Maximum temperature of compressed air must be:

- **160 °C** for single-cylinder compressors;
- **140 °C** per stage for multi-stage compressors.

Cooling water quality

- For normal operation, soft water must be used.
- Dirty or hard water forms deposits on cylinder and pipe walls, hindering performance.
- Regardless of water quality, cooling devices and pipes must be cleaned every two months.

Control equipment

Compressors must be equipped with:

- Pressure gauges;
- Safety valves;
- Thermometers.

For safe working conditions:

- The rotating parts and drive must be enclosed.

Compressor station building:

- Must be built of fire-resistant material.
- Must have a flat roof without attic.
- Must be separated from other buildings.

Static electricity hazard:

- When contaminated air flows through pipelines at 20 m/s, static electricity is generated.
- Voltage can reach 10,000 V, causing explosions.
- To prevent this, protective grounding is required.

Table 11.2. Air velocity variation by pressure

Air pressure, MPa	**0.6**	**0.6 - 1.0**	**1.0 - 2.0**	**2.0 – 3.0**	**3.0 – 10.0**	**10.0 – 20.0**
Air velocity, m/s	20.0	15.0	10.0	8.0	6.0	3.5

Sanitary norms:

- Free passage between units **≥ 1.5 m.**
- Distance from walls **≥ 1 m.**
- Temperature:
- Winter ≥ 10 ℃
- Summer ≤ 26 ℃

Additional note:

This section highlights that compressor safety depends not only on equipment but also on **environmental conditions, water quality, and building design.**

ISO 5389 and **ISO 10440** provide the internationally recognized framework for the safe operation of compressors, specifying design principles, performance testing, and maintenance requirements to ensure reliability under high-pressure conditions. **ISO 4126** complements this by defining safety devices such as relief valves, which protect compressors from overpressure events. **IEC 60079** integrates electrical

11.7. Compressor Maintenance and Lubrication

Importance of Lubrication

- Cylinder lubrication is essential for safe and efficient compressor operation.
- **Insufficient oil** → increased wear, premature failure of parts.
- **Excessive oil** → residue buildup in reservoirs and pipelines, risk of explosion.

Deposited oil contaminated with dust gradually turns into **carbon residue**, which is highly flammable.

- Excessive residue → piston jamming → compressor failure.
- Therefore, **lubricant quality** is critically important.

Oil Properties:

- **Explosion temperature** ≥ 220–240 ℃;
- **Autoignition temperature** ≥ 400 ℃.

Key characteristics:

- Viscosity;
- Thermal stability;
- Chemical resistance.
- Lubricants used:
- Compressor oil;
- Glycerin-based oil solutions.

Maintenance Schedule

- **Oil pump cleaning —** at least every 1.5 months;
- **Oil filter cleaning —** every 2 months.

Personnel Requirements

- Only individuals **18+ years old** with safety training may operate compressors

Knowledge checks:

- Workers — annually;
- Engineers — every 3 years;
- A safety instruction sheet must be posted in a visible location.

Pre-Startup Inspection

Check:

- Lubrication system;
- Cooling system.

Shutdown Conditions

- Compressor must be stopped if temperature or pressure exceeds allowable limits;
- For long downtimes → drain water via special valve.

Residue Removal

Cylinder walls cleaned using:

- Soap solution;
- 2–3% sulfonoid solution.

Control Instruments

Compressor must be equipped with:

- Pressure gauges;
- Thermometers;
- Safety valves.

Additional note:

Both under- and over-lubrication pose direct risks to compressor safety and reliability.

ISO 10440 provides the internationally recognized framework for the maintenance and lubrication of compressor units, specifying inspection intervals, lubrication methods, and performance testing to ensure reliability under high-pressure conditions. **ISO 4126** complements this by defining safety devices such as relief valves, which must be regularly maintained to prevent overpressure events. **IEC 60079** integrates electrical safety considerations, requiring maintenance protocols for compressors operating in hazardous environments where explosive atmospheres may occur. **ISO 45001** further strengthens occupational health and safety management systems by requiring preventive strategies, worker training, and continuous monitoring of maintenance activities. **WHO** recommendations add a public health perspective, emphasizing the importance of protective equipment, ventilation, and emergency preparedness during lubrication and servicing operations. By linking the maintenance and lubrication of compressor units to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

11.8. Steam and Hot-Water Boilers

Purpose

The purpose of boiler houses is to supply enterprises with steam and hot water for both technological processes and heating needs.

Classification of Boilers

Boilers are divided into two groups according to safety:

1. **High-pressure boilers**

- Steam boilers with operating (excess) pressure **greater than 0.07 Mpa;**
- Hot-water boilers with water temperature **above 115 °C.**

2. **Low-pressure boilers**

- Steam boilers with operating (excess) pressure **less than 0.07 MPa,** equipped with pressure-limiting safety devices;
- Hot-water boilers with water temperature **below 115 °C.**

Safety Requirements

- Steam boilers and apparatus are **closed high-pressure systems** requiring strict adherence to safety rules.
- Improper operation may lead to **explosions.**

Causes of Explosions

Based on statistical data, the main causes of boiler explosions are:

1. **Water shortage in the boiler —** water level must be at least 100 mm above the firebox ceiling.
2. **Scale formation on the inner wall —** poor heat transfer leads to overheating.
3. **Chemical corrosion of boiler walls —** reduces metal strength.
4. **Structural defects** and other factors.

Required Equipment

Every boiler must be equipped with:

- Water level indicator
- Pressure gauge
- Pump
- Safety valve
- Other auxiliary devices

These must be inspected within prescribed intervals.

Boiler House Construction

- Boilers must be installed in **separate buildings** with **two exits.**

• Walls must be **fire-resistant,** roofs **light and easily removable** to reduce explosion wave resistance.

Doors must open outward.

• Passage between boilers **≥ 1 m**, service space near firebox **≥ 2 m.**

Fig. 11.7. General view of a steam boiler

Lighting and Ventilation

- Boiler houses must have sufficient **natural and artificial lighting:**
- ≥50 lux at measuring instruments;
- ≥20 lux in other areas.
- Ventilation must ensure sanitary-hygienic conditions:
- Winter ≥12 °C;
- Summer ≤ outdoor temperature +5 °C.

Registration

• All high-pressure boilers (>0.07 MPa, up to 50 °C) must be **registered with state supervisory authorities.**

Registration requires:

- Passport with drawings;
- Manufacturing certificate;
- Building plan;
- Installation certificate;
- Data on materials, welding, test results, flushing;
- Certificate of wall durability at 450 °C.

Periodic Inspection

• Internal inspection — **every 4 years;**

• Hydraulic test — **every 2-8 years** (testing is performed once every 2-8 years, depending on the purpose of the device)**.**

• Hydraulic testing is also required before commissioning, after repair, and periodically during operation.

Hydraulic Testing

• Conducted at **1.5 times working pressure** (The **ASME BPVC VIII-1** standard indicates a coefficient of **1.3,** the European standard **EN 13445** - a coefficient of **1.25**, and ISO 4126 **does not indicate a numerical value** at all.);

• Boiler must withstand test pressure for 5 minutes;
• Results are satisfactory if **no cracks, ruptures, or residual deformations** are observed.

Circulation

• All boilers must operate under continuous water circulation;
• Violation leads to system damage.

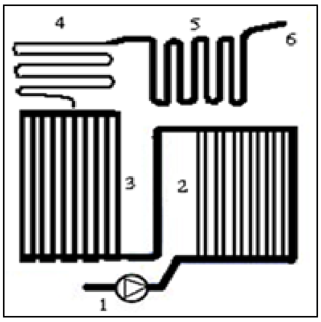

Fig. 11.8. Water and steam circulation in a direct-fired boiler:
1 - pump; 2 - flow controller; 3, 4 - evaporation pipeline;
5 - steam superheater; 6 - consumer

Fittings and Control Instruments

• Boilers must be equipped with:
• Drain and shut-off devices;
• Valves;
• Measuring instruments;
• Small boilers may use **one safety valve;**
• Boilers with capacity >100 m³ steam/hour require **two safety valves;**
• Valves automatically release steam when pressure exceeds normal limits;
• Only spring-type valves are used for excess pressure;
• If pressure exceeds working pressure by 5%, the **valve must open immediately.**

Blowdown

• Valve performance is checked by **blowdown.**
• Frequency:

$P_{\{work\}} \leq 2$ MPa → at least once daily;
$P_{\{work\}} \geq 2$ MPa → at least once per shift.

• Blowdown is performed by **two operators:**
• One monitors **pressure and water;**
• The other alternately **opens and closes valves;**
• Sequence: **open second valve, then first**; close in **reverse order;**
• After testing, water level must be **≥3 cm above** permissible minimum;
• Blowdown is performed 8–10 minutes after water supply stops.

Safety Valve Calculation

Safety valves are calculated using formula (11.13), recommended by the Georgian State Technical Supervision Inspectorate

$$nd_{valve}h = \frac{Qg}{kP(t-c\cdot 10^2)} \tag{11.13}$$

where: Q- maximum heat quantity, kJ; $g = 9.81$ m/s² - gravitational acceleration; n - number of valves; h - valve liftheight, mm; d_{valve} - valve diameter, mm; k - coefficient for low-pressure valves; P - maximum allowable pressure, Mpa; c - specific heat capacity, kJ/(kg·°C).

Valve operation is tested by **lifting the handle:**

- At red zone of pressure gauge, valve must open;
- Valves are adjusted to slightly above normal pressure.

Pressure Gauges and Water Control

- All steam boilers must have **sealed, tested pressure gauges;**
- At least *two depth gauges* for water level control.

Installation Location

Boiler houses must not be located near or inside residential buildings.

- If close, a **solid wall** must be built and condition met

$$(t - 100)V \leq 5 \tag{11.14}$$

where: t - fluid temperature during compression, °C; V - boiler volume, m³;

- In industrial buildings, steam boilers ≤4 t/h capacity are allowed
- Hot-water boilers must meet conditio:

$$(t - 100)V \leq 100 \tag{11.15}$$

where t - saturated steam temperature at working pressure, °C; V - water volume in boiler, m³.

Additional Requirements

- All fittings and instruments must be accessible for service;
- Electrical lighting allowed, voltage ≤13 V;
- Boilers operating on liquid or gas fuel must follow special instructions;
- Special attention must be paid to ignition procedures and gas leakage prevention;
- Personnel must take effective measures in case of accidents.

Final Note:

Section 11.8 comprehensively outlines the **purpose, classification, safety requirements, registration, inspection, blowdown procedures, valve calculations, installation rules, and operational guidelines** for steam and hot-water boilers.

ISO 16528 provides the internationally recognized framework for the design, construction, and operation of steam and hot-water boilers, ensuring that equipment meets essential safety requirements. **ISO 4126** complements this by specifying safety devices such as pressure relief valves, which protect boilers from overpressure events. **IEC 60079** integrates electrical safety considerations, particularly in boiler rooms where explosive atmospheres may occur, requiring proper installation and maintenance of electrical systems. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training for safe boiler operation. **WHO** recommendations add a public health perspective, emphasizing ventilation, protective clothing, and emergency preparedness to minimize risks of burns, explosions, or suffocation. By linking the discussion of steam and hot-water boilers to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

11.9. Safe Operation of High-Pressure Pipelines

General Requirements

The State Technical Supervision Inspectorate has established regulations concerning:

- The installation and operation of **high-pressure pipelines;**
- Pipelines used for transporting gases and liquids at **temperatures above 120 °C** and **pressures above 0.1 MPa.**

Calculation and Construction

- Pipeline dimensions are selected according to the **quality and quantity of the transported material.**
- **Steel pipelines** are most widely used, with joints made exclusively **by welding.**
- All pipelines carrying hot steam or hot water with external temperatures above 45 °C must be **insulated with protective materials.**

Safety Color Coding

Pipelines must be painted differently for safe identification:

- **Superheated steam** → black stripes on a red background;
- **Technical water** → black stripes on a green background;
- **Compressed air** → black stripes on a blue background.

Thermal Expansion

Length variation is determined by

$$\Delta L = aL(t_2 - t_1) \tag{11.16}$$

where: ΔL - increase in pipeline length, m; L - initial length, m; a - coefficient of linear expansion; t_1, t_2 - initial and final temperatures, °C.

Allowable thermal stress is calculated by

$$\sigma_1 = E\frac{\Delta L 10^{-3}}{L} \tag{11.17}$$

where: σ_1 - thermal stress, MPa; E - modulus of elasticity for the pipeline material, Pa.

Installation Requirements

- Pipelines under roads or alongside them must be at least **4.5 m below** the surface.
- Pipelines crossing railways must be buried at least **6 m deep.**
- Horizontal sections must have a slope of at least **0.1% (1‰) with drainage.**
- Pipelines may be installed in **walls and channels of buildings.**
- Hot water and steam pipelines must be placed **above ground in accessible locations.**
- All joints must be made by **welding only.**
- Air pipelines must be **insulated** to prevent freezing.
- Pipelines near heat-radiating equipment must be protected against temperature rise.
- Distance from cables, electrical lines, and equipment must be at least **0.5 m.**
- Pipelines must be fixed only on **fire-resistant structures.**
- Frozen pipelines may be thawed only with **hot water.**
- Pipelines must be cleaned of oily deposits at least once **every 6 months.**

Operation and Documentation

- Every high-pressure air pipeline must have a **passport** recording inspections and modifications during operation.

- Operation is permitted:
- **With authorization from the Boiler Inspectorate,** if the pipeline is registered;
- **With authorization from a responsible person appointed by the administration,** if not registered.

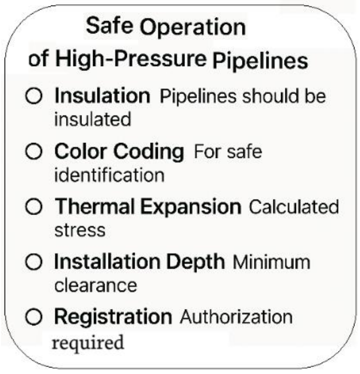

Fig. 11.9. Safe Operation of High-Pressure Pipelines

ISO 13623 provides the internationally recognized framework for the design, operation, and maintenance of high-pressure pipelines, specifying requirements for integrity management, corrosion protection, and emergency response**. ISO 4126** complements this by defining safety devices such as relief valves, which protect pipelines from overpressure events. **IEC 60079** integrates electrical safety considerations, requiring proper installation and monitoring of electrical systems in hazardous areas where pipelines may transport flammable substances. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training for safe pipeline operation. **WHO recommendations** add a public health perspective, emphasizing emergency preparedness, protective equipment, and awareness campaigns to minimize risks of explosion, toxic exposure, or mechanical failure. By linking the safe operation of high-pressure pipelines to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

11.10. Cylinders for Compressed and Liquefied Gases

Construction and Operating Conditions

Gas cylinders are made of **carbon or alloy steel**, with a **cylindrical shape, convex bottom**, and **narrow neck.** They are designed to transport compressed, dissolved, or liquefied gases within a temperature range of **–50 °C to +50 °C.**

Capacity and Pressure

Cylinders are classified by volume:

- **Small —** up to 12 liters;
- **Medium —** up to 50 liters;
- **Large —** above 50 liters.

