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Environmentally safe management of cadmium and mercury.

Case: nickel-cadmium battery and compact fluorescent lamp

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ABSTRACT

The main purpose of the thesis was to create the recommendations for the environmentally friendly management of cadmium and mercury on the example of nickel-cadmium battery and a compact fluorescent lamp. The objects of research are a nickel-cadmium battery and a compact fluorescent lamp. Three research objectives were defined: (1) Assessment of the life cycle of a nickel-cadmium battery and a compact fluorescent lamp, development of recommendations for rational use, (2) analysis of regulatory documents in the field of chemicals management and (3) analysis of methods for assessing the life cycle of hazardous substances.

The thesis included SFA method (Substance Flow Analysis) and the Life Cycle Assessment Method (tool Eco-indicator 99). The first study assumed the use of the SFA method. The method was based on the implementation of several stages. SFA is an analysis method that is used to assess the flow of a substance. The method involved the use of the principle of mass balance in order to identify the relationship between material flows and human activities (product life cycle). Substance flows were examined and tracked based on the identified system boundaries. Another method (that was) used in the study was LCA (life cycle assessment), a particular method of which was Eco-indicator 99. The LCA method is based on identifying the environmental characteristics of a product. Eco-indicator 99 is based on determining environmental damage throughout the entire life cycle of a product using easy-to-assess eco-indicators. Based on the results the life cycle assessment of cadmium in a battery and mercury in CFLs, recommendations were proposed for enterprises and for government bodies (authorities) based on the organization of cooperation, industry and international enterprises; development of an informative base for the management of chemical waste, emissions and discharges of enterprises; risk management, reducing the likelihood of risks arising from the handling of chemicals. The developed recommendations will be used for environmentally safe management of cadmium and mercury.

Keywords: life cycle assessment of substances; cadmium nickel-cadmium battery mercury; compact fluorescent lamp; substance flow analysis (SFA) method; SimaPro software; Eco-indicator 99 method; rational use of chemicals

CONTENTS

1 INTRODUCTION

Urbanization processes, the development of the industrial sector and an increase in the number of enterprises lead to anthropogenic pressure on the environment. In particular, substances that are used in enterprises have a negative impact on nature. The life cycle assessment (LCA) of chemicals for the purpose of environmentally sound management of the use of toxic chemicals is a solution to this environmental problem.

The relevance of developing recommendations for the safe handling of chemicals is confirmed by the need to achieve the goals of the 2030 Agenda for Sustainable Development and national goals of a comfortable and safe environment established by the decree of the President of the Russian Federation on August 21, 2020. One of the target indicators for achieving this goal is to reduce emissions of hazardous pollutants that have the greatest negative impact on the environment and human health by 2 times.

Life Cycle Assessment (LCA) is a process that aims to identify the negative effects of substances from the initial stage of production to disposal. In author's opinion, the final analysis of the produced life cycle allows us to identify the main shortcomings in the technological process of the enterprise, it is a management tool for support in the field of environmental management of the enterprise.

The main purpose of the thesis was to create the recommendations for the environmentally friendly management of cadmium and mercury on the example of nickel-cadmium battery and a compact fluorescent lamp. The objects are a nickel-cadmium battery and a compact fluorescent lamp. The following research objectives were defined:

- Assessment of the life cycle of a nickel-cadmium battery and a compact fluorescent lamp, development of recommendations for rational use.
- Analysis of regulatory documents in the field of chemicals management.
- Analysis of methods for assessing the life cycle of hazardous substances.

2 ANALYSIS OF RUSSIAN AND INTERNATIONAL LEGISLATION IN THE FIELD OF SAFE MANAGEMENT OF THE USE OF TOXIC CHEMICALS

2.1 Legislation of the Russian Federation

In the field of safe management of the use of toxic chemicals, several control documents should be highlighted. The main control document of the Russian Federation is Federal Law of the Russian Federation of January 10, 2002 N 7-FZ "On Environmental Protection". This law is based on the principles of environmental protection. Preservation of environmental quality is one of the key concepts of this guidance document. The federal law controls the legal relations of activities between society and nature (economic and other activities).

One of the goals of life cycle assessment of chemicals is the prevention of environmental pollution. Article 1 of Chapter I explains the concept of "environmental pollution" as the release into the environment of a substance and (or) energy, the properties, location, or quantity of which have a negative impact on the environment (Federal Law of the Russian Federation N 7-FZ2002).

Article 47 of Chapter VII states that the production and circulation of chemicals is allowed only with a preliminary assessment (study) based on toxicological-hygienic and toxicological principles. At the same time, it is necessary to determine the procedure for handling these substances, establish standards and register these substances.

Guidelines are used to conduct accurate studies to determine the level of hazard of substances. Thus, P 1.2.3156-13 "Assessment of the toxicity and danger of chemicals and their mixtures for human health" contains rules for ensuring the process of state registration of substances that are introduced into production (P 1.2.3156-13, 2013). The purpose of the manual is to maintain a unified system for assessing the safety of substances, products containing these substances.

Hazardous chemicals found in products are also controlled by various regulations. It should be noted that control of products and processes is possible after a life cycle assessment. The life cycle is the main stages from the production of a product to its disposal. This takes into account the impact on the environment. This process is called life cycle impact assessment (LCIA). According to GOST R ISO 14040-2010 “Life cycle impact assessment (LCIA): A life cycle assessment stage aimed at understanding and assessing the magnitude and significance of possible environmental impacts for a product life cycle system throughout the product life cycle (GOST R ISO 14040-2010).

The content of pollutants in environmental objects is controlled based on several environmental documents. In accordance with the Order of the Ministry of Agriculture of the Russian Federation dated December 13, 2016 N 552 "On the approval of water quality standards for water bodies of fishery value, including the standards of maximum permissible concentrations of harmful substances in the waters of water bodies of fishery value" MPC (maximum permissible concentration) of cadmium is 0.005 mg/dm^3 and 0.01 mg/dm^3 (for sea water) in the waters of water bodies of fishery importance, for mercury - 0.00001 mg/dm^3 and 0.0001 mg/dm^3 for sea water (Order of the Ministry 2016). MPC of cadmium in water for domestic and domestic water use should not exceed 0.001 mg/l (SanPiN 2.1.5.980-00, 2001). The value for mercury is not given in this document.