Maximum working pressure: **19.6 MPa**

- Cylinders rated at 9.8, 14.7, or 19.6 MPa are made seamless from **carbon steel;**

- 14.7 and 19.6 MPa cylinders may also be made from **alloy steel;**
- Cylinders with pressure <3 MPa may be **welded.**

Common sizes: 0.4; 0.7; 1.0; 1.3; 2; 3; 4; 5; 6; 7; 8; 10; 12; 20; 25; 32; 40; 50 liters

Explosion Risks

All gas-filled cylinders pose explosion risks, regardless of gas type.

- **Acetylene cylinders** are especially dangerous if pressure exceeds **0.2 MPa;**
- To mitigate this, acetylene is absorbed into **porous material**, allowing safe pressure up to **1.6 MPa;**
- **Oxygen cylinders** may explode if the neck or fittings are contaminated with **oil or grease;**
- Cylinders must be cleaned with solvents before filling.

Other causes of explosion:

- Gas expansion due to overheating
- Valve detachment from the neck
- Cylinder impact or fall
- Extreme temperatures
- Filling with incompatible gases
- Overly rapid filling

Pressure-Temperature Relationship for Liquefied Gases

$$\Delta L = aL(t_2 - t_1)$$

where ΔL - increase in the length of the pipeline, m; a - thermal expansion coefficient; L - initial length of the pipeline, m; t_1, t_2 - initial and final temperatures, ℃.

Safety valves must be sized so that vapor pressure does not exceed working pressure by more than 15%.

Free Volume for Thermal Expansion

$$\sigma_1 = E\frac{\Delta L 10^{-3}}{L}$$

where σ_1- thermal stress, MPa; E - modulus of elasticity for a given pipeline, Pa.

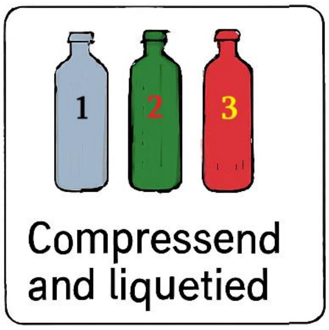

Fig. 11.10. Color coding and marking of cylinders:
1 - oxygen (cylinder - light blue, inscription - black, compressed);
2 - hydrogen (cylinder - dark green, inscription - red, compressed);
3 - propane (cylinder - red, inscription - yellow, liquefied)

Cylinder Marking

Markings are applied to the **neck** and **body** at the factory:

- Manufacturer's logo;
- Serial number;
- Date of manufacture and next inspection;
- Type of thermal treatment;
- Working and test pressure (kg/cm² or bar);
- Volume (L);
- Mass without valve and cap (kg);
- Warranty period: **2 years.**

Color Coding and Identification

To avoid errors, cylinders are painted according to gas type.

Table 11.3. Cylinder Colors and Labels

Gas	State	Pressure, kg/cm²	Color	Label	Label Color
Acetylene	Dissolved	19	White	Acetylene	Red
Butane	Liquefied	16	Red	Butane	White
Hydrogen	Compressed	150	Dark Green	Hydrogen	Red
Oxygen	Compressed	150	Light Blue	Oxygen	Black
Methane	Compressed	150	Red	Methane	Yellow
Propane	Liquefied	16	Red	Propane	Yellow

Safety Measures:

1. Store cylinders in locations protected from **impact, sparks, chemicals, and temperatures >40 ℃;**
2. Secure cylinders on **racks or carts,** shielded from **rain and sunlight;**
3. Prevent **oil or grease** contamination on **oxygen cylinders;**
4. Repairs must be done **only at filling stations;**
5. Maintain **≥1 m distance from radiators, ≥5 m from open flames;**
6. Avoid contact with **electrical conductors;**
7. During filling, pressure must match **Table 11.4** for temperatures between **–50** ℃ **and +30** ℃**.**

Table 11.4. Pressure Norms for Cylinders

Temperature, ℃	**Pressure at 14.7 MPa group, MPa/kg/cm²**	**Pressure at 19.6 MPa group, (MPa/kg/cm²**
-50	9.1 (93)	12.0 (123)
-40	9.8 (102)	13.2 (135)
-30	10.8 (111)	14.3 (146)
-20	11.7 (119)	15.5 (158)
-10	12.4 (127)	16.6 (169)
0	13.2 (135)	17.5 (179)
+10	14.0 (143)	18.6 (190)
+20	14.7 (150)	19.6 (200)
+30	15.4 (157)	20.6 (210)

Note:

- For 14.7 MPa group → allowable deviation ±0.05 MPa (±5 kg/cm²)
- For 19.6 MPa group → allowable deviation ±0.10 MPa (±10 kg/cm²)

Personnel Requirements

Only individuals who have completed **specialized training** and follow **technical safety rules** may work with cylinders.

Unit Conversion Reference

- 9.8 MPa = 100 kg/cm² = 100 atm
- 14.7 MPa = 150 kg/cm² = 150 atm
- 19.6 MPa = 200 kg/cm² = 200 atm

ISO 11625 and **ISO 9809** provide the internationally recognized framework for the safe design, handling, and storage of compressed and liquefied gas cylinders. These standards specify cylinder construction requirements, testing procedures, and labeling practices to ensure reliability and safety in industrial and laboratory environments. **IEC 60079** complements this by integrating gas cylinder safety into electrical installations, particularly in hazardous areas where explosive atmospheres may occur. **ISO 45001** further strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training for handling compressed and liquefied gases. **WHO recommendations** add a public health perspective, emphasizing the importance of ventilation, protective equipment, and emergency protocols to reduce risks of suffocation, fire, or explosion. By linking the discussion of gas cylinders to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

11.11. Sample Practical Calculations

Example 1: Explosion Work and Power

Given:

- Initial pressure P_1=8 MPa
- Final pressure P_2=0.1 MPa
- Volume V =0.05 m³
- Adiabatic index k=1.41

Explosion work formula:

$$A = \frac{P_1 \cdot V}{k-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right]$$

Steps:

1. Pressure ratio:

$$\frac{P_2}{P_1} = \frac{1 \cdot 10^5}{8 \cdot 10^6} = 0.0125$$

2. Exponent:

$$\frac{k-1}{k} = \frac{0.41}{1.41} \approx 0.291$$

3. Power of ratio:

$$\left(\frac{P_2}{P_1}\right)^{0.291} = (0.0125)^{0.291} \approx 0.33$$

4. Bracket: 1-0.33=0.67
5. Multiply:

$$\frac{P_1 \cdot V}{k-1} = \frac{8 \cdot 10^6 \cdot 0.05}{0.41} = \frac{400000}{0.41} \approx 975610$$

6. Final result:

$$A = 975610 \cdot 0.67 \approx 653{,}000\,\text{J}$$

Power Calculation for Different Time Intervals

Explosion work: $A \approx 6.53 \cdot 10^5$ J

Formula: $N = \frac{A}{t}$

Calculation:

1. **= 0.1 s**

$$N = \frac{6.53 \cdot 10^5}{0.1} = 6.53 \cdot 10^6\ \text{W} = 6.53\,\text{MW}$$

2. **t = 0.05 s**

$$N = \frac{6.53 \cdot 10^5}{0.05} = 1.306 \cdot 10^7\ \text{W} = 13.06\,\text{MW}$$

3. **t = 0.01 s**

$$N = \frac{6.53 \cdot 10^5}{0.01} = 6.53 \cdot 10^7 W = 65.3\,\text{MW}$$

Conclusion:

Explosion power is **inversely proportional to time**.

Faster expansion → higher power.

At 0.01 s, power reaches **65 MW**, equivalent to a large power plant.

Example 2: Explosion Power in Air

Given:

- Explosion work A=5000 J
- Time t=0.1 s

Power:

N=$\frac{5000}{0.1}$ = 50000 W = 50 kW.

Student Exercises

1. Convert 0.07 MPa to pascals, atmospheres, and kg/cm^2

   → 70,000 Pa ≈ 0.69 atm ≈ 7.14 kg/cm^2

2. Convert 2.5 MPa to atmospheres

   → $\frac{2.5 \cdot 10^6}{101{,}325} \approx 24.7$ atm

3. Convert 1 MW to kg/cm^2

   → $\frac{1 \cdot 10^6}{9{,}800} \approx 102$ kg/cm^2.

Applicable Standards

- **ISO 4126** — Safety valves
- **EN 13445** — Pressure vessel design
- **ASME BPVC** — International boiler and pressure vessel code
- **IEC 61508** — Functional safety
- **ILO** — Occupational safety norms

The examples presented in this section are provided for illustrative and educational purposes only. They demonstrate how theoretical principles and risk assessment methods can be applied in practice, helping students and professionals understand the logic behind calculations. These examples are not intended to replace or supersede the requirements of **ISO 11625**, **ISO 9809**, **IEC 60079**, or other international standards. For actual design, installation, or safety evaluations, practitioners must always rely on the official standards and validated measurement procedures. By including practical calculations alongside theoretical explanations, the monograph enhances accessibility and didactic clarity, while maintaining alignment with internationally recognized safety frameworks.

12. Cement Production

12.1. Guide for Chapter Twelve

Data on cement production (2020–2025): From a global perspective, cement production remains one of the most energy-intensive and environmentally harmful — highly polluting — sectors. In 2023, the industry emitted approximately 2.4 billion tons of CO_2 (about 6% of total global emissions). By 2025, production is expected to exceed 4 billion tons, with CO_2 emissions projected to account for more than ~8% of the global total.

The key environmental indicators for the specified period are summarized in Table 1.

Table 1. Key Environmental Indicators (2020–2025)

Indicator	2020	2023	2025 (Forecast)	Note
CO^2 emissions	~2.3 Gt	2.4 Gt [4]	>4 Gt [7]	Industry is the 4th largest global polluter
Emission intensity	0.60 tCO^2e/t	0.58 tCO^2e/t [57]	Slightly reduced	High clinker share continues to raise intensity [9]
NO_x	High level	Stable	Reduction attempts (water injection, low-NO_x burners) [10]	Main source: kilns
SO^2	Regionally variable	Increases with high sulfur content	Scrubbers and $\frac{CaO}{Ca(OH)^2}$ sorbents applied [1]	-
Dust (PM10/PM2.5)	High	Controlled with filters	Closed systems, cyclones, fabric filters [1]	-
Energy consumption	~3.3 GJ/t	Stable	Reduced through use of alternative fuels [10]	-

In Table 12.1, practical examples of emission reduction can be observed in Germany, Turkey, and Denmark.

- **Heidelberg Cement (Germany):** NO_x reduction is achieved through water injection into the kiln.
- **Turkey:** Heat recovery from clinker coolers is used for electricity generation, improving efficiency.
- **Denmark:** RDF (Refuse Derived Fuel) is used instead of coal. This example deserves closer attention.

Denmark successfully implements the European cement industry's strategy, which aims for more than 60% of fuel to be waste-based by 2050. Denmark is considered one of the leaders in this transition.

- **Alternative fuels:** Many Danish cement plants already replace coal with municipal waste, biomass, and non-hazardous industrial residues.
- **Co-processing:** This process simultaneously provides energy and recycles materials, aligning with the principles of the circular economy.

Denmark's example is illustrated in comparative Table 12.2.

Table 12.2 — Fuel Sources in Cement Production [50, 51]

Fuel Source	Use in Denmark	Environmental Effect
Coal	Minimized	High CO^2, NO_x
Natural gas	Limited	Relatively lower CO^2

Waste (RDF, municipal, industrial)	Widely used	Reduces waste volume and fossil fuel use
Biomass	Increasing share	Renewable, low emissions

Why Table 12.2 is important:

- **Ecological benefit:** Waste utilization reduces CO_2 emissions and decreases landfill loads.
- **Economic benefit:** Fuel costs are reduced, since waste is often cheaper than coal or gas.
- **Strategic benefit:** Denmark strengthens energy security by reducing dependence on imported coal.

This guide introduces the scope of Chapter XII, outlining the principles of safety and risk management in cement production. It emphasizes that the following sections are aligned with internationally recognized standards, including **ISO 14001** for environmental management, **ISO 45001** for occupational health and safety, and **IEC 60079** for electrical safety in hazardous environments. By framing the chapter with these standards, the guide ensures that readers understand both the theoretical foundations and the practical measures required for safe, sustainable, and efficient cement production.

12.2. Hazardous and Harmful Factors in Cement Production

International technical standards and guidelines on labor, health, and environmental protection — Environmental, Health, and Safety Guidelines for Cement and Lime Manufacturing (EHSGCLM) — provide examples based on international industry practices. The application of this technical documentation must be harmonized with hazard and risk factors, which should be defined and assessed for each specific project in accordance with environmental requirements.

Environmental assessments must take into account the country's specific conditions, the environment's assimilation capacity, and other relevant factors. Specific technical recommendations should be applied only on the basis of conclusions made by qualified and experienced specialists.

If international requirements and national regulations in the field of technical standards do not align, then in projects financed by the International Finance Corporation (IFC), stricter requirements must be applied.

Cement production has used and continues to use different types of kilns:

- **PHP (Preheater-Precalciner Kiln) —** operating on preheating and precalcination principles;
- **PH (Preheater Kiln) —** operating only on preheating principles;
- **LD (Long Dry Kiln) —** operating on long dry processes.

All of these can function under semi-dry, semi-wet, and wet methods. From an environmental perspective, PHP kilns are preferred. Shaft kilns are also used, but they are economically viable only for small-scale production and are usually phased out during equipment replacement or modernization.

Cement production requires large amounts of energy for raw material processing. The raw mix for clinker production mainly consists of:

- limestone ($CaCO_3$),
- clay (aluminum silicates),
- sand (SiO_2),
- iron ore.

Clinker is ground together with gypsum or limestone to produce cement. The production process is schematically shown in Figure 12.1.

After preliminary mixing, the raw materials are ground to obtain a homogeneous blend. The quality of grinding and particle size distribution are crucial for the efficiency of clinker calcination.

The next stage is calcination in a rotary kiln — the decomposition of $CaCO_3$ at approximately 900 °C. During this process, CO_2 (carbon dioxide), a greenhouse gas, is released, and quicklime (CaO) is obtained.

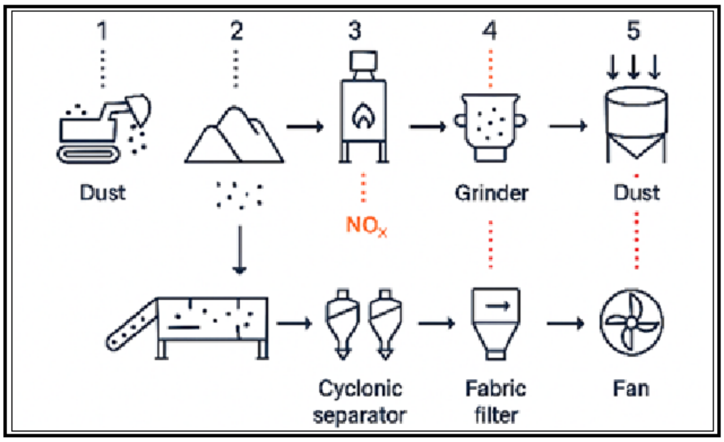

Fig. 12.1. Cement production process flow (raw material → clinker → cooling → grinding → storage)

The next stage is **clinker formation:** quicklime (CaO) at higher temperatures (1400–1500 °C) reacts with silicon oxides, aluminum oxides, and iron oxides. To achieve the required composition, additional components may be added to the raw mix (e.g., quartz sand, molding sand, iron oxide residues, aluminum oxide residues, blast furnace slag, gypsum residues). At this stage, the flame and exhaust gases in the kiln reach temperatures of around 2000 °C.

Clinker cooling: Hot clinker discharged from the kiln must be cooled rapidly in a cooler to improve quality. For energy recovery, secondary air is heated in the cooler. Modern production mainly uses grate coolers, which have replaced older satellite coolers.

Grinding and final product: The cooled clinker is ground together with gypsum and limestone to produce Portland cement. With the addition of other components, composite or multi-component cement can be obtained.

Storage: The finished cement is stored either in bags or silos. In silos, cement is kept in bulk form; in bags, it must be stacked on wooden pallets of standard size and strength, with or without wheels.

Environmental control: During production, monitoring must cover:

1. Atmospheric emissions;
2. Types of energy and fuels used;
3. Wastewater discharges;
4. Solid waste;
5. Noise.

Additional note: Cement production accounts for ~6–8% of global CO_2 emissions.

ISO 14001 provides the internationally recognized framework for identifying and mitigating environmental hazards in cement production, including dust emissions, noise, and waste management. **ISO 45001** complements this by requiring hazard identification, preventive strategies, and worker training to address occupational risks such as respiratory diseases, chemical exposure, and mechanical injuries. **IEC 60079** integrates electrical safety considerations, particularly in areas where combustible dust may create explosive atmospheres. **WHO recommendations** add a public health perspective, emphasizing protective equipment, ventilation, and awareness campaigns to reduce risks of long-term health effects. By linking the discussion of hazardous and harmful factors in cement production to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

12.3. Emissions into the atmosphere

The main sources of atmospheric emissions are:

1. Loading and unloading of raw materials and finished products;
2. Storage of raw materials, intermediate products, and cement;
3. Operation of rotary kilns;
4. Operation of mills;
5. Operation of clinker coolers.

Dust reduction measures:

- Avoid repeated loading and unloading;
- Use enclosed belt conveyors;
- Organize cleaning of empty belts;
- Store ground raw materials in closed bunkers;
- Store coal, coal dust, and coke in closed silos;
- Store waste in sheltered areas to reduce wind and weather impact;
- Store clinker in closed bunkers with automatic dust removal;
- Store cement in silos with automatic loading systems;
- Perform technical maintenance according to regulations to prevent uncontrolled air and water leakage;

- Process materials in closed systems with negative pressure, where air is extracted and returned to the atmosphere through cyclones or fabric filters;
- Maximize automation of cement bagging (rotary machines, automatic weight control, belt conveyors, closed pallet storage).

Kiln and cooler control:

- Collect dust with filters and return it to the kiln or cooler;
- Control fine particles with electrostatic or fabric filters;
- Clean cooler exhaust gases with cyclones and fabric filters (CO concentration ≤0.5% — sensors automatically cut off power to prevent explosions);
- Collect dust from mills with fabric filters and return it (electrostatic filters are not recommended).

In cement production, fuel combustion is the primary energy source, generating flue gases. Emission standards up to 50 MW thermal capacity are defined in the EHSGC guidelines, while larger capacities follow thermal power plant regulations.

Nitrogen Oxides (NO_x):

- NO_x is formed at high temperatures in kilns, with NO (nitric oxide) accounting for ~90% of total NO_x.

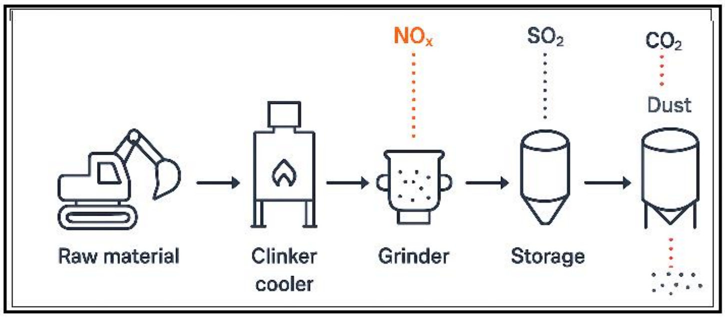

Fig. 12.2. Sources of Atmospheric Emissions and Control Mechanisms

Safety measures:

- Maintain secondary air oxygen concentration at the lowest possible level;
- Add water to the fuel or directly inject water into the flame to lower temperature (this increases OH radicals and reduces NO_x, but raises fuel consumption and CO^2 emissions by 2–3%);
- Use low- NO_x burners, applicable in PHP and PH kilns.
- In lime production, NO_x emissions are significantly lower compared to cement production.

Sulfur Dioxide (SO^2):

- SO^2 emissions mainly result from raw materials with volatile or active sulfur content (e.g., pyrite FeS).
- Fuel combustion contributes relatively little to SO^2 emissions.
- Control recommendations:
- Control recommendations:
- Use vertical mills, where SO^2 concentration is reduced through the formation of $CaSO^4$(gypsum) via reactions with $CaCO^3$ (limestone);

- Inject sorbents ($Ca(OH)^2$, CaO, fly ash) into the gas stream before filtration;
- Use fuels with lower sulfur content;
- Apply gas scrubbers, either dry or wet. Dry scrubbing is more expensive and is used when SO^2 concentration ≥1500 mg/m³.
- In lime production, SO^2 emissions are also lower.

Greenhouse gases (CO^2):

In cement production, the primary greenhouse gas emitted is carbon dioxide (CO^2). Other greenhouse gases include N^2O and CO.

- **N^2O:** Not emitted in cement production due to complete combustion at high temperatures.
- **CO:** Should account for only 0.5–1.0% of total flue gases. Higher concentrations indicate incomplete combustion and process inefficiency. If CO exceeds 1%, the gas-air mixture becomes explosive, especially when electrostatic filters are used.

Sources of CO^2 emissions:

- Fuel combustion;
- Limestone decarbonization ($CaCO^3 \rightarrow CaO + CO^2$), where ~44% of mass is CO^2.

Recommendations to reduce CO^2 emissions:

- Produce multi-component cement to lower fuel demand;
- Use energy-efficient processes (drying, preheating, precalcination);
- Use fuels with high calorific value and low carbon content (natural gas, diesel, certain waste fuels);
- Select raw materials with low organic content.

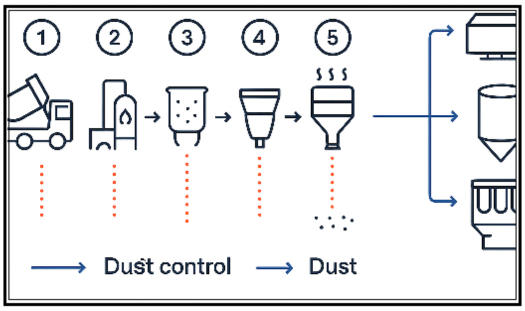

Fig. 12.3 — Sources of atmospheric emissions and dust control (Numbered sources + filters)

Heavy metals and other pollutants:

- Cement production may release lead, cadmium, and mercury into the air.
- Sources include raw materials, organic fuels, and waste-derived fuels.
- About 90% of mercury originates from raw materials, and filters are ineffective at capturing it.

Control measures:

- Apply all dust emission reduction recommendations;
- At very high concentrations (especially mercury), use activated carbon as a sorbent;
- Operate kilns continuously to avoid electrostatic filter shutdowns;
- Avoid using waste fuels during kiln start-up and shutdown.

ISO 14001 provides the internationally recognized framework for managing atmospheric emissions in cement production, requiring monitoring, reporting, and continuous improvement of environmental performance. **ISO 50001** complements this by integrating energy management systems that reduce emissions through efficient energy use. IEC 60079 adds electrical safety considerations in areas where dust emissions may create explosive atmospheres. **WHO recommendations** emphasize the public health perspective, highlighting the importance of dust control, ventilation, and protective equipment to reduce respiratory diseases among workers and surrounding communities. By linking the discussion of emissions into the atmosphere to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

12.4. Energy and fuel use

Fuel types:

The most commonly used fuels are coal dust and lignite. Petroleum coke, a cheaper alternative, is increasingly used. However, both coal and petroleum coke result in more intense greenhouse gas emissions compared to diesel and natural gas. According to 2007 data, only 6% of cement in Europe was produced using diesel or natural gas.

Coal emits approximately 65% more greenhouse gases than natural gas. The high sulfur content in petroleum coke leads to undesirable deposits on kiln rings.

Alternative fuels:

Waste-derived fuels are increasingly used in cement production. In EU countries, about 12% of cement is produced using various alternative fuels. However, emissions must be carefully considered, as discussed earlier and in more detail below.

Fuel use in lime production:

Waste fuels are not used in lime production due to strict quality requirements. Preferred fuels include natural gas, petroleum, and low-sulfur coal. Therefore, lime production must be distinguished from lime used as an intermediate product in cement manufacturing.

High-temperature fuel use:

In the strongly alkaline atmosphere and high flame temperatures (~2000 °C) of cement kilns, high-calorific waste materials can be used as fuel, such as:

- spent solvents,
- used oils,
- worn tires,
- plastic waste,
- organic chemicals,
- expired chlorinated pesticides,
- other chlorinated compounds,
- sewage sludge.

Sewage sludge is increasingly used in EU countries.

Regulatory requirements:

Use of waste fuels requires local administrative approval specifying:

- the type and quantity of raw material,
- fuel standards (calorific value and list of toxic or hazardous substances).

Recommended mitigation measures:

- Wet gas scrubbing or activated carbon filtration depending on the type of volatile heavy metals;
- Direct injection of heavy-metal-containing fuels only through the main burner, not auxiliary burners;
- Avoid using fuels with high halogen content during secondary combustion or kiln start-up/shutdown stages;
- Minimize the cooling time of kiln exhaust gases from 500 °C to 200 °C to prevent reformation of harmful compounds (high temperatures destroy them, but they may reappear in this lower range — PHP and PH kilns help reduce this risk);
- Proper storage, loading, and unloading of waste fuels as described in Environmental, Health, and Safety Guidelines (EHSG).

Energy cost:

Energy and fuel expenses account for approximately 40–50% of total production costs. In addition to general energy-saving recommendations outlined in the Environmental, Health, and Safety Guidelines (EHSG), the following kiln-specific practices should be considered:

Kilns:

International best practices for clinker production recommend dry-process kilns with multi-stage preheating and precalcination — specifically PHP-type kilns.

- These kilns require the least fuel due to:
- heat recovery from exhaust gases via cyclones,
- reduced heat loss within the kiln,
- elimination of heat loss from moisture evaporation.
- Wet-process kilns use slurry and require additional energy to evaporate water, making them less efficient.

PH-type kilns are also fuel-efficient (slightly higher consumption than PHP), but their productivity is significantly lower.

Other kiln types — LD (long dry), semi-dry, semi-wet, and wet — are considered outdated.

- As of 2007, 80% of cement in Europe was produced using dry technologies.
- LD kilns consume substantially more heat and pose maintenance challenges with higher operational costs.

Lepol kilns (semi-dry/semi-wet) have moderate fuel consumption due to the high moisture content of granulated feed.

- Semi-wet kilns also consume more electricity and require costly maintenance due to pressure filters.
- Wet kilns are largely phased out due to their reliance on the oldest vertical kiln technology, highest heat consumption, and lowest productivity.
- Today, wet-process technology is no longer considered viable for cement manufacturing.

Coolers:

Modern cement plants use **grate coolers** for clinker.

- Their key function is to rapidly reduce clinker temperature and simultaneously heat secondary air to the highest possible temperature, thereby reducing fuel consumption.

ISO 50001 provides the internationally recognized framework for energy management in cement production, specifying methods for optimizing energy use, reducing waste, and improving efficiency. **ISO 14001** complements this by requiring environmental management systems that minimize the ecological impact of energy consumption and heat generation. **IEC 60079** integrates electrical safety considerations, ensuring that energy systems in hazardous environments are properly designed and maintained. **ISO 45001** strengthens occupational health and safety management systems by requiring preventive strategies and worker training to reduce risks associated with high-temperature processes**. WHO recommendations** add a public health perspective, emphasizing protective equipment, safe working practices, and awareness campaigns to minimize risks of burns, heat stress, and long-term health effects. By linking the use of energy and heat to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

12.5. Wastewater, solid waste, noise

Industrial wastewater treatment:

Wastewater mainly originates from cooling operations at different stages of the production process. In some cases, wastewater may contain high levels of suspended particles and elevated pH. Treatment involves pH adjustment and particle removal through sedimentation in ponds or filtration. These standards are outlined in the Environmental, Health, and Safety Guidelines (EHSG).