A common substance of cadmium that is formed at enterprises and released into the atmosphere is cadmium oxide. In accordance with GN 2.1.6.3492-17 Maximum Permissible Concentrations (MPC) of pollutants in the atmospheric air of urban and rural settlements, the average daily MPC for cadmium oxide is 0.0003 mg/m^3. The daily average MPC for mercury is 0.0003 mg/m^3 (GN 2.1.6.3492-17, 2017)

According to MU 2.1.7.730-99, the MPC of mercury in soil, taking into account the background, is 2.1 mg/kg (hazard class 1) (MU 2.1.7.730-99, 1999). This value for cadmium is not given in the document.

2.2 International regulatory framework

The international organization for standardization ISO has developed the ISO standards with life cycle assessment. Enterprises use standards that have been approved at the international level. The international regulatory framework on the life cycle assessment of substances in products includes several documents of the ISO standards - ISO 14040, ISO 14044, ISO 14047, ISO 14048.

ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework defines the basic principles and sequence of life cycle assessment (LCA), contributes to the achievement of goal 13 in the field of sustainable development - Combating climate change. According to this document, Life Cycle Assessment (LCA) is the collection and evaluation of inputs and outputs, as well as potential environmental impacts from a product system at all stages of a product's life cycle (ISO 14040 2006). This document includes the purpose of the LCA application, the life cycle inventory (LCI) steps, the impact evaluation steps, the LCA critical review reviews, the relationship between the LCA and the selected element values.

ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines (Environmental management. Life cycle assessment. Requirements and recommendations) is identical to GOST R ISO 14044-2019. This document contributes to the achievement of 12 and 13 Sustainable Development Goals (Responsible consumption and production; Combating climate change) (ISO 14044, 2006). To determine the purpose of using an LCA, one should describe the exact life cycle system of the product under consideration, designate the functional unit, identify the functions and boundaries of the product life cycle system, the requirements of information sources and data quality, clarify some possible assumptions in the system, the selected values, the format of the data report. To describe LCA, the concepts of input and output flows are used, supplementing them with exclusion criteria - mass, energy and environmental significance criteria.

ISO/TR 14047:2012 "Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations" is identical to ISO/TR 14047:2012 "Environmental management - Life cycle assessment - Examples of the application of ISO 14044 to exposure situations", GOST R 56269-2014. The document is explanatory, complementary to ISO 14044. In addition, it provides examples of determining the impact categories of indicators, intermediate parameters and final objects of the category of negative impact on the environment, describes the sequence mechanism in the implementation of LCA, examples of mandatory components of LCA.

ISO/TS 14048:2002 "Environmental management - Life cycle assessment - Data documentation format" is identical to ISO/TS 14048:2002 "Environmental management. Life cycle assessment. Data documentation format" (GOST R ISO/TS 14048, 2002). The standard establishes provisions that describe a regulated data reporting standard for accurately assessing the life cycle of a product. The document includes information on the requirements for the number of pages of the report, the structure of questionnaires and other documents for conducting a life cycle assessment. Therefore, the standard is designed to achieve uniformity in the reporting of LCA results.

2.3 Conventions and agreements

The main provisions for the safe management of toxic chemicals are enshrined in conventions and agreements. They reflect the basic rules for dealing with harmful chemicals.

Agenda 21 was adopted at the UN Conference on Environment and Development in Rio de Janeiro (June 3-14, 1992). The program reflects environmental problems and ways to solve them. Section II "Conservation and management of resources for development" includes program areas, their objectives, activities and means of implementation. This section provides six program areas (Chapter 19 " Environmentally sound management of toxic chemicals, including prevention of illegal international traffic in toxic and dangerous products"), which are aimed at addressing issues related to chemical safety (Figure 1).

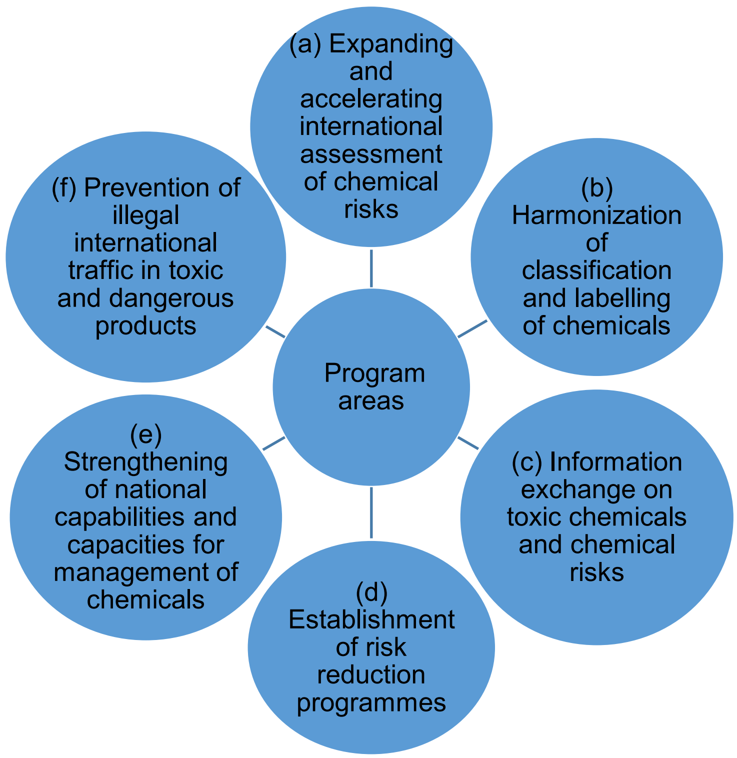


Figure 1. Program areas of Chapter 19 of Agenda 21 (1992)

To characterize program areas, their objectives should be described. The goal of program area A is to improve the hazard assessment system, develop principles for the management of toxic substances based on expert analysis. Program area B implies the implementation of a common international labeling system. In program area C, the goal is to create an open system for the communication of information on toxic substances and their hazards. Program branch D aims to reduce the risks associated with the hazard of chemicals based on the life cycle of substances. The next program area, E, involves the implementation in countries of national systems that justify the environmentally sound use of substances. The objectives of program area F are to control the international transport of toxic substances and to prevent the illegal import of dangerous products.

The management of toxic substances also implies the control of the movement of waste products of these substances. Thus, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal includes the obligations of the parties involved in the process of importing hazardous wastes, the rules for appointing authorities to carry out control activities under this convention, the rules for transboundary movements of wastes for two countries (export and import), and actions of the state of import and export in case of illegal traffic in toxic chemicals.