Fig. 12.4. Diagram of the three main environmental challenges of cement production: 1 - Wastewater; 2 - Solid waste; 3 - Noise

Other wastewater sources and water use:

Guidelines for wastewater discharge and water consumption are also provided in the EHSG. Contaminated water must be directed to industrial wastewater treatment systems.

- Rainwater runoff from open stockpiles of petroleum coke, coal, and waste is typically contaminated.
- To prevent this, fuels should be stored in enclosed facilities, or stockpiles should be covered with impermeable sheets and surrounded by drainage channels.
- If runoff cannot be avoided, surfaces must be prepared to prevent soil contamination (e.g., asphalt or concrete paving). A newer material called Soily can be sprayed to form an impermeable layer lasting 2–3 years.
- Wastewater should be collected in ponds to allow particle sedimentation.
- In all cases, water conservation measures must be strictly implemented.

Solid waste:

Solid waste primarily consists of discarded rock from clinker production. Other sources include kiln dust and small amounts generated during equipment maintenance. In older plants, alkaline residues from filter presses may also be present. Waste utilization and disposal practices are specified in the EHSG.

Noise pollution:

Noise emissions occur throughout production stages, from raw material extraction to storage of finished products. High noise levels may also result from exhaust fans and mills. Noise levels and reduction measures are detailed in the EHSG.

ISO 14001 provides the internationally recognized framework for managing environmental impacts of wastewater, solid waste, and noise in cement production, requiring monitoring, reporting, and continuous improvement of environmental performance. **ISO 9001** complements this by ensuring quality management systems that integrate waste reduction and process optimization. **IEC 60079** adds electrical safety considerations in waste treatment areas where combustible dust or gases may create hazardous atmospheres**. ISO 45001** strengthens occupational health and safety management systems by requiring hazard identification, preventive strategies, and worker training to reduce risks associated with waste handling and noise exposure. **WHO** recommendations add a public health perspective, emphasizing protective equipment, ventilation, and awareness campaigns to minimize risks of respiratory diseases, hearing loss, and environmental contamination. By linking the management of wastewater, solid waste, and noise to these standards, the monograph ensures that theoretical explanations and practical safety strategies are scientifically validated and internationally comparable.

12.6. Occupational safety

Ensuring safe working conditions involves the use of effective and reliable methods, technologies, and equipment to prevent occupational injuries and diseases. The most significant risks arise directly from the cement production process. Key hazardous and harmful factors include:

1. Dust

2. Heated air and surfaces
3. Noise and vibration
4. Physical hazards (rotating, moving, vibrating parts, energy sources, etc.)
5. Radiation
6. Chemical hazards and hygiene-related issues

Let's examine each factor individually:

Dust:

Dust is most prevalent at quarries, during raw material handling, and clinker grinding.

- The American Conference of Governmental Industrial Hygienists (ACGIH) classifies Portland cement dust as harmful.
- Prolonged exposure can cause pneumoconiosis, emphysema, bronchitis, and fibrosis.

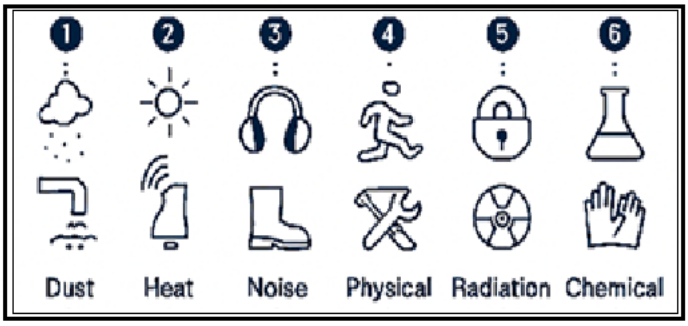

Fig. 12.5. Occupational safety in cement production and means of protection to reduce hazards

Dust control methods:

- Cleanliness and dust containment;
- Enclosed chambers with conditioned air;
- Dust extraction and air recirculation systems, especially at mills and packaging stations;
- Use of appropriate personal protective equipment (PPE);
- Vacuum-based dust collection systems.

Additional information on silica inhalation is available at:

[https://www.osha.gov/SLTC/etools/silica/index.html] — published by OSHA (U.S. Department of Labor).

- Prolonged inhalation of silica (SiO^2) causes pneumoconiosis; coal dust causes anthracosis — common among miners.

Heated surfaces:

Mainly found around kilns.

- Protective measures include:
- Shielding hot surfaces at workstations;
- PPE (boots, clothing, gloves);
- Shorter work shifts;
- Respirators with clean air or oxygen supply;
- Kiln doors must not be opened during operation;
- Special procedures during lime slaking.

Noise and vibration:

Generated by exhaust fans and mills.

- Reduction methods include:
- Mufflers, acoustic enclosures, noise barriers;
- If background noise remains high, PPE must be used — as discussed in Chapter 7.

Physical hazards:

Injuries often result from falls, falling objects, or lifting heavy loads.

- Contact with moving parts or entanglement is also a risk.
- Maintenance work poses significant danger — especially during operation, adjustment, or repair of crushers, mills, separators, fans, coolers, and conveyors.

Radiation:

X-ray devices are used for continuous monitoring of raw material mix on conveyor belts.

- Radiation protection is covered in Chapter 6 of the EHSG.

Chemical hazards and hygiene issues:

Studies show American cement contains 0.05–1.24% chromium; European cement contains 0.32–1.76%.

- EU standards require soluble chromium content not to exceed 0.0002% of dry mass to prevent allergic dermatitis.
- Protection involves reducing chromium content or using PPE.

Community health and safety:

Guidelines for protecting local populations during construction, operation, and decommissioning are provided in the EHSG.

Monitoring and compliance:

Occupational safety performance must be evaluated according to international standards, including:

- NIOSH (U.S. National Institute for Occupational Safety and Health),
- ACGIH (American Conference of Governmental Industrial Hygienists),
- OSHA (U.S. Department of Labor – Permissible Exposure Limits),
- EU occupational exposure limits, and similar sources.

Incident tracking:

Facilities must maintain a logbook recording accidents, injuries, occupational diseases, and emergency incidents.

ISO 45001 provides the internationally recognized framework for occupational health and safety management systems, requiring hazard identification, preventive strategies, and worker training to minimize risks in cement production. **ISO 14001** complements this by integrating environmental management practices that reduce harmful exposure to dust, noise, and chemical agents. **IEC 60079** adds electrical safety considerations, particularly in areas where combustible dust may create explosive atmospheres. **WHO recommendations** strengthen the public health perspective, emphasizing protective clothing, respiratory protection, ventilation, and emergency preparedness to safeguard workers against long-term health effects. By linking occupational safety and safety techniques to these standards, the monograph ensures that theoretical explanations and practical strategies are scientifically validated and internationally comparable

12.7. Environmental protection

Environmental protection standards are presented in tabular form. These values reflect international best practices and are aligned with the regulatory frameworks of countries that maintain recognized normative systems. The listed standards apply under normal operating conditions in facilities designed and operated according to the principles described in this guide — including the use of emission control and mitigation methods outlined in previous sections.

The specified limits must be maintained for at least 95% of the total operating time. If deviations occur, an environmental assessment must determine whether local conditions allow for assimilation of harmful or toxic substances.

Table 12.3. Atmospheric Emission Limits in Cement Production

Pollutant	Unit	Regulatory Limit
Solid particles (new kiln)	mg/m³	30
Solid particles (existing kiln)	mg/m³	100
Dust (including clinker cooling and cement grinding)	mg/m³	50
SO_2	mg/m³	400
NO_X	mg/m³	600
HCl	mg/m³	10
Hydrogen fluoride	mg/m³	1.0
Organic carbon	mg/m³	10
Dioxins and furans	mg/m³	0.1
Cadmium and thallium	mg/m³	0.05
Mercury	mg/m³	0.05
Arsenic, lead, cobalt, chromium, copper, manganese, nickel, vanadium, antimony (total)	mg/m³	0.5

Water treatment standards may also be adjusted based on local assimilation capacity, provided that proper justification is documented.

Table 12.4. Allowable Pollution Levels in Wastewater (cement and lime production)

Pollutant	Unit	Standard
pH	pHunits	6-9
Suspended solids	mg/L	50
Temperature increase	℃	≤3

Table 12.5. Energy and Resource Consumption

Input per unit of product	Unit	Industry Benchmark
Fuel energy (cement)	GJ/t clinker	3.0-4.2
Electricity (cement)	kWh/t cement	90-150
Electricity for clinker grinding	kWh/t	40-45
Raw substitution in clinker production	%	2-10

Raw substitution in cement production	%	0–70/80 (slag + fly ash 0–30)

Table 12.6. Waste Generation

Per unit of product	**Unit**	**Industry Benchmark**
Waste	kg/t cement	0.25-0.60
Dust	g/t cement	20-50
NO_X	g/t cement	600-800
CO_2 (decarbonization)	kg/t cement	400-525
CO_2 (Fuel combustion)	kg/t cement	150-350

Table 12.7. Kiln Heat Consumption and Productivity

Kiln type	**Heat consumption (MJ/t clinker)**	**Max productivity (t/day)**
Preheater (3–6 stage Precalciner)	3000-3800	12000
Preheater	3100-4200	4000
Long dry	≥ 5000	3800
Lepol kiln (semi-dry/semi-wet)	3300-4500	2500
Wet process	5000-6000	1500-2000

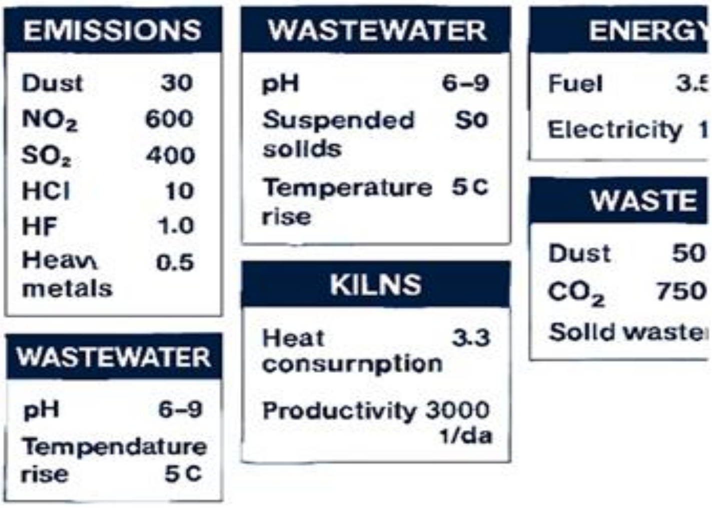

Fig. 12.6. Environmental Performance Monitoring

A visual infographic has been prepared that consolidates these tables into five categories:

1. Emissions (dust, NO_x, SO^2, HCl, HF, heavy metals);
2. Wastewater (pH, solids, temperature rise);
3. Energy (fuel and electricity consumption);
4. Waste (dust, CO^2, solid waste);
5. Kilns (heat consumption and productivity).

ISO 14001 provides the internationally recognized framework for environmental management systems, requiring cement production facilities to monitor, control, and continuously improve their environmental performance. **ISO 50001** complements this by integrating energy management practices that reduce emissions and resource consumption, thereby strengthening environmental protection. **IEC 60079** adds electrical safety considerations, ensuring that equipment used in dusty or hazardous environments does not contribute to environmental contamination or explosion risks. **ISO 45001** reinforces occupational health and safety by requiring preventive strategies that protect both workers and the surrounding environment. **WHO recommendations** add a public health perspective, emphasizing community awareness, protective measures, and emergency preparedness to minimize the environmental and health impacts of cement production. By linking environmental protection to these standards, the monograph ensures that theoretical explanations and practical strategies are scientifically validated and internationally comparable.

12.8. Abbreviations and Practical Calculation Examples

- PHP – Preheater-Precalciner Kiln
- PH – Preheater Kiln
- LD – Long Dry Kiln
- EHSGCLM – Environmental, Health and Safety Guidelines for Cement and Lime Manufacturing
- IFC – International Finance Corporation
- NO_x – Nitrogen Oxides
- SO_2 – Sulfur Dioxide
- CO_2 – Carbon Dioxide
- PM – Particulate Matter

ISO / IEC / ILO / WHO / IAEA / ICNIRP

These standards are referenced in the glossary, but in the context of Chapter 12, they are used for risk assessment in cement production.

Examples:

- ISO 31000 / ISO 31010 → Risk management and assessment
- ILO Convention 155 → Worker safety
- WHO Occupational Health Guidelines → Health recommendations
- IEC 60529 → IP codes (dust and water protection, relevant for dust emission control)

1. Calculation of CO^2 release during $CaCO^3$ decomposition

- **Task:** Calculate how many kg of CO^2 are released from 1 ton of limestone ($CaCO^3$) during decarbonization.
- **Data:**

$M_{CaCO^3} = 100\ g/mol, M_{CO^2} = 44\ g/mol$

- **Formula:**

$$m_{CO^2} = \frac{44}{100} \cdot m_{CaCO^3}$$

- **Answer:** From 1 ton of limestone → 0.44 tons of $\boldsymbol{CO^2}$.

2. Energy consumption by kiln types

- **Task:** Compare PHP and LD kilns in terms of energy consumption per 1 ton of clinker production.
- **Data:** PHP ≈ 3.2 GJ/t, LD ≈ 5.5 GJ/t
- **Formula:**

$$\Delta E = 5.5 - 3.2 = 2.3\ GJ/t$$

- **Answer:** PHP kiln saves 2.3 GJ/t of energy.

3. NO_x reduction effect by water injection

- **Task:** If the initial NO_x concentration is 1200 mg/m³, calculate the concentration reduced by 20%.
- **Formula:**

$$C_{new} = C_{old} \cdot (1 - 0.20)$$

Answer: $1200 \cdot 0.8 = 960\, mg/m^3$.

4. SO^2 control with CaO

- **Task:** Calculate how many kg of CaO are required to absorb 1000 kg of SO^2.
- **Reaction:** SO^2 + CaO → $CaSO_3$
- **Molar masses:** M_{SO^2}=64 g/mol, M_{CaO}=56 g/mol,
- **Formula:**

$$m_{CaO} = \frac{56}{64} \cdot m_{SO^2}$$

- **Answer:** 1000 kg SO^2 → 875 kg CaO.

5. Assessment of CO explosion risk

- **Task:** If CO concentration in gas is 1.2%, determine the risk.
- **Normative data:** Critical threshold ≤ 1%
- **Answer:** Explosion risk is high; process correction is required.

6. Advantage of multi-component cement

- **Task:** If Portland cement production consumes 4.0 GJ/t of energy, and multi-component cement consumes 3.5 GJ/t, calculate energy savings for 1 million tons.
- **Formula:**

$$\Delta E = (4.0 - 3.5) \cdot 10^6 = 0.5 \cdot 10^6\, GJ$$

- **Answer:** 500,000 GJ saved.

7. Control of dust particles (PM10) concentration

- **Task:** If dust concentration without filter is 200 µg/m³, and filter efficiency is 85%, calculate the final concentration.

Formula:

$$C_{\{final\}} = C_{\{old\}} \cdot (1 - 0.85)$$

- **Answer:** $200x\ 0.15 = 30\ \frac{\mu g}{m^3}$

Applicable Standards:

- EHSGCLM — Environmental norms
- ISO 31000/31010 — Risk management and assessment

- IFC — Strict requirements
- WHO/ILO — Health and safety recommendations

The examples presented in this section are provided for illustrative and educational purposes only. They demonstrate how theoretical principles and risk assessment methods can be applied in cement production, helping students and professionals understand the logic behind calculations. These examples are not intended to replace or supersede the requirements of **ISO 14001** for environmental management, **ISO 50001** for energy efficiency, **ISO 45001** for occupational health and safety, or **IEC 60079** for electrical safety in hazardous environments. For actual design, installation, or safety evaluations, practitioners must always rely on the official standards and validated measurement procedures. By including practical calculations alongside theoretical explanations, the monograph enhances accessibility and didactic clarity, while maintaining alignment with internationally recognized safety frameworks.

13. Multi-factor Analysis

Chapter XIII introduces the methodology of multi-factor analysis, expanding the foundations established in Chapter I. The purpose of this guide is to show how environmental; energy, occupational safety, and public health factors can be integrated into a single analytical framework. **ISO 14001** provides the internationally recognized structure for environmental management, **ISO 50001** for energy efficiency, **ISO 45001** for occupational health and safety, and **IEC 60079** for electrical safety in hazardous environments. **WHO recommendations** complement these standards by adding a public health perspective, ensuring that risk indices and formulas reflect both workplace safety and community well-being. By framing the chapter with these standards, the guide ensures that readers understand the theoretical foundations, the practical applications, and the international comparability of multi-factor evaluation.

13.1. Preliminary Considerations

Chapter 13 represents a direct continuation of the index model introduced in Chapter 1. While Chapter 1 presented a single-factor index (Probability × Severity), here the approach is expanded into multi-factor analysis, where each component is assigned a corresponding weight and combined into a unified index. In this way, the reader can see how the foundational methodology evolves into a complex systemic model. In this chapter, we deepen the quantitative assessment of risk, moving from single-factor indices to multi-factor models. The aim is to enable the researcher to simultaneously account for several parameters, perform normalization, determine weights, conduct sensitivity testing, and interpret results, thereby reaching scientifically grounded and practically applicable decisions.

It should be noted that the risk scale gradation remains unchanged regardless of the number of factors. Accordingly, even in multi-factor cases, the same gradation discussed earlier under the 0–1 scale applies. In this case, risk gradation is as follows: 0–0.33 → low risk; 0.34–0.66 → medium risk; 0.67–1.00 → high risk. It is evident that with other scales the gradation will differ. For example, under a 0–10 scale, a mechanically transferred gradation would be: 0–3.3 → low risk; 3.4–6.6 → medium risk; 6.7–10.0 → high risk. In reality, the purpose of changing the scale is to increase its sensitivity and precision. A mechanically altered scale, as in our example, is meaningless and not encountered in practice.

Among multiple factors, some may be negative while others positive, yet quantitative assessment is always performed in terms of risk, which is evaluated according to negative influence. For instance, in mines, methane concentration is a negative risk factor, while strong ventilation reduces concentration and is a positive factor. The challenge is how to reflect these two opposing factors within a unified index. In other words, the positive index must be expressed through a negative equivalent, ensuring uniformity of indices and their impact. In this case, all factors contribute equally to the risk share. The reflection of a positive index through a negative equivalent is called inverse normalization, which we explain with an example. On a 0–1 scale, methane concentration is given as 0.6, while ventilation efficiency is 0.7. Inverse normalization means determining the difference (1 – 0.7 = 0.3). As we can see, the difference is taken from the maximum value of the 0–1 scale, i.e., 1, and the subtracted value is the positive indicator — ventilation efficiency of 0.7. The resulting magnitude, 0.3, functions as a risk factor alongside methane concentration.

Thus, negative factors directly reflect risk and do not require inversion; inversion is necessary only for positive factors. Regardless of their number, each positive factor must undergo inverse normalization, which is the difference calculation described above. This difference represents the negative reflection of the positive index alongside other directly negative factors.

Purpose and Context

- **Purpose:** Through multi-factor analysis, to obtain a more precise, consistently balanced, and universally applicable picture of risk across different sectors.
- **Context:** The index-based perspective established in this manual is extended to cases where multiple factors exert influence, potentially in different directions. The index approach is expanded into composite indices and model-based methods.
- **Why multi-factor:** A single factor rarely describes the full reality. Better results can be achieved by combining several factors. For example, in mining, methane risk depends on multiple factors: concentration, ventilation, sensor response time, geomechanically stability, and organizational rules. The effects of these factors are often opposing, and their indices must be determined analogously to the method described above.

Theoretical Foundations

- **Expanded base formula:** The extended index for multi-factor risk can be calculated using the formula

$$R_{\text{comp}} = \sum_{i=1}^{n} P_i \cdot S_i \cdot W_i \quad (13.1)$$

where R_{comp} is the composite (multi-factor) risk index; P_i — probability of risk realization; S_i — severity of the resulting outcome; W_i — weight assigned to each factor, expressed in fractions (on a 0–1 scale).

- **Application:** When the outcome of risk realization is simultaneously influenced by several causal factors (physical, chemical, technical, organizational, etc.).

- **Interpretation:** Each factor contributes proportionally to its effect; the sum yields a total magnitude interpretable by sector. Weights, expressed numerically, provide control and highlight the more significant factors in terms of impact — effectively ranking them. The inverse approach converts every positive factor into its equivalent risk factor within the index.

This section introduces the preliminary considerations for multi-factor analysis, emphasizing that the methodology integrates environmental, energy, occupational safety, and public health factors. **ISO 14001**, **ISO 50001**, **ISO 45001**, and **IEC 60079** provide the internationally recognized frameworks for these domains, while **WHO recommendations** add a public health perspective. By framing the analysis with these standards, the guide ensures that readers understand both the theoretical foundations and the practical measures required for scientifically validated and internationally comparable multi-factor evaluation.

13.2. Multi-factor Indices and Formulas

Composite Risk Index

Idea: The essence of using the Composite Risk Index (CRI) is to combine several indicators grouped within one category into a unified index, which can be calculated using the following formula

$$\mathrm{CRI} = \sum_{i=1}^{n}(X_i^* \cdot W_i) \tag{13.2}$$

where X_i^* is a normalized characteristic (on a 0–1 scale); $\sum W_i = 1$.

Fields of application: Mining, healthcare, digital security, construction, and other sectors where it is necessary to simultaneously account for various factors, including technical and organizational ones.

Weighted Impact Index

Idea: The Weighted Impact Index (WII) reflects the influence of an individual factor in its weighted form. It represents the decomposition of the extended multi-factor risk index expressed in formula (13.1) into the impacts of individual factors

$$\mathrm{WII_i} = P_i \cdot S_i \cdot W_i \tag{13.3}$$

Interpretation: This helps establish priorities — identifying which factor is more severe or which occurs more frequently. In this case, severity and frequency are presented as indicators within the same category.

Multivariate Safety Index

Idea: The Multivariate Safety Index (MSI) can be defined by a formula that contains a sum of products, where one term consists of composite risk, weighted impact, and integrated safety indices, and the other term consists of specific calibration coefficients. Statistical data or results obtained through modeling may be used here.

$$MSI = \alpha \cdot CRI + \beta \cdot \sum WII_i + \gamma \cdot SII \tag{13.4}$$

where α, β, γ are sector-specific calibration coefficients.

Sector-specific calibration coefficients are not universal constants; they are determined by data from the specific industry and expert evaluation.

- α defines the share of the Composite Risk Index within the overall safety index.
- β reflects the significance of the Weighted Impact Index, i.e., how strongly the weight of each factor's frequency and severity contributes.
- γ expresses the share of the Supplementary Safety Index (SII), which may derive from statistical or model-based data.

These coefficients derive from two sources:

1. Statistical or empirical data — analysis of historical incidents or observations.
2. Expert calibration — priorities defined by specialists and sector-specific requirements.

Thus, α, β, γ provide flexibility to the indices: their values may differ across sectors so that the index realistically reflects the risk profile of a given industry. In practice, these coefficients are determined through the following steps:

1. Data analysis:

Collect statistical data on historical incidents, accidents, or cases. For example, how frequently a specific type of incident occurs and what severity it has.

2. Expert evaluation:

Specialists define priorities — which factor has greater impact on safety. Consequently, α, β, γ may vary depending on the sector (mining, healthcare, cybersecurity, etc.).

3. Calibration process:

Combine the collected data with expert assessments. For example:

- If the Composite Risk Index (CRI) reflects reality more accurately, coefficient α will take a higher value (e.g., 0.5–0.7).
- If the weight of individual factors (WII) is critical, coefficient β may be higher (e.g., 0.3–0.5).
- If the Supplementary Safety Index (SII) is important, coefficient γ will take its share (e.g., 0.1–0.3).

4. Defining variability ranges:

All coefficients must be positive, and their sum is not fixed — they are determined according to sectoral needs. In practice, α, β, γ are often distributed within the 0.1–0.7 range, ensuring that the index remains flexible and adaptable.

5. Validation:

The chosen coefficients must be tested through sensitivity analysis — small changes should not alter the overall picture of the situation.

Thus, α, β, γ are not mechanically selected numbers; they represent a synthesis of data and expert judgment, ensuring the realism and reliability of the index. The numerical variability of sector-specific calibration coefficients is presented in Table 13.1.

Table 13.1. Variability of Sector-specific Calibration Coefficients

Coefficient	Role in the index	Range	Determination method
$\propto$	Share of the Composite Risk Index within the overall Safety Index.	0.3 – 0.7 (if CRI reflects reality more accurately, $\propto$ is higher).	Statistical data analysis + expert evaluation.

β	Significance of the Weighted Impact Index — how strong the factors of frequency and severity are.	0.2 – 0.5 (if the weight of individual factors is critical, β takes higher values).	Statistics of incident frequency and severity + expert priorities.
γ	Share of the Supplementary Safety Index (SII) — reflecting additional data or model results.	0.1 – 0.3 (if the supplementary index is important, γ increases).	Modeling simulations, statistical data, expert calibration.

Data Normalization and Weight Determination

- **Normalization (0–1 or 0–10 scale):**
  - 0–1 scale: Simple interpretation of weight distribution, relatively easy to allocate weights.
  - 0–10 scale: Increased sensitivity for more adequate distribution of weights, easily perceived in educational contexts.
- **Weights W_i:**
  - Determined by experts: sectoral priorities.
  - Determined by data

$$W_i = \frac{x_i}{\sum_{j=1}^{n} x_j} \quad (13.5)$$

Principle: $\sum W_i = 1$ — ensures a balanced sum of determined weights.

- **Documentation:** Always specify the source, method, and rationale for using a particular scale — this increases credibility.
- **Sensitivity test:**
  - Scenarios: Possible use of 0–10 or 0–8 scales; slight adjustments of weights; proper definition of min–max intervals according to the scale.
  - Result: Assessment of index stability or change. Minor adjustments of weights should not significantly alter the magnitude of the index. Specifically, the researcher can pre-define the allowable variability of magnitude in percentage terms, e.g., within 3–5%, and maintain this threshold under scale changes.

The indices and formulas presented in this section are **provided for illustrative and educational purposes only**. They demonstrate how multiple factors—environmental emissions, energy efficiency, occupational safety, and public health—can be integrated into a single analytical framework. These examples are not intended to replace or supersede the requirements of **ISO 14001**, **ISO 50001**, **ISO 45001**, **IEC 60079**, or **WHO recommendations**. For actual design, installation, or safety evaluations, practitioners must always rely on official standards and validated measurement procedures. By including multi-factor indices and formulas alongside theoretical explanations, the monograph enhances accessibility and didactic clarity, while maintaining alignment with internationally recognized safety frameworks.

13.3. Research Methods in Multi-factor Cases

Multiple Regression Analysis

- **Purpose:** To predict an outcome by simultaneously considering several explanatory variables.

Formula

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \varepsilon \quad (13.6)$$

- **Practical application:** For example, predicting the frequency of incidents based on environmental conditions (temperature, humidity, ventilation).
- **How it works:** Each factor (X_i) receives its coefficient (β_i), which reflects its share in the outcome (Y).
- **Educational value:** Students see that reality is rarely single-factor; regression demonstrates interdependence and priorities.

Thus, multiple regression analysis is used when the outcome depends on several explanatory variables simultaneously. Each factor (X_i) receives its coefficient (β_i), which reflects its contribution to the final result (Y). In practice, this method allows us to estimate incident frequency based on environmental conditions (e.g., temperature, humidity, ventilation intensity).

Analysis of Variance and Covariance (ANOVA/ANCOVA)

- **Purpose:** To test differences between groups while accounting for covariates.
- **Practical application:** For example, comparing the effectiveness of safety programs across different enterprises where environmental conditions vary.
- **How it works:** ANOVA tests differences in mean values between groups; ANCOVA adds additional explanatory variables to make the result more reliable.
- **Educational value:** Students learn that comparing only mean values is insufficient — covariates must be considered.
- **Definition:** Covariates are additional explanatory variables that may influence the outcome and are included in the analysis to make results more reliable.
- **For example**, when comparing the effectiveness of safety programs across different enterprises, covariates may include environmental conditions (temperature, humidity, duration of work), which influence the outcome. This ensures that differences between groups are not explained solely by program effectiveness.

Thus, ANOVA is used to test differences in mean values between groups, while ANCOVA adds covariates to improve reliability. For instance, in comparing safety program effectiveness across enterprises, covariates may include environmental conditions (temperature, humidity, duration of work).