The Rio Declaration on Environment and Development is based on 27 principles. The purpose of the convention is to establish partnership relations between the three parts - the state, society and people. At the same time, the environmental system is based on constant development. Points 10 and 14 should be noted. 10 principle is based on the availability of information about the environment and hazardous materials for the citizens of the country. The use of judicial procedures is permitted. Principle 14 includes the concept of the transfer and transfer of pollutants (Rio Declaration on Environment and Development, 1992). These processes must be controlled through the cooperation of states in order to prevent environmental damage.

Another important document is the Declaration of the United Nations Conference on the Human Environment, which was adopted in 1972 at a meeting of the United Nations Conference on the Human Environment. The research topics correspond to principles 6 and 10 of this document. Principle 6 is based on the cessation of the introduction of toxic substances in concentrations that cannot be neutralized when released into the environment. The goal is to reduce damage to ecosystems. Principle 10 is based on economic and environmental factors that need to be taken into account when stabilizing prices and income from goods and materials in order to manage environmental impact (Declaration of the United Nations Conference on the Human Environment, 1972). In other words, goods and materials must be valued equivalent to the environmental processes that take place during their production.

Since the work is based on consideration of the life cycle of two substances, mercury and cadmium, it is necessary to review the conventions for these substances. The Minamata Convention on Mercury is a document that protects people and nature from hazardous emissions of mercury and its chemical compounds (Minamata Convention on Mercury, 2013). In 2020, the production (import and export) of products that contain mercury is prohibited. This number includes electric batteries, some types of compact fluorescent lamps (CFLs).

Annex III of the Protocol on Heavy Metals (to the 1979 Convention on Long-range Transboundary Air Pollution) describes methods for reducing and controlling emissions of heavy metals and their compounds from sources. This document is aimed at controlling emissions of cadmium, mercury and lead, introducing new measures to effectively reduce emissions of these pollutants. The Best Available Techniques (BAT) described include the efficient use of technology, including the steps from design to production of installations.

2.4 Sustainable Development Goals

The Sustainable Development Goals (SDGs) were approved by the UN in 2015. The 2030 Agenda for Sustainable Development reflects goals that aim to improve the quality of life of people, eliminate poverty, and improve the state of the environment. The program consists of 17 goals that are shown in Figure 2 (Sustainable Development Goals 2015).

Figure 2. Sustainable Development Goals (SDGs)

Sustainable Development Goal 12 (Sustainable Development Goals 2015, page number if used in the source) includes a target:

> 12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international principles, and significantly reduce their release to air, water and soil, in order to minimize their negative impact on human health and the environment.

Determination of the degree of progress is carried out using the System of Global Indicators for the achievement of the Sustainable Development Goals and the achievement of the objectives of the Agenda for Sustainable Development for the period up to 2030 (Agenda for Sustainable Development for the period up to 2030, 2018). For Sustainable Development Goal 12, the following indicators are used to implement the sound management of chemicals:

> 12.4.1 Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement (Tier I)
> 12.4.2 (a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment (Tier II).

These indicators will allow to control environmental activities in this area.

3 SELECTED SUBSTANCES AND IDENTIFICATION

3.1 Cadmium and mercury

Cadmium and mercury are heavy metals. Any metal (or metalloid) species may be considered a “contaminant” if it occurs where it is unwanted, or in a form or concentration that causes a detrimental human or environmental effect (Singh R et al. 2011). Cadmium is a chemical element with atomic number 48. In the periodic system of chemical elements, it is in a side subgroup of the second group of the V period. Silver-colored metal is malleable. The main properties are presented in Table 1. Long-term low-level exposure of cadmium leads to primarily affect renal tubular function of reabsorbing protein, sugar and amino acids (Rajesh Kumar Sharma et al. 2005).

Table 1. Chemical properties of cadmium

Properties	
Aggregate state (at room temperature)	solid
Atomic weight, amu	112.42
Density	8650 kg/m^3
Heat of vaporization	99.87 kJ/kg
Melting heat	6,21 kJ/mol
Melting temperature	321.07 ^0C (594.22 K)
Boiling temperature	767 ^0C (1040 K)
Molar heat capacity	20.02 kJ/mol*K (at 25 ^0C)
Toxicological and ecotoxicological information	causes cancer, long-term exposure leads to adverse effects on the lungs and kidneys

In the periodic system of Mendeleev, cadmium is in the same group as mercury. The chemical properties of these substances are similar. Mercury and cadmium oxides, sulfides are insoluble in water. In nature, they are found in composition with other minerals, but it is always found in zinc minerals. The percentage of cadmium in the earth's crust is $1.3*10^{-5}$ %. Cadmium is found in hydrothermal deposits with other elements that form tellurides, selenides. Sedimentary rocks also contain concentrations of cadmium, the highest concentration of cadmium (0.3 mg/kg) was found in clays.

However, there are some forms of cadmium in the form of its minerals, such as otavite, selenide, monteponite, and griconite. Such components do not form their own deposits. They are impurities in copper, lead and zinc ores, but at the same time they are sources of cadmium extraction. The extensive use of cadmium in industrial applications is based on its properties. Hard coal is also the major source for cadmium emissions to air (Proposals for measures and actions for the reduction of pollution from hazardous substances for the Baltic Sea Action Plan 2007). It is used in almost all areas of activity according to Table 2. Mercury intake led to minimata disease, where liver accumulates substantial amounts of Hg (Rajesh Kumar Sharma et al. 2005).

Table 2. Use of cadmium

Scope of use	Substance
Chemical industry: reagents	Cadmium, cadmium oxide
Electrical industry: nickel-cadmium batteries	Cadmium, cadmium oxide
Metalworking	Cadmium
Corrosion protection of products: machine structures prone to corrosion in wet environments	Coatings with cadmium
Wires (tram and telephone)	Alloy Cu+Cd
Jewelry production	Alloy Cd+Au
Medicine: Eye Treatment	Cadmium sulfate
Photo	Cadmium halide salts
Fertilizers	Cadmium
Pigments for plastics and paints	Cadmium sulfide, cadmium selenide
Uranium decay reactions	Cadmium

Mercury is a chemical element with atomic number 80. In the periodic system of chemical elements, it is in a side subgroup of II group of VI period. It is silvery liquid metal . The main properties are presented in Table 3.

Table 3. Chemical properties of mercury

Properties	
Aggregate state (at room temperature)	liquid substance
Atomic weight, amu	200.59
Density	13540 kg/m^3
Heat of vaporization	300 kJ/kg
Melting heat	2.295 kJ/mol
Melting temperature	-38.83 ^{0}C (234.32 K)
Boiling temperature	357 ^{0}C (629.9 K)
Molar heat capacity	27.98 kJ/mol*K (at 25 ^{0}C)
Toxicological and ecotoxicological information	causes acute poisoning of the body, chills, causes cancer, long-term exposure leads to adverse effects on the lungs and kidneys

Mercury is presented in different forms, metallic (elemental), inorganic (mercury in the workplace), and organic. These forms differ in the degree of toxicity and varying degrees of impact on the organ systems (digestive, nervous and immune) of a person.