Monte Carlo Simulation

- **Purpose:** To model uncertainties through repeated generation of random variables.
- **Practical application:** For example, assessing the distribution of a risk index, obtaining Value-at-Risk (VaR) measures.

- **How it works:** Thousands of random scenarios are generated, the index is calculated in each, and then the distribution of results is analyzed.
- **Educational value:** Students see that reality always contains uncertainty, and simulation provides a picture of the possible range of outcomes.

Thus, Monte Carlo simulation is used to model uncertainties by generating multiple random scenarios. In practice, this means creating thousands of scenarios, calculating the risk index in each, and analyzing the distribution of results. One accepted method in this case is numerical modeling.

Definitions:

- **Value-at-Risk (VaR):** A risk measure showing the maximum expected loss within a defined time period and confidence level (e.g., 95% or 99%).
- **Monte Carlo simulation:** Generation of random scenarios (thousands or millions) based on possible variability of factors.

Process:

1. Define probability distributions for each factor (e.g., concentration, ventilation).
2. Generate random values through simulation.
3. Calculate the risk index in each scenario.
4. Extract the tail of the distribution — for example, the 5% most severe outcomes.

Interpretation: VaR shows the level to which risk may increase in the worst case, with a defined probability.

Decision Tree / Random Forest

- **Purpose:** To capture priorities through rule-based structures and detect non-linear dependencies.
- **Practical application:** For example, predicting incident probability based on combinations of factors (ventilation, sensors, organizational rules).
- **How it works:** A Decision Tree creates a decision path based on factors; a Random Forest builds multiple Decision Trees and aggregates them to produce a more stable result.
- **Educational value:** Students learn that complex systems can be explained through decision rules and that multi-model approaches are more reliable.

Definition:

- **Decision Tree:** A transparent rule-based structure where each tree describes the logic of the data, allowing students to see how outcomes are reached.
- **Random Forest:** A collection of many trees — a forest that together produces a more stable and reliable picture. When describing each tree, one must not lose sight of the forest; when describing the forest, one must remember it is composed of individual trees.

Thus, a Decision Tree creates a rule-based structure where each factor defines a decision path. A Random Forest builds multiple Decision Trees and aggregates them to produce a more stable result. In practice, these methods are used to predict incident probability based on combinations of factors (ventilation, sensors, organizational rules).

Principal Component Analysis (PCA)

- **Purpose:** To reduce multiple correlated factors into principal components, thereby decreasing dimensionality and noise.

- **Practical application:** For example, condensing multidimensional safety data (sensors, environmental conditions, organizational factors) into a few principal components. Ordered by decreasing importance, typically the first 2 or 3 components account for most of the information accuracy.
- **How it works:** PCA identifies new variables (principal components) that explain the maximum variance in the data.
- **Educational value:** Students learn that large datasets can be compressed without losing essential information.

Definitions:

- Noise: A technical term emphasizing random, irrelevant variability in data.
- Deviations: A more neutral, everyday term showing students that PCA reduces minor, random deviations in data.

Noise in data means the presence of insignificant deviations that obscure the perception of the main signal. Removing noise clarifies the real picture.

Dimensionality reduction: When many factors exist (e.g., 10–20 parameters), PCA transforms them into a few principal components that explain the largest variance.

Noise reduction: Data often contains random, insignificant variability — such as minor sensor errors, random environmental fluctuations, or factors with little real impact on outcomes. PCA reduces this noise by retaining only the most important components.

Process:

1. Compute the covariance matrix.
2. Determine components using eigenvalues/eigenvectors.
3. Retain only those components that explain the greatest variance.

Educational interpretation: Students see that PCA not only compresses data but also removes excess, random variability, leaving only truly significant information.

Thus, PCA is used to condense multiple correlated factors into principal components, reducing dimensionality and noise. In practice, this means condensing multidimensional safety data (sensors, environmental conditions, organizational factors, etc.) into a few principal components.

Summary of Multi-factor Research Methods (Table 13.2 and schematic visualization):

- Regression analysis → Prediction
- ANOVA/ANCOVA → Group comparison
- Monte Carlo → Modeling uncertainty
- Decision Tree / Random Forest → Rule-based structure
- PCA → Dimensionality reduction

Table 13.2. Multi-factor Research Methods

Method	**Purpose**	**Practical application**	**How it works**	**Educational value**
Multiple Regression	Predicting outcomes using several	Predicting incident frequency based on environmental conditions	Each factor receives a coefficient (β_i) that reflects its	Demonstrates interdependence and priorities

	explanatory variables	(temperature, humidity, ventilation)	share in the outcome (Y)	
ANOVA/ANCOVA (Analysis of Variance / Covariance)	Testing differences between groups	Comparing safety programs across enterprises	ANOVA tests mean values; ANCOVA adds covariates (additional explanatory variables)	Teaches that comparing only mean values is insufficient — covariates must be considered
Monte Carlo Simulation	Modeling uncertainties	Assessing risk index distribution, Value-at-Risk measures	Generating thousands of random scenarios and analyzing the distribution of results	Shows the range of possible outcomes and the importance of uncertainty
Decision Tree / Random Forest	Capturing priorities through rule-based structures	Predicting incident probability based on combinations of factors	Decision Tree creates decision paths; Random Forest aggregates multiple Decision Trees	Teaches that complex systems can be explained by rules and that multi-model approaches are more reliable
PCA (Principal Component Analysis)	Dimensionality reduction and noise reduction	Condensing multidimensional safety data into principal components	Identifies new variables (principal components) that explain maximum variance in the data	Shows that large datasets can be compressed without losing essential information

Research methods in multi-factor cases must integrate quantitative and qualitative approaches to capture the complexity of environmental, energy, occupational safety, and public health factors. **ISO 14001** provides the framework for environmental monitoring and reporting, while **ISO 50001** establishes validated methods for measuring and improving energy efficiency. **ISO 45001** requires systematic hazard identification and risk assessment techniques to ensure worker safety, and **IEC 60079** adds specialized methodologies for evaluating electrical risks in hazardous environments. **WHO recommendations** complement these standards by emphasizing epidemiological methods, health surveillance, and community-based risk assessments. By linking research methods in multi-factor cases to these standards, the monograph ensures that theoretical models and practical investigations are scientifically validated, internationally comparable, and ethically grounded.

13.4. Practical Examples of Using Multi-factor Indices

Presenting numerical sources and terms in tabular form makes the solution procedure clearer and more adequate.

Table 13.3. Sources and Terms of Numerical Values

Term	Definition
Obtained	Data directly measured or observed. Example: concentration recorded by a sensor.
Selected	Parameter pre-defined by the researcher or expert to be included in the model. Example: using ventilation efficiency.
Determined	Value derived through normalization, calibration, or formula based on obtained data or expert evaluation. Example: response time after normalization.
Upper bound	Upper limit of scale variability (on 0–1 scale = 1; on 0–10 scale = 10).
Positive index	Value of a positive factor, which is transformed into a difference during inversion.
Difference	Subtraction of the positive index from the upper bound. This represents the negative share of the positive index alongside other directly negative factors.

Example A – Mining Industry: Composite Methane Risks (CRI)

Methane concentration - obtained by sensor measurement. Ventilation efficiency - selected as a factor. Response time - determined through normalization.

Selected factors:

- Ventilation efficiency (0–1; higher = better → inversion required).
- $\boldsymbol{T}_{\mathrm{s}}$ - Sensor response time (seconds; normalized to 0–1; shorter time = better → inversion).

Inverse normalization:

- Ventilation: $V^* = 1 - V_{\mathrm{e}}$
- Response time: $T^* = 1 - T_{\mathrm{s}}{}^*$ (where $T_{\mathrm{s}}{}^*$ is normalized within 0–1 range)

Weights: $\{W_C, W_V, W_T\} = \{0.5,0.3,0.2\}, \sum W = 1$.

Composite index:

$$\mathrm{CRI}_{\mathrm{methane}} = C_m \cdot W_C + V^* \cdot W_V + T^* \cdot W_T$$

Numerical example:

- Data: $C_m = 0.6$ — obtained by sensor measurement.
- $V_e = 0.7$— selected as a positive factor.
- $V^* = 1 - V_\mathrm{e} = 1 - 0.7 = 0.3$ — normalized by inversion.
- $T_s = 10$ sec — obtained by observation; $T^* = 0.5$ — normalized by inversion.

Inversion reflects the negative share of the positive index alongside other directly negative factors.

Calculation:

$$CRI = 0.6 \cdot 0.5 + 0.3 \cdot 0.3 + 0.5 \cdot 0.2 = 0.30 + 0.09 + 0.10 = 0.49$$

Interpretation: $CRI = 0.49$ — medium-high composite risk. Priority: improve ventilation and accelerate sensor response.

Why is 0.49 medium-high risk?

1. **Scale definition:**
   - CRI is usually normalized within 0–1.
   - 0 means no risk, 1 means maximum risk.
2. **Interval interpretation:**
   - 0–0.33 → Low risk
   - 0.34–0.66 → Medium risk
   - 0.67–1.00 → High risk
3. **Our result:**
   - Obtained $CRI = 0.49$.
   - This value lies in the middle, but above the lower bound of medium (0.34).
   - Therefore, interpretation: **medium-high risk**.

Example B – Healthcare: Infection Multi-factor Index ($WII + CRI$)

Hygiene compliance - obtained through observation. Percentage of functioning equipment - obtained through audit. Consistency of work processes - determined by expert evaluation.

Factors:

- Probability of spread $P = 0.30$ — obtained from statistical data.
- Severity of outcome $S = 4$ — selected by expert classification.
- Weight of category $W = 1.0$ (under a 0–1 scale, the sum of all category weights $\sum W_i = 1$; since here we have only one category, its weight is equal to 1).

Weighted Impact Index (WII, analogous to Chapter 1):

$$WII = P \cdot S \cdot W = 0.30 \cdot 4 \cdot 1.0 = 1.20$$

CRI expansion (with preventive factors):

- $\mathbf{H}_\mathrm{h}$: Hygiene compliance (0–1; inversion: $H^* = 1 - H_\mathrm{h}$).
- $\mathbf{E}_\mathrm{e}$: Percentage of functioning equipment (0–1; inversion: $E^* = 1 - E_\mathrm{e}$).
- $\boldsymbol{W}_\mathrm{r}$: Consistency of work processes (0–1; inversion as needed).

Inversion reflects the negative share of the positive index alongside other directly negative factors.

Weights:

$\{W_H, W_E, W_W\} = \{0.4, 0.4, 0.2\}, \quad \sum W = 1.$

Numerical example:

- $H_h = 0.8$ — obtained by observation.
- $H^* = 0.2$ — normalized by inversion.
- $E_e = 0.9$ — obtained from audit data.
- $E^* = 0.1$ — normalized by inversion.
- $W_r = 0.7$ — determined by expert evaluation.
- $W^* = 0.3$ — normalized by inversion.

Composite Risk Index:

$$CRI_{\text{inf}} = 0.2 \cdot 0.4 + 0.1 \cdot 0.4 + 0.3 \cdot 0.2 = 0.08 + 0.04 + 0.06 = 0.18$$

Interpretation:

$WII = 1.20 \rightarrow$ significant impact.

- $CRI = 0.18 \rightarrow$ prevention gap at medium-low level.
- **Priority:** Strengthen hygiene procedures and conduct regular audits of equipment.

Example C – Digital Technologies: Cybersecurity (MSI)

- Attack frequency Attack frequency $P_a = 0.27$ — obtained from statistical data.
- Severity $S_a = 5$ — selected by expert classification.
- Controls maturity $C_m = 0.6$ — obtained through audit.
  - $C^* = 0.4$ — normalized by inversion.
  - User awareness $U_a = 0.5$ — obtained through survey.
- $U^* = 0.5$ — normalized by inversion.

Inversion reflects the negative share of the positive index alongside other directly negative factors.

Weighted Impact Index (cyber-attack):

$\text{WII}_{\text{cyber}} = 0.27 \cdot 5 \cdot W_{\text{cyber}}; \quad W_{\text{cyber}} = 0.53 \Rightarrow \text{WII} = 1.35$

Composite Risk Index (controls + awareness):

- **Weights:** $\{W_C, W_U\} = \{0.6, 0.4\}, \sum W = 1.$
- **CRI:** $\text{CRI}_{\text{ctrl}} = 0.4 \cdot 0.6 + 0.5 \cdot 0.4 = 0.24 + 0.20 = 0.44$

Multivariate Safety Index (calibrated combination):

$\text{MSI} = \alpha \cdot \text{CRI}_{\text{ctrl}} + \beta \cdot \text{WII}_{\text{cyber}}$

Interpretation: $MSI \approx 0.99$ — high integrated risk.

Priority: Increase controls maturity (IAM, SIEM, patching) and strengthen user awareness programs.

Definitions (specific to Example C):

- **MSI (Multivariate Safety Index):** A multi-variable safety index; in cybersecurity, it can be used to assess controls maturity.
- **Controls maturity:**
- *IAM (Identity and Access Management):* How well user identification and access control are organized.
- *SIEM (Security Information and Event Management):* Effectiveness of collecting, analyzing, and responding to security events.
- *Patching:* Timeliness of system updates and vulnerability remediation.

Levels of maturity:

- **Low:** Controls are partial or inconsistent.
- **Medium:** Controls are standardized but still have gaps.
- **High:** Controls are integrated, automated, and continuously monitored.

Interpretation: MSI integrates the maturity of these controls into a unified index, enabling organizations to assess their overall level of security.

Explanations for All Examples

As seen from the examples above, inversion is the change of scale direction so that all factors are interpreted uniformly and negatively within the multi-factor index:

- A negative factor enters the multi-factor index directly with its own value.
- A positive factor does not enter the multi-factor index directly with its value (V_e), but rather with the difference $1 - V_e$.
- Uniform interpretation means that the positive factor is represented negatively according to its numerical magnitude (V_e).

This is necessary because some factors are naturally the higher, the better (e.g., ventilation efficiency), while others are the higher, the worse (e.g., methane concentration). If they were added directly, the overall index would be distorted. Inversion ensures that all factors are consistently perceived as risk and reflected coherently in the composite index. In this case, ventilation is a positive factor whose negativity is expressed by the difference $1 - V_e$. Thus, every factor's contribution — whether positive or negative — must be represented in the composite measure as negative influence.

It is essential to correctly define the multi-factor index, so let us explain step by step the related issues, which also serve as a summary of the paragraph.

1. Nature of factors

- **Positive factor:** the higher, the better (e.g., ventilation efficiency).
- **Negative factor:** the higher, the worse (e.g., methane concentration).
- **Neutral/mixed factor:** may act in both directions depending on context (e.g., response time).

2. Normalization

All factors are converted to a unified scale (0–1 or 0–10).

- Negative factors are used directly (higher = higher risk).
- Positive factors are inverted ($X^* = 1 - X$) so that a high positive value becomes low risk.

3. Weight assignment

- Each factor is assigned a weight (W_i) representing its importance in the overall picture.
- The sum of all weights must always equal 1 ($\sum W_i = 1$).

4. Composite measure calculation

All factor contributions are combined using the formula:

$$CRI = \sum_{i=1}^{n} X_i^* \cdot W_i$$

where X_i^* is the normalized/inverted value, and W_i is the weight.

Result: A composite measure reflecting the combined influence of all factors.

5. Interpretation

• Positive factor: after inversion, its good side becomes low risk, while its bad side becomes high risk.

• Negative factor: its direct value already reflects risk.

• Composite measure: all contributions (positive and negative) are combined to provide the overall picture.

The practical examples presented in this section are provided for **illustrative and educational purposes only**. They demonstrate how multi-factor indices and formulas can be applied to cement production and related industrial processes, integrating environmental, energy, occupational safety, and public health considerations. **ISO 14001** offers validated methods for environmental monitoring, **ISO 50001** provides frameworks for energy efficiency calculations, **ISO 45001** establishes occupational risk assessment procedures, and **IEC 60079** ensures electrical safety in hazardous environments. **WHO recommendations** complement these standards by emphasizing protective measures, epidemiological monitoring, and community health awareness. These examples are not intended to replace or supersede official standards; rather, they serve to clarify theoretical concepts and show how internationally recognized frameworks can be applied in practice. By linking practical examples to these standards, the monograph ensures that illustrative calculations remain scientifically validated, ethically grounded, and internationally comparable.

13.5. Methodological Map and Visual Scheme

Steps for the researcher:

• **Step 1 – Goal formulation:** What category is being studied? What outcome is to be evaluated?

The researcher must first define the category under study and the outcome to be assessed. Example: Risk of methane explosion or Probability of infection spread. Clear goal formulation determines what data must be collected and which methods should be applied.

• **Step 2 – Factor selection:** Technical, organizational, human.

Factors may be technical, organizational, or human. In selection, the researcher must ensure that each factor truly influences the outcome. Example: ventilation, sensor response time, hygiene procedures.

• **Step 3 – Normalization:**

Factors must be converted to a unified scale (0–1 or 0–10). Positive factors are inverted into negative equivalents. Inversion uses the difference between upper bound and positive value, since this difference represents the negative reflection of the positive index.

• **Step 4 – Weighting:**

Factors are assigned weights (W_i), the sum of which must equal 1 ($\sum W_i = 1$). Weights may be determined by experts (based on priorities) or by data (formula: $W_i = \frac{X_i}{\sum X_j}$). This ensures that more important factors receive greater share.

• **Step 5 – Indices:** CRI, WII, MSI as needed.

The researcher calculates the Composite Risk Index (CRI), the Weighted Impact Index (WII), or, if necessary, the Multivariate Safety Index (MSI). Each provides a different perspective: CRI integrates factors, WII shows the weight of individual factors, MSI creates an integrated picture.

- **Step 6 – Sensitivity analysis:** Testing scales, weights, scenarios.

Scenario testing is required: scale changes (0–10 → 0–8), small weight adjustments (±0.05), definition of min–max intervals. Allowable error must be pre-defined. This shows how stable the index is and how sensitive it is to changes.

- **Step 7 – Validation:** Triangulation (observation + statistics + interviews).

Results must be validated by multiple methods: triangulation (observation + statistics + interviews), cross-validation (comparing data across different sites). This increases credibility and reduces error probability.

- **Step 8 – Interpretation:** Priorities, control measures, integration into PDCA cycle.

Finally, the researcher must define priorities and control measures. Results should be integrated into the PDCA cycle (Plan–Do–Check–Act), so that the obtained index becomes a practical decision.

Visual scheme (textual):

Hazard identification → Factor selection → Normalization → Weighting → Index calculation (CRI/WII/MSI) → Prioritization → Control measures → Monitoring (PDCA).

Table 13.4. Steps for the Researcher

Step	**Content**	**Practical application**	**Educational value**
Step 1 – Goal formulation	Define what category is being studied and what outcome is to be evaluated	Risk of methane explosion or Probability of infection spread	Shows that research begins with a clear goal
Step 2 – Factor selection	Define technical, organizational, and human factors	Ventilation, sensor response time, hygiene procedures	Teaches that outcomes are influenced by multiple factors
Step 3 – Normalization	Convert factors to a unified scale (0–1 or 0–10)	Inversion of positive factors: upper bound – positive value – difference	Shows how data is represented uniformly
Step 4 – Weighting	Assign each factor a weight (W_i), with $\sum W_i = 1$	Determined by experts or by data	Teaches that more important factors receive greater share
Step 5 – Index calculation	CRI, WII, MSI if necessary	CRI integrates factors; WII shows individual weight;	Shows that different indices provide

		MSI creates an integrated picture	different perspectives
Step 6 – Sensitivity analysis	Test scenarios: scale changes, weight adjustments	0–10 → 0–8; ±0.05 on weights	Teaches that results must remain stable under small changes
Step 7 – Validation	Confirm results using multiple methods	Triangulation (observation + statistics + interview), cross-validation	Shows that credibility increases with multi-method verification
Step 8 – Interpretation	Define priorities and establish control measures	Integrate into PDCA cycle (Plan–Do–Check–Act)	Teaches that the index must be transformed into practical decisions

Extended Practical Examples for the Researcher

These examples provide not only formulas and results but also a transparent path showing how each numerical value was determined — whether obtained by measurement, selected by experts, or determined through normalization/formulas.

Example A – Mining Industry: Composite Methane Risk (CRI)

Data:

$C_m = 0.6$ — obtained by sensor measurement (methane concentration).

$V_e = 0.7$ — selected as a positive factor (ventilation efficiency, obtained from audit data).

$T_s = 10$ s — obtained by observation (sensor response time).

Normalization and inversion:

$V^* = 1 - V_e = 0.3$ — determined by inversion.

$T_s^* = 0.5$ — determined by normalization (10 sec scaled to 0–1).

$T^* = 1 - T_s^* = 0.5$ — determined by inversion.

Weights: $\{W_C, W_V, W_T\} = \{0.5, 0.3, 0.2\}$ — selected by expert priorities.

Calculation:

$$CRI = 0.6 \cdot 0.5 + 0.3 \cdot 0.3 + 0.5 \cdot 0.2 = 0.49$$

Interpretation: 0.49 — medium-high risk.

Example B – Healthcare: Infection Multi-factor Index ($WII + CRI$)

Data:

- $P = 0.30$ — obtained from statistical data (probability of infection spread).
- $S = 4$ — selected by expert classification (severity of outcome).
- $W = 1.0$ — selected as categorical weight.

Weighted Impact Index:

$$WII = P \cdot S \cdot W = 0.30 \cdot 4 \cdot 1.0 = 1.20$$

Preventive factors:

- $H_h = 0.8$ — obtained by observation (hygiene compliance).
- $E_e = 0.9$ — obtained from audit data (equipment functionality).

- $W_r = 0.7$ — determined by expert evaluation (process consistency).

Inversion:

- $H^* = 1 - H_h = 0.2$
- $E^* = 1 - E_e = 0.1$
- $W^* = 1 - W_r = 0.3$

Weights: $\{W_H, W_E, W_W\} = \{0.4, 0.4, 0.2\}$ — selected by experts.

Composite Risk Index:

$$CRI = 0.2 \cdot 0.4 + 0.1 \cdot 0.4 + 0.3 \cdot 0.2 = 0.18$$

Interpretation: $WII = 1.20$ (serious impact); $CRI = 0.18$ (medium-low prevention gap).

Example C – Cybersecurity: MSI

Data:

- $P_a = 0.27$ — obtained from statistical data (attack frequency).
- $S_a = 5$ — selected by expert classification (severity).
- $C_m = 0.6$ — obtained through audit (controls maturity).
- $U_a = 0.5$ — obtained through survey (user awareness).

Inversion:

- $C^* = 1 - C_m = 0.4$
- $U^* = 1 - U_a = 0.5$

Weighted Impact Index (cyber-attack):

$$WII_{\text{cyber}} = P_a \cdot S_a \cdot W_{\text{cyber}} = 0.27 \cdot 5 \cdot 0.53 = 1.35$$

($W_{\text{cyber}} = 0.53$ — selected by experts).

Composite Risk Index (controls + awareness):

$$CRI_{\text{ctrl}} = 0.4 \cdot 0.6 + 0.5 \cdot 0.4 = 0.44$$

($\{ W\_C, W\_U\} = \{ 0.6, 0.4\}$ — selected by experts).

Multivariate Safety Index*:*

$$MSI = \alpha \cdot CRI_{\text{ctrl}} + \beta \cdot WII_{\text{cyber}}$$

(α, β — determined by calibration; e.g., $\alpha = 0.4, \beta = 0.6$).

Interpretation: $MSI \approx 0.99$ — high integrated risk.

Table 13.5. Mining Industry: Composite Methane Risk (CRI)

Parameter	Value	Source	Explanation
C_m	0.6	**Obtained**	Methane concentration measured by sensor
V_e	0.7	**Selected**	Ventilation efficiency, from audit data
T_s	10 sec	**Obtained**	Response time measured by observation
V^*	0.3	**Determined**	Inversion: $1 - V_e$
T_s^*	0.5	**Determined**	Normalization: 10 sec scaled to 0–1
T^*	0.5	**Determined**	Inversion: $1 - T_s^*$
Weights	{0.5,0.3,0.2}	**Selected**	Expert priorities

Table 13.6. Healthcare: Infection Multi-factor Index (WII + CRI)

Parameter	Value	Source	Explanation
F	0.30	**Obtained**	Probability of spread from statistical data
S	4	**Selected**	Severity defined by expert classification
W	1.0	**Selected**	Weight when only one category exists
H_h	0.8	**Obtained**	Hygiene compliance measured by observation
E_e	0.9	**Obtained**	Equipment functionality from audit data
W_r	0.7	**Determined**	Process consistency defined by expert evaluation
H^*	0.2	**Determined**	Inversion: $1 - H_h$
E^*	0.1	**Determined**	Inversion: $1 - E_e$
W^*	0.3	**Determined**	Inversion: $1 - W_r$
Weights	{0.4,0.4,0.2}	**Selected**	Expert priorities

Table 13.7. Cybersecurity: MSI

Parameter	Value	Source	Explanation
S_a	0.27	**Obtained**	Attack frequency from statistical data
S_a	5	**Selected**	Severity defined by expert classification
C_m	0.6	**Obtained**	Controls maturity from audit
U_a	0.5	**Obtained**	User awareness from survey
C^*	0.4	**Determined**	Inversion: 1-C_m
U^*	0.5	**Determined**	Inversion: 1-U_a
W_{cyber}	0.53	**Selected**	Expert priorities
Weights	{0.6, 0.4}	**Selected**	Expert priorities
α, β	0.4, 0.6	**Determined**	Calibration process, synthesis of data and expert evaluation

Summary:

Each numerical value is transparently explained:

- **Obtained** — through measurement, observation, statistics, audit, or survey.
- **Selected** — by expert priorities or classification.
- **Determined** — through normalization, inversion, calibration, or formula.

The methodological map and visual scheme serve as a structured representation of multi-factor analysis, showing how environmental, energy, occupational safety, and public health dimensions interact within a unified framework. **ISO 14001** provides the foundation for environmental monitoring, **ISO 50001** for energy efficiency, **ISO 45001** for occupational health and safety, and **IEC 60079** for electrical safety in hazardous environments. **WHO recommendations** complement these standards by emphasizing community health, protective measures, and emergency preparedness. By visually mapping these interconnections, the scheme ensures that theoretical models are transparent, practically applicable, and internationally comparable. The diagrammatic approach enhances didactic clarity, allowing students and professionals to see how each factor contributes to the overall risk index and how standards anchor every calculation.

13.6. Policy Recommendations and Interpretation

- **Prioritization:**

High WII → Immediate control
High CRI → Process strengthening
High MSI → Strategic reform

- **Resource allocation:**

Based on weights and indices — focus on the most influential categories.

- **Integration with PDCA:**

Plan: Calibration of indices, targeted programs.
Do: Implementation of control measures.
Check: Audit, review of indices.
Act: Corrections, reassessment of standard strictness levels.

- **Communication:**

Use short, interpretable ranges; visualization; consistent terminology (maintain EN–KA parallel).

- **Gradation ranges:**

For the 0–1 scale, ranges are fixed (0–0.33, 0.34–0.66, 0.67–1.00), regardless of the number of factors. Gradation ranges also remain unchanged for other scales (0–10, etc.). The presence of multiple factors increases accuracy but does not alter boundaries.

Terminological Glossary

Term	Definition	Note
Hazard	Source of potential harm	Must not be confused with risk
Risk	$R = PxS$ — Probability × Severity	ISO 31000
Probability (P)	Frequency / likelihood of occurrence	Indicate source: Measured / Selected / Determined
Severity (S)	Magnitude / seriousness of outcome	Scale of consequences
Intensity	Strength / sharpness of exposure	Use only in exposure context
Hazardous situation	Conditions where real risk exists	ISO 45001
Individual case	One injured person	Use individual instead of single
Multiple-casualty event	More than one injured person	Group or Multiple
Safety	Reduction of risks to acceptable level	Acceptable level
Occupational safety	Safety of the work environment	ISO 45001
Risk assessment	Identification, analysis, evaluation	ISO 31000
Risk management	Actions to reduce risks	PDCA cycle
Control measures	Technical / organizational / individual	Collective measures prioritized
Mining	Sectoral context	Standardized form
Certification	Confirmation of compliance	ISO 31000 not subject to certification

Dosimetry	Monitoring of ionizing radiation doses	IAEA

Standardization Rules:

- Formula: [R = P × S].
- ISO references: First mention with full name + year, then only acronym.
- PDCA: Use bilingual unified form — PDCA (Plan–Do–Check–Act).
- Numerical values: Always indicate source (Measured / Selected / Determined).