In nature, mercury, like cadmium, is found in the earth's crust. The total content of mercury is approximately 1.6*10^{12} tons. About 100 mercury-containing minerals are known in the world. The most widely used mineral in industry is cinnabar, mercury (II) sulfide. Together with cinnabar, metacinnabarite, native mercury, and fahlore with mercury are usually mined. Mercury is also found in mineral ores, and mercury also accumulates in oil shale, bauxite, natural gas and oil. Mercury enters the environment through volcanic activity or human activities, for example, when using coal as a raw material for generating energy in power plants, or burning it in homes for heating, or extracting mercury and other metallic natural resources.

Mercury is used in almost all industries (Table 4). The major source of air emission of mercury is the burning of hard coal in the energy sector, in industrial heating, cement production, and municipal and domestic heating (Proposals for measures and actions for the reduction of pollution from hazardous substances for the Baltic Sea Action Plan 2007). It is used in mercury lamps, as a catalyst in chemical processes, in medicine, in agriculture, and in various devices such as pressure gauges, polarographs, thermometers.

Table 4. Use of mercury

Scope of use	Substance
Chemical industry: chlorine production, catalysts, vaccines, plant protection products	Mercury, mercury(II) chloride, mercury(II) iodide, mercury(II) nitrate, mercury aminochloride
Measuring instruments: Manometers, thermometers, barometers	Mercury
Production of mercury lamps: Fluorescent lamps	Mercury, mercury sulfides
Dentistry: dental amalgams	Mercury
Production of semiconductor materials	Mercury, mercury(I) sulfate

3.2 Assessment of the impact of substances on the environment

The assessment of the environmental impact of substances is part of the life cycle assessment. Any substance that entered the Technosphere in the form of an input flow in the future enters the environment in the form of emissions, effluents, or waste (output flow).

Cadmium is a non-essential element that has high rates of soil to plant transference compared with other non-essential elements, and certain plant species accumulate large amounts of cadmium from low cadmium content soils (Soisungwan Satarug et al. 2003). Cadmium is a highly toxic metal whose ions are highly mobile in soils. This high mobility of cadmium ions implies easy movement and accumulation of cadmium in plants. The accumulation of cadmium in plants causes chlorosis. This is visible in reddening of the leaves, stunted growth and damage to the roots of the plant. Cadmium is a phototoxic metal for plants, inhibiting the process of photosynthesis, disrupting the removal of water through the stomata of plants. One of the properties of cadmium is based on the substitution of zinc in chemical processes and disruption of enzymes.

In the last century, cadmium has been used in almost all areas of industrial activity. This explains the large number of emissions (Figure 3). However, today there is a trend towards a decrease in cadmium emissions from anthropogenic sources (HELCOM).

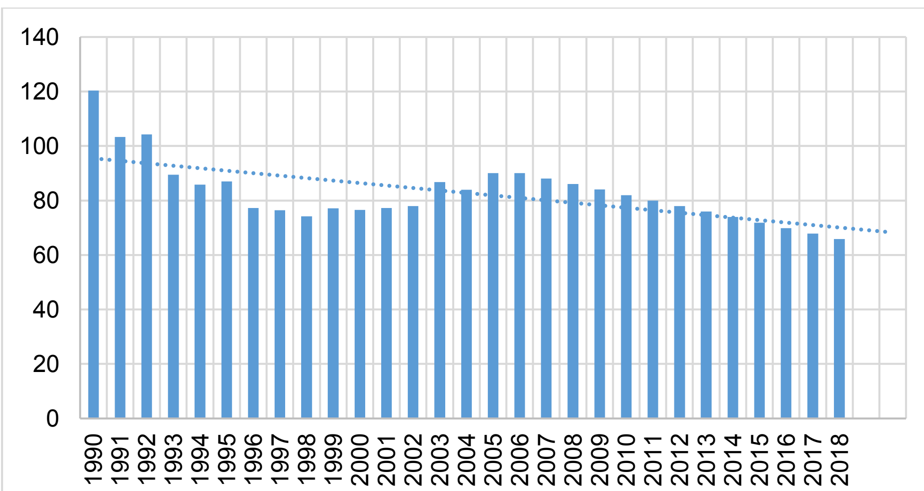


Figure 3. Cadmium emissions from anthropogenic sources in Russia, tones/year

The toxic effect of cadmium on the environment is based on the easy evaporation of cadmium and a high degree of solubility in water (especially at pH=5). Cadmium is able to enter the hydrosphere during the cycle of substances and accumulate there in the form of sediments at the bottom. Subsequently, the process of bioaccumulation of cadmium by aquatic organisms occurs and cadmium enters the trophic chains and lingers there for a long time. Cadmium is classified by the International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1) (Balali-Mood et al. 2021).

In water, cadmium is present in the form of sulfate, cadmium nitrate, chloride and in a suspended state, in elemental form. The pH of the aquatic environment is a determining factor that affects the state of cadmium in water: at pH>7, cadmium hydroxide is formed, which precipitates.

Mercury is a toxic metal that is classified by the WHO (World Health Organization) as a chemical that is hazardous to health. After mercury enters the environment, it is converted into another compound, methylmercury, by the action of bacterial activity. This substance may accumulate in aquatic organisms. Moreover, this process occurs if the concentration of a chemical in the body is higher than the concentration of this substance in the environment. At the same time, predatory organisms contain more mercury than lower trophic levels in the ocean biomass pyramid, since small fish accumulate mercury while eating plankton.

As with cadmium, the past century has seen heavy use of mercury in all sectors of the economy, which has contributed to the release of mercury in large quantities as emissions (Figure 4). However, today there is a trend towards a decrease in mercury emissions from anthropogenic sources (HELCOM).

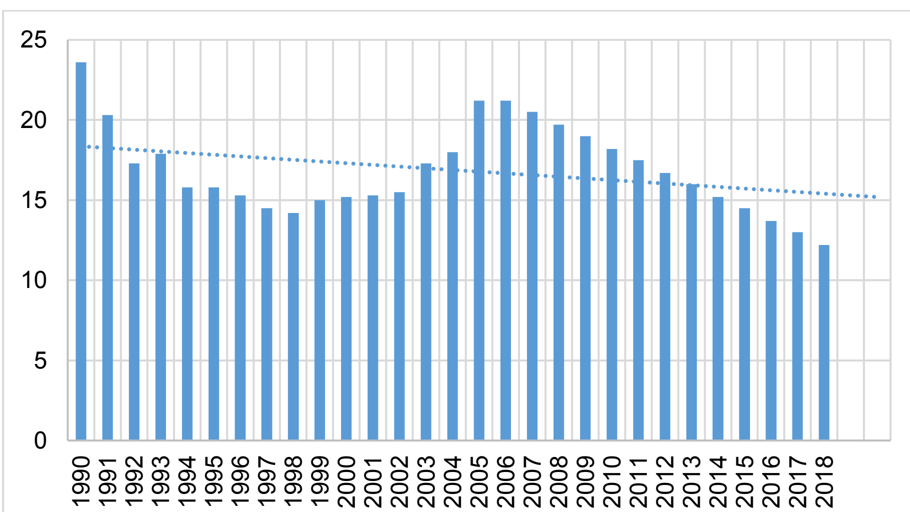


Figure 4. Mercury emissions from anthropogenic sources in Russia, tones/year

The distribution of mercury in nature is carried out in the form of 2 circulations of substances - global and local. The global circulation includes the transfer of mercury vapor from atmospheric air to the hydrosphere and lithosphere. Local circulation implies the process of methylation of inorganic mercury. Mercury methylation by microbes depends on pH, temperature, presence of ligands, and adsorption surfaces. In this process, inorganic mercury is converted into organometallic, methylmercury salts are formed, which are lipophilic and pose a high danger to living organisms. However, methylmercury is a more toxic form than pure mercury. Methylmercury (CH_3Hg^+) is the form of mercury that is primarily associated with mercury contamination of fish, shellfish, and the birds and mammals that feed on them (Weinberg 2007).

Once mercury enters the atmosphere, it can travel long distances, move to the earth's surface, and even evaporate later. Part of the mercury that does not evaporate is bound by organic compounds through chemical reactions. In addition, mercury can move into water bodies, remain undissolved for some time, accumulate in fish and in the future enter the human body. The order of increasing toxicity related to different forms of mercury is defined as $Hg^0 < Hg^{2+}$, $Hg^+ < CH^{3-}Hg$ (Balali-Mood et al. 2021).

In atmospheric air, mercury is present in the form of a gas or associated with aerosols. Pure mercury can be converted to mercury chlorides. GEM (gaseous elemental mercury) does not dissolve in water. It is a stable form of mercury, which can be in the air for up to 2 years.

In water, mercury is usually found in three states (oxidized) - Hg (III), Hg (II), and Hg (0). Mercury is a substance capable of forming complexes with organic ligands, humic, and fulvic acids. In addition, mercury in water bodies can be found in the form of methylated mercury.

3.3 Identification of chemicals and chemical products

Identification is an important step in the qualitative analysis carried out by the manufacturer. Chemical products in accordance with Decree N 1019 must be identified. This regulation establishes requirements for hazard classification criteria for chemicals and mixtures, for human health and the environment, as well as hazards due to their physical and chemical properties, as well as elements of the information system, including requirements for labeling and safety data sheet. Figure 5 shows the main steps for identification of chemicals.

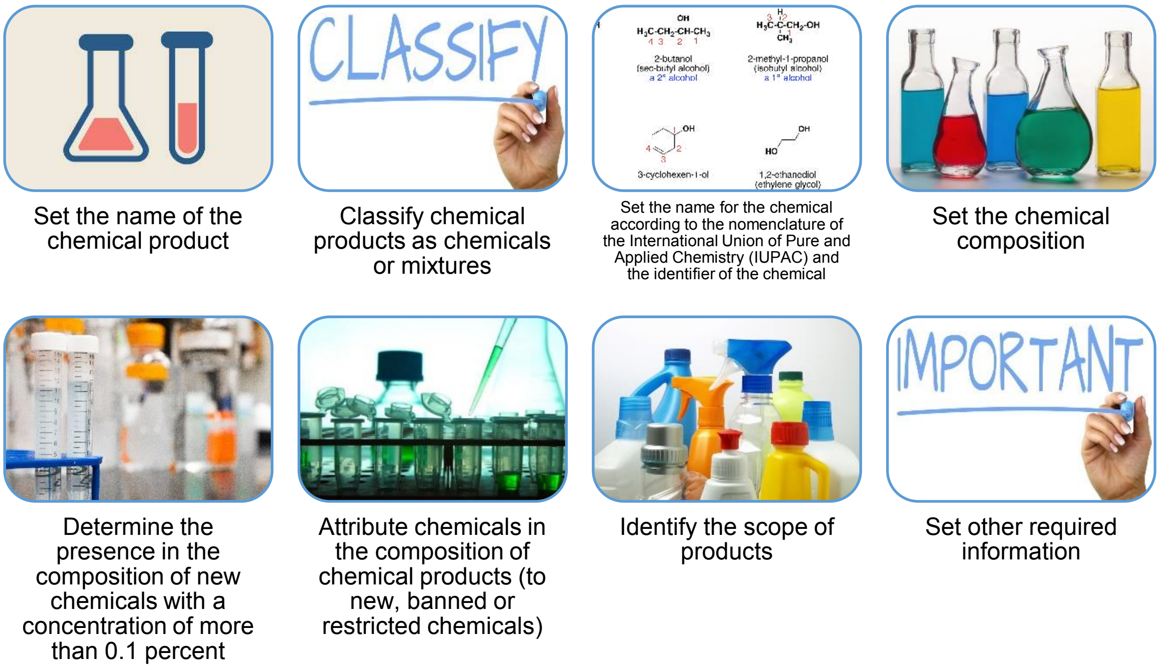


Figure 5. Identification of chemicals

3.4 Material Safety Data Sheets

Description of the basic rules for the content and execution of the safety data sheet for substances based on GOST 30333-2007 Safety data sheet for chemical products. GOST 30333-2007 provides rules for the content and execution of a safety data sheet for substances. This document is being developed in order to clarify information in it that concerns not only the safety of workers, but also the health of people. This standard is based on the regulations of the UN Recommendations (GHS). Based on this standard, when developing a safety data sheet, the safety data sheet should inform about the danger of a substance or mixture and provide information on how to ensure the safety of its storage, handling, and disposal.

The development of safety data sheets is aimed primarily at preventing public health hazards, environmental hazards, and physical hazards. It should be noted that the carcinogenic and toxic effects of chemicals are also taken into account when developing safety data sheets. Figure 6 shows what is indicated in the safety data sheet in accordance with the standard.

Figure 6. Safety data sheet structure

3.5 General safety requirements for handling chemically hazardous substances

Throughout the life cycle, it is necessary to control the handling of chemically hazardous substances. Incorrect organization of activities with such substances and non-compliance with the requirements can lead to the occurrence of dangerous diseases for the health of workers or lead to poisoning. To prevent such possible consequences, any activity related to the handling of hazardous toxic substances is carried out and controlled in accordance with the provisions of the labor protection rules. One of these documents is the Rules for labor protection when using certain types of chemicals and materials, during dry cleaning, washing, disinfection and decontamination, 2020. This document includes regulatory requirements in the field of implementation of the processes of enterprises whose activities are based on the use of chemically hazardous substances. In addition, the rules provide requirements for production units, placement of equipment for technological processes, and requirements for handling chemicals in the laboratory.

When moving any chemically hazardous substances, safety must be ensured. To achieve safe transportation conditions, the quantity and properties of the substance are taken into account, the route of movement and the conditions of loading and unloading operations are preliminarily developed, and the integrity of the package is observed throughout all stages of the movement of the substance. When transporting the chemical outside the plant, a prerequisite is labeling of the contents, with an accurate indication of possible hazards.

Storage of chemicals should be carried out based on the principles of safety. The allowable amount of the substance to be stored, the integrity of the containers, the loading performed, the implementation of labeling and re-labeling are recorded. Storage of substances should be carried out with regulated parameters of the microclimate of storage facilities (humidity, temperature, pressure, ventilation, etc.). The storage of chemicals takes place using technological maps, which are developed on the basis of the safety data sheet of chemical products.

Possible emergencies (explosions, fires, releases of substances, leakages of substances) are indicated in this document.

The section IX of the document on the requirements of labor protection of production processes, including the use of mercury. The use of mercury should be carried out without contact of workers with this toxic substance. It is also necessary to control the degree of air pollution of the working area with mercury. Technological processes, including the production of fluorescent lamps, must be carried out in special conditions with exhaust ventilation, workers must use personal protective equipment, such as rubber or vinyl chloride gloves, and masks. Before removing gloves, they need to be cleaned with water and soapy water. The utensils used should have thick walls or be made of durable glass. For the transfusion of mercury, it is needed to use a funnel with a drawn capillary. In this case, mercury should flow down the walls of the vessel.

Used waste solutions containing mercury residues must be disposed of with preliminary precipitation of mercury in a porcelain cup with a large volume and avoiding the ingress of mercury into water (waste water). The ventilation of the fume hood must be turned on 15 minutes before the start of work with open mercury and must be turned off only after 30 minutes after the end of work. When ventilation is on, mercury should also be heated in vertical furnaces. In the warehouse of the enterprise, mercury should be stored in special cylinders with taps on the bottom. The release of the chemical must exactly match the daily rate. The demercurization process should also be carried out in mercury-free cylinders. Subsequently, the cylinders are returned to a specially designated place in the warehouse.

In case of emergencies, mercury on the floor, its spill should be immediately collected and then washed off with a jet with a pressure of 2 atm. Droplet-liquid type mercury must be collected with enameled iron scoops and placed in a thin-walled glass dish filled with an acidified solution of potassium permanganate (Rules for labor protection when using certain types of chemicals and materials, during dry cleaning, washing, disinfection and decontamination 2020).

4 MATERIALS AND METHODS

4.1 Research methods and data collection

The main idea of the thesis is to ensure the environmentally sound management of hazardous chemicals, and to explain obtaining information after the researching process using SimaPro software. In the study a quantitative method was used to achieve it because this kind of data processing is statistical measurement. It can give the opportunity to obtain results mathematically. The results are presented through pictures and graphs. To assess the life cycle of cadmium, a battery containing cadmium was chosen as a functional unit. To assess the life cycle of mercury, a compact fluorescent lamp, which contains mercury, is selected as a functional unit.

The implementation of the tasks set and the development of the life cycle is based on the processing of information and the performance of some calculations. It is quite difficult to manually assess the impact of products or processes. SimaPro software was used to simplify the data analysis process. SimaPro version 9.1.1 was used for this study (Figure 7).

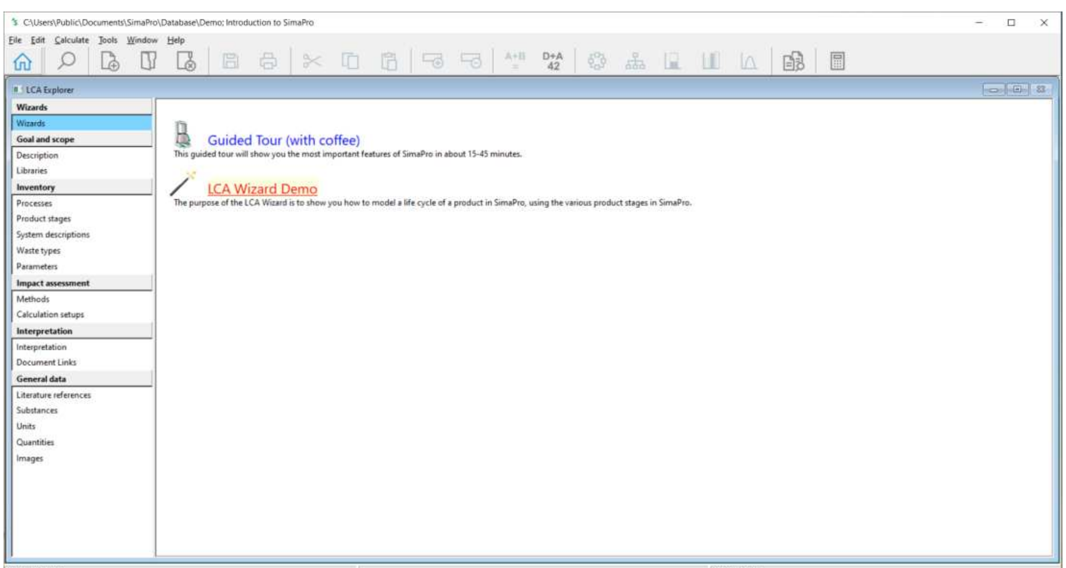


Figure 7. SimaPro interface

This program allows the user to assess the degree of sustainability of products and services. In addition, it is possible to calculate the carbon and water footprint and evaluate product performance, develop environmental product declarations. The main advantage of the program is the implementation of modeling complex life cycles in a simple way. In addition, the program allows to assess the impact of the product on the environment.

The life cycle assessment methodology is a long and complex process, which is based on the use of a large amount of information. There are a number of LCA methods, among which EIA (Environmental Impact Assessment), EMA (Environmental Management Accounting), SFA (Substance Flow Analysis) and MFA (Material Flow Analysis) are often used. To achieve the goal of this work, the method of analyzing the flow of substances SFA was chosen, since it is convenient for identifying substances, representing the flows of substances in a technological system and developing recommendations to reduce the negative impact on the environment. The main processes considered in the SFA diagram are Production, Import and Distribution, Retail Trade and Use, Waste collection, Recycling and Reuse.

To understand the life cycle of substances and develop recommendations for rational use of chemicals it’s important to do an assessment of the life cycle of a battery containing cadmium and a compact fluorescent lamp (CFL, CFL, Compact Fluorescent Lamp) containing mercury.

It is necessary to establish the principles of operation and stages of the life cycle of products, build diagrams of substance flux analysis (SFA), on the basis of which recommendations for reducing the anthropogenic impact of the selected products should be developed.

The principle of operation and battery life cycle includes a description of the main manufacturing processes and life cycle for nickel-cadmium battery (Raw materials and mining; Production; Product use; Disposal of products - waste disposal, recycling, reuse) based on Eco-indicator 99 method and Substance flow analysis diagram (SFA). Th eprinciple of operation and life cycle of a compact fluorescent lamp includes description of the main manufacturing processes and life cycle for compact fluorescent lamp (Raw Materials and Mining, Production, Product Use, Disposal of Products – Waste Disposal, Recycling, Reuse) based on Eco-indicator 99 method and Substance flow analysis diagram (SFA). After SFA (Substance flow analysis) a table with three sections of recommendations for the rational use of chemically hazardous substances are shown as final result of the work.

5 RESULTS

5.1 Analysis of the methodology for assessing the life cycle of substances

This study was conducted to evaluate the life cycle of a battery containing cadmium and a compact fluorescent lamp (CFL) containing mercury. The principles of operation and stages of the life cycle of the substances under consideration are established, diagrams of the analysis of substance flows are shown, on the basis of which recommendations are developed to reduce the anthropogenic impact of the selected products.

5.2 Methodology and structure of the life cycle of substances

The life cycle assessment procedure is a complex multi-stage process (ISO 14040 2006), (Figure 8).

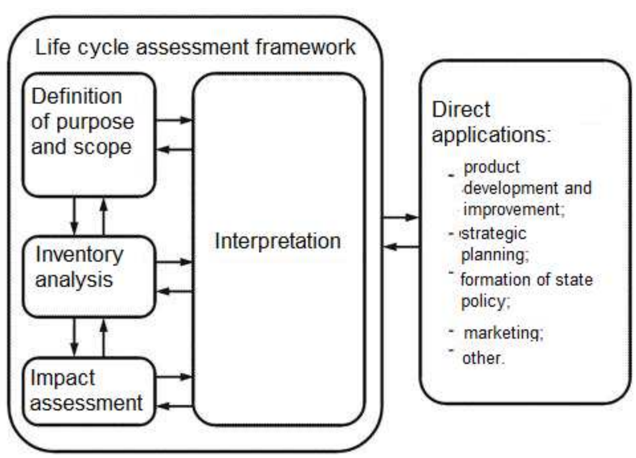


Figure 8. Life cycle assessment

As shown in Figure 8, the application of the LCA method is based on its importance for identifying the impact of products on the environment, as well as making management decisions to optimize and ecologization of the products. This method includes the use of environmental performance indicators. The goals include reducing the negative impact of products on the environment, preventing various kinds of risks, achieving environmental performance, developing the environmental aspects of the enterprise. Based on the conducted LCA, products can be labeled in accordance with the globally harmonized system of classification and labeling of chemicals (Globally harmonized system of classification and labelling of chemicals 2011). The method is applicable for changing the production process, informing about the stages of production, expanding production, implementing the main production policy.

The LCA method is based on environmental impact management, but it is not based on the economic aspects of the enterprise and has some limiting factors. These include:

- LCA is a laborious and long process;
- A large amount of data can lead to errors, it is possible to obtain uncertainty in the results of the conducted LCA;
- There are clear boundaries of the data set under consideration and a clear representation of the boundaries of the system;
- The method is relative, based on a functional unit;
- The same inventory models may not be suitable for all product types;
- When comparing some results from different LCAs, it is important to consider method compatibility.

In accordance with GOST R ISO 14040-2010, the tools for describing LCA are EIA (Environmental impact assessment), EMA (Environmental management accounting), various models for policy assessment, chemical risk assessment, enterprise risk management and analysis, LCM (Life Cycle Management), product management, LCC (Life-Cycle Costing), SFA (Substance Flow Analysis) and MFA (Material Flow Analysis) and others.

SFA (Substance Flow Analysis) and MFA (Material Flow Analysis) are two methods that are used to study and identify all substances and materials entering or leaving the production system of an enterprise (Baiet al. 2015). The methods are effective for quantifying all materials and substances in order to manage the resources used and reduce the level of negative impact on the environment.

This study involves the use of the SFA method. The method is based on the implementation of certain stages. The main steps are shown in Figure 9. SFA is a method of analysis that is used to evaluate the flow of a substance. The method involves the use of the principle of mass balance in order to identify the relationship between the substance flow and human activities (product life cycle). Matter flows are considered and tracked based on the identified system boundaries. The implementation of the method contributes to the assessment of the stability of the system under consideration, the analysis of the use of resources. The investigated component of the SFA method can be metallic or biogenic elements or toxic substances.

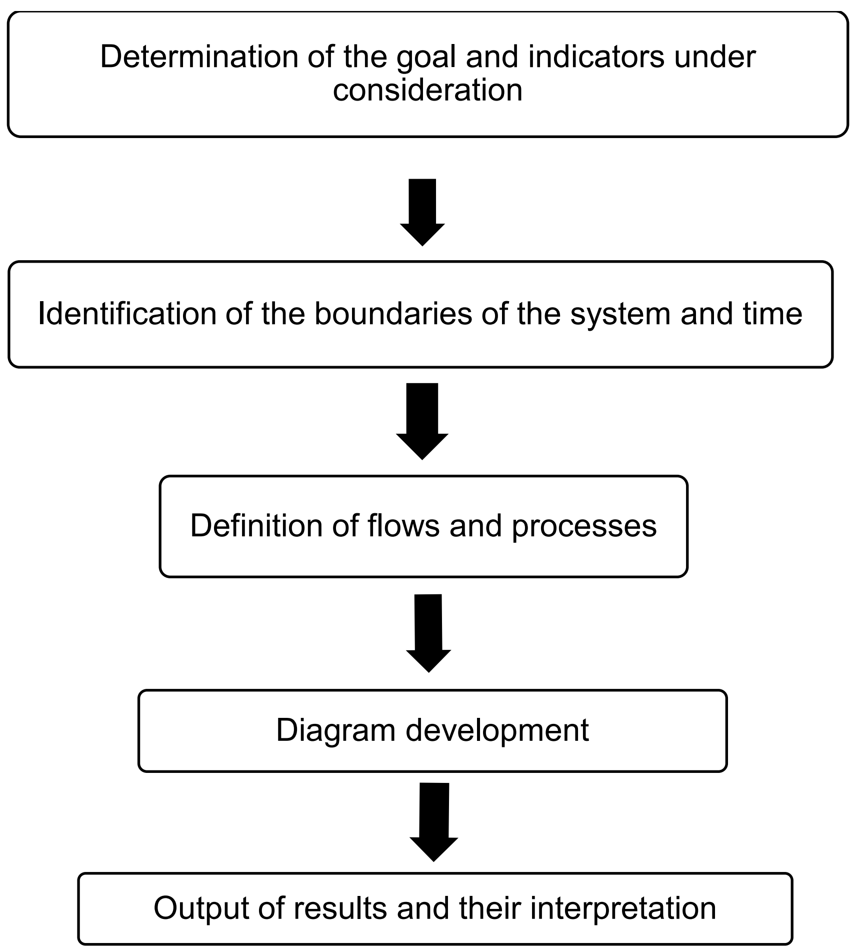


Figure 9. Main steps of the SFA method

Another method used in the study is LCA (life cycle assessment), a particular method of which is Eco-indicator 99. The LCA method is based on the identification of the environmental characteristics of a product. Eco-indicator 99 is based on the determination of environmental damage throughout the life cycle of a product using easy-to-assess eco-indicators. Eco-indicator 99 is the new Eco-indicator 95 method. The new method includes more environmental aspects (Table 5).

Table 5. Use of mercury

Human health	**Ecosystem quality**	**Resources**
Carcinogens	Ecotoxicity	Minerals
Respiratory organic effects (Resp.organics)	Acidification/Eutrophication	Fossil fuels
Respiratory inorganic effects (Resp.organics)	Land use	
Climate change		
Radiation		
Disappearance of the ozone layer (Ozone layer)		

Thus, this method determines environmental damage based on 3 categories - human health, ecosystem quality, resources.

5.3 The principle of operation and the life cycle of the battery

The principle of operation of a nickel-cadmium battery is based on the chemical processes that take place on the battery. The accumulator of a nickel-cadmium battery consists of two electrodes - nickel and cadmium. The positive electrode is a nickel oxide electrode with graphite. Lithium hydroxide is added to the electrolyte to preserve the composition of the electrode itself. Positive electrodes are gradually discharged during operation. This process releases oxygen.

The reaction that occurs at the positive electrode occurs in the following form:

$$NiOOH + H_2O + e^- \leftrightarrow Ni(OH)_2 + OH^-$$

The negative electrode consists of CdO and Fe_2O_3. Titanium dioxide, antimony oxide and manganese dioxide can be added as additives. To maintain the capacity of the negative electrode, solar oil (6-9%) is added to it. Manganese dioxide is used as a substance that prevents the formation of passivating oxides. At the negative electrode, one of two reactions is possible:

a) $Cd + 2OH^- \leftrightarrow Cd(OH)_2 + 2e^-$
b) $Cd + 3OH^- \leftrightarrow HCdO_2 + H_2O + 2e^-$
$CdO_2^- + H_2O \leftrightarrow Cd(OH)_2 + OH^-$

The final total reaction of the accumulator is as follows:

$$2NiOOH + 2H_2O + Cd \leftrightarrow 2Ni(OH)_2 + Cd(OH)_2$$

Battery life cycle

Production. Raw materials and mining. At the stage of collecting raw materials for production, pyrolusite (MnO2) is mined. The mineral is manganese oxide, which contains approximately 60% manganese, some alkali metals and barium. Pyrolusite is a brittle, dark gray mineral that can dissolve using hydrochloric acid and release chlorine. According to the classification, pyrolusite belongs to oxide manganese ore.

Pyrolusite ore is mined in sea basins, on the coast. River water carries water with a colloidal solution, and then under the influence of mineral salts in the sea, the process of coagulation occurs.

The manufacturing process is defined as the technological process of creating a product. The first step in battery production is the development of a steel container. The size of the battery is determined by the size of the steel container.

The next stage of production includes the process of granulation of the material (manganese dioxide, electrolyte and graphite) with the subsequent production of steel rings. 4 steel rings are placed in one battery.

Steel containers are sent to the assembly line. A tube is made from paper tape, the bottom of which is sealed. This tape is inserted into the middle of the battery (silver rings) and is a separator. The separator serves to prevent contact between the cathode and the anode and to prevent a short circuit. The separator is filled with electrolyte. The electrolyte is usually potassium hydroxide or sodium hydroxide, which are necessary for ion transport. Potassium hydroxide conducts electricity better than sodium hydroxide, but sodium hydroxide does not seep much.

During the process of absorption of liquid electrolyte in the separator, potassium hydroxide solution and zinc powder are fed into the mixer. After a while, a blue paste, a zinc gel, is formed. It is the gel that later on is the anode of the battery and is poured into the separator.

At the last stage, a battery plug is created. The tip with the current collector is connected to the steel disk, the disk is connected to the plastic plate. The steel container is deformed to tightly seal the battery.

Ready-made batteries are placed in plastic packages in order to prevent impacts, water ingress, temperature changes and ensure sealed storage conditions. The packaging contains information about the product itself, including weight, product size, type, marking marks, disposal markings, storage measures, and the manufacturer's company logo.

Product use. Ready-made nickel-cadmium batteries are used in devices that require a large current. Batteries of this type have the advantage of stable power. Other benefits in use are long shelf life and no heat build-up during use, as these batteries operate with an endothermic process of chemical reactions inside the battery. Such batteries are used for building hand-held electrical appliances.

Product disposal (waste collection, recycling, reuse). Nickel-cadmium batteries are recycled to release nickel, but this process is not economically