Policy recommendations in multi-factor analysis must be grounded in internationally recognized standards to ensure both scientific validity and practical applicability. **ISO 14001** provides the framework for environmental policy, requiring continuous improvement and compliance with ecological regulations. **ISO 50001** complements this by guiding energy efficiency policies that reduce emissions and resource consumption. **ISO 45001** establishes occupational safety policies, mandating hazard identification, preventive strategies, and worker participation. **IEC 60079** adds electrical safety policies for hazardous environments, ensuring that installations and maintenance practices minimize explosion risks. **WHO recommendations** strengthen the public health dimension, emphasizing community health protection, emergency preparedness, and awareness campaigns. Interpretation of multi-factor results must therefore align with these standards, ensuring that theoretical models translate into actionable, ethically grounded, and internationally comparable policies.

APPENDICES

Appendix Table AT1. International Standards

Abbreviation	Full Name	Current Standard/Reference	Revision Cycle	Summary
ISO	International Organization for Standardization	ISO 45001:2018 – Occupational Health & Safety Management Systems; ISO 14001:2015 Environmental Management Systems; ISO 9001:2015 Quality Management Systems	Usually every 5 years; ISO 45001 new revision expected in 2027	Provides universal standards for harmonizing safety, environmental, and quality management systems
ILO	International Labour Organization	ILO Convention C167 – Safety and Health in Construction	Regular revision according to international practice	Establishes various occupational safety rules
NFPA	National Fire Protection Association	NFPA 10 – Standard for Portable Fire Extinguishers	Periodic updates based on practical needs	Typology and usage rules for fire extinguishers

IEC 60479	International Electrotechnical Commission	IEC 60479 – Effects of current on human beings and livestock	Every 10 years	Defines electrical safety rules
WHO	World Health Organization	Occupational Health Guidelines	Updated as needed	Provides recommendations for workers' health and workplace safety
IAEA	International Atomic Energy Agency	IAEA Safety Standards Series GSR Part 3 – Radiation Protection and Safety of Radiation Sources	Every 10 years	Establishes international rules for radiation safety
ICNIRP	International Commission on Non-Ionizing Radiation Protection	ICNIRP Guidelines (2020) – Radiofrequency EMF exposure limits	Every 10 years	Defines safety limits for non-ionizing radiation

Explanatory Notes

• **ISO** → Standards revised every 5 years to reflect new scientific data. Example: ISO 45001:2018 revision expected in 2027.

• **ILO** → Construction Safety Convention (C167) directly addresses scaffolding, ladders, and construction site arrangements.

• **NFPA 10** → Fire extinguisher color coding: Water – Red; Dry Powder – Blue; CO_2 – Black; Quick Evaporation – Green; Foam – Cream.

• **IEC 60364** → Defines electrical installation safety rules in buildings, including grounding and lightning protection.

• **IEC 60479** → Threshold of current effect on humans: ≤10 ohms resistance for safe grounding; effects classified as perceptible, dangerous, and lethal.

• **WHO** → Guidelines cover use of personal protective equipment, control of workplace microclimate, and prevention of injuries.

• **IAEA** → Radiation protection standards apply not only in nuclear fields but also in medical imaging (X-ray, CT).

• **ICNIRP** → Defines limits for radiofrequency and electromagnetic fields to avoid health risks.

Appendix Table AT2. Additional International Standards

Abbreviation	Full Name	Current Standard/Reference	Revision Cycle	Summary
ISO 31000	Risk Management – Guidelines	ISO 31000:2018	Every 5 years (next revision expected 2023–2025)	Defines principles and processes of risk management; universal framework for all sectors
ISO 31010	Risk Assessment Techniques	ISO 31010:2019	Every 5 years (next revision expected 2024–2025)	Supplements ISO 31000; describes over 30 practical methods (HAZOP, FMEA, FTA, etc.)
ISO 8995-1		ISO 8995-1:2021	Every 5 years	Sets minimum lighting levels and visual comfort

	Lighting of Work Places			requirements for workplaces
ISO 1999	Acoustics — Determination of Occupational Noise Exposure	ISO 1999:2013	Every 10 years	Defines occupational noise limits (85 dB over 8 hours) and dose modeling
IEC 60529	Degrees of Protection Provided by Enclosures (IP Code)	IEC 60529:1989 + Amd2:2013 + Cor1:2019	Every 10 years	Defines protection levels of equipment against dust and water (IP codes)
IEC 60079	Explosive Atmospheres	IEC 60079 series	Every 10 years	Safety requirements for equipment used in explosive atmospheres
EN 13445	Unfired Pressure Vessels	EN 13445:2021	Periodic updates	European standard for construction of high-pressure vessels
ASME BPVC	Boiler and Pressure Vessel Code Section VIII	ASME BPVC Section VIII, Division 1 (2025)	Periodic updates	American code for safe construction of pressure vessels
IEC 61508	Functional Safety of Electrical/Electronic Systems	IEC 61508:2010	Every 10 years	Defines functional safety requirements for electronic systems
NFPA 77	Recommended Practice on Static Electricity	NFPA 77:2023	Periodic updates	Practical rules for managing static electricity
EHSGCLM	Environmental, Health, and Safety Guidelines for Cement and Lime Manufacturing	IFC EHSGCLM (latest version on IFC website)	Periodic updates	Defines environmental, health, and safety requirements in cement/lime production
IFC PS	International Finance Corporation – Performance Standards	IFC PS (latest version on IFC website)	Periodic updates	Provides stricter requirements for international projects when local regulations are less stringent

Appendix Table AT3. Basic Units of Physical Quantities

Physical Quantity	Dimension	Unit Name	Symbol
Length	L	Meter	m
Mass	M	Kilogram	kg
Time	T	Second	s
Electric Current	I	Ampere	A
Thermodynamic Temperature	θ	Kelvin	K
Amount of Substance	N	Mole	mol

Luminous Intensity	J	Candela	cd

Appendix Table AT4. Supplementary Units

Physical Quantity	Unit Name	Symbol
Plane Angle	Radian	rad
Solid Angle	Steradian	sr

Appendix Table AT5. Derived Units (from Basic and Supplementary Units)

Physical Quantity	Dimension	Unit Name	Symbol
Area	L^2	Square meter	m^2
Volume	L^3	Cubic meter	m^3
Speed	LT^{-1}	Meter per second	m/s
Angular Speed	T^{-1}	Radian per second	rad/s
Acceleration	LT^{-2}	Meter per second squared	m/s^2
Angular Acceleration	T^{-2}	Radian per second squared	rad/s^2
Wave Number	L^{-1}	Reciprocal meter	m^{-1}
Density	$L^{-3}M$	Kilogram per cubic meter	kg/m^3
Specific Volume	L^3M^{-1}	Cubic meter per kilogram	m^3/kg
Electric Current Density	L^2M^{-1}	Ampere per square meter	A/m^2
Magnetic Field Strength	$L^{-1}I$	Ampere per square meter	A/m
Molar Concentration	$L^{-3}N$	Mole per cubic meter	mol/m^3
Flux of Ionizing Particles	T^{-1}	Reciprocal second	s^{-1}
Flux Density of Ionizing Particles	$L^{-2}T^{-1}$	Reciprocal second per square meter	$s^{-1}m^{-2}$
Luminance	$L^{-2}J$	Candela per square meter	cd/m^2

Appendix Table AT6. Derived Units with Special Names

Physical Quantity	Dimension	Unit Name	Symbol
Frequency	T^{-1}	Hertz	Hz
Force, Weight	LMT^{-2}	Newton	N
Pressure, Mechanical Stress, Elastic Modulus	$L^{-1}MT^{-2}$	Pascal	Pa
Energy, Work, Heat	L^2MT^{-2}	Joule	J
Power, Energy Flux	L^2MT^{-3}	Watt	W
Electric Charge (Quantity of Electricity)	TI	Coulomb	C
Electric Voltage, Potential Difference, Electromotive Force	$L^2MT^{-3}I^{-1}$	Volt	V
Electric Capacitance	$L^{-2}M^{-1}T^4I^2$	Farad	F
Electrical Resistance	$L^2MT^{-3}I^{-2}$	Ohm	□
Electrical Conductance	$L^2M^{-1}T^3I^2$	Siemens	S
Magnetic Flux	$L^2MT^{-2}I^{-1}$	Weber	Wb
Magnetic Flux Density, Magnetic Induction	$MT^{-2}I^{-1}$	Tesla	T

Inductance, Mutual Inductance	$L^2MT^{-2}I^{-2}$	Henry	H
Luminous Flux	J	Lumen	lm
Illuminance	$L^{-2}J$	Lux	lx
Radioactive Activity	T^{-1}	Becquerel	Bg
Absorbed Dose, Kerma, Dose Rate	L^2T^{-2}	Gray	Gy

Appendix Table AT7. Derived Units Based on Special Names

Physical Quantity	Dimension	Unit Name	Symbol
Moment of Force	L^2MT^{-2}	Newton-meter	N.m
Surface Tension	MT^{-2}	Newton per meter	N/m
Dynamic Viscosity	$L^{-1}MT^{-1}$	Pascal-second	Pa.s
Electric Charge Density (Volumetric)	$L^{-3}TI$	Coulomb per cubic meter	C/m^3
Electric Charge Density (Surface)	$L^{-2}TI$	Coulomb per square meter	C/m^2
Electric Field Strength	$LMT^{-3}I^{-1}$	Volt per meter	V/m
Absolute Dielectric Permittivity	$L^{-3}M^{-1}T^4I^2$	Farad per meter	F/m
Absolute Magnetic Permeability	$LMT^{-2}I^2$	Henry per meter	H/m
Specific Energy	L^2T^{-2}	Joule per kilogram	J/kg
Heat Capacity, Entropy	L^2MT^{-2}□□□	Joule per Kelvin	J/K
Specific Heat Capacity, Specific Entropy	L^2T^{-2}□□□	Joule per kilogram-Kelvin	J/(kg.K)
Energy Flux Density	MT^{-3}	Watt per square meter	W/m^2
Thermal Conductivity	LMT^{-3}□□□	Watt per meter-Kelvin	W/(m.K)
Molar Internal Energy	$L^2MT^{-2}N^{-1}$	Joule per mole	J/mol
Molar Entropy, Molar Heat Capacity, Mass Transfer Potential	L^2MT^{-2}□□□N^{-1}	Joule per mole-Kelvin	J/(mol.K)
Radiant Intensity	L^2MT^{-3}	Watt per steradian	W/sr
Exposure (X-ray, Gamma Radiation)	$M^{-1}TI$	Coulomb per kilogram	C/kg
Absorbed Dose Rate	L^2T^{-3}	Gray per second	Gy/s

Appendix Table AT8. Prefixes Established for Forming Multiples and Submultiples of Units

Multiple or Fraction	Prefix Name	Abbreviation
1, 000, 000, 000, 000 = 10^{12}	Tera	T
1, 000, 000, 000 = 10^9	Giga	G
1, 000, 000 = 10^6	Mega	M
1, 000 = 10^3	kilo	k
100 = 10^2	Hecto	h
10 = 10^1	Deca	da
0.1 = 10^{-1}	Deci	d
0.01 = 10^{-2}	Centi	c
0.001 = 10^{-3}	Milli	m
0.000001 = 10^{-6}	Micro	µ
0.000000001 = 10^{-9}	Nano	n
0.0000000000001 = 10^{-12}	Pico	p

Appendix Table AT9. Units for Evaluating Ionizing Radiation

Rest Mass of Particle:

SI: kilogram [kg]
Non-SI: atomic mass unit [amu]
$1\,amu = 1.66057 \times 10^{-27}\,kg$

Energy of Ionizing Radiation:
SI: joule [J]
Non-SI: 1. electronvolt [eV]; 2. erg [erg]
$1\,eV = 1.60219 \times 10^{-19}\,J$
$1\,erg = 1.0 \times 10^{-7}\,J$

Absorbed Dose:
SI: gray [Gy]
Non-SI: rad [rad]
$1\ Gy = 1\ J/kg = 100\ rad$

Absorbed Dose Rate:
SI: gray per second [Gy/s]
Non-SI: 1. rad per second [rad/s]; 2. gray per minute [Gy/min]
$1\,rad/s = 1.0 \times 10^{-2}\,Gy/s$
$1\,Gy/min = 1.666 \times 10^{-2}\,Gy/s$

Exposure Dose:
SI: coulomb per kilogram [C/kg]
Non-SI: roentgen [R]
$1\,R = 2.57976 \times 10^{-4}\,C/kg$

Exposure Dose Rate:
SI: ampere per kilogram [A/kg]
Non-SI: roentgen per second [R/s]
$1\,R/s = 2.57976 \times 10^{-4}\,A/kg$

Equivalent Dose:
SI: sievert [Sv]
Non-SI: rem [rem]
$1\,rem = 1.0 \times 10^{-2}\,Sv$ *(rem = roentgen equivalent man)*

Equivalent Dose Rate:
SI: sievert per second [Sv/s]
Non-SI: rem per second [rem/s]
$1\,rem/s = 1.0 \times 10^{-2}\,Sv/s$

Radionuclide Activity:
SI: becquerel [Bq]
Non-SI: curie [Ci]
$1\,Ci = 3.70 \times 10^{10}\,Bq$

Specific Activity of Radionuclide:
SI: becquerel per kilogram [Bq/kg]
Non-SI: curie per kilogram [Ci/kg]
$1\,Ci/kg = 3.70 \times 10^{10}\,Bq/kg$

Energy Flux of Ionizing Radiation:
SI: watt [W]
Non-SI: erg per second [erg/s]
$1\,erg/s = 1.0 \times 10^{-7}\,W$

Energy Flux Density of Ionizing Radiation:
SI: watt per square meter [W/m^2]
Non-SI: erg per second per square centimeter [$erg/(s \cdot cm^2)$]

$1\, erg/(s \cdot cm^2) = 1.0 \times 10^{-3}\, W/m^2$

Table A1.1. Comparison of International Standards

Standard	Focus Area	Application in Safety Management
ISO 31000	Risk Management Framework	Identification, evaluation, prioritization of risks
ISO 45001	Occupational Health & Safety	Preventive measures, employee involvement, PDCA cycle
ICNIRP	Non-Ionizing Radiation	Exposure limits for EMF and RF fields
IAEA	Ionizing Radiation	Dosimetry, waste management, personnel protection
WHO	Public Health & Workplace Safety	Guidelines for PPE, microclimate, injury prevention

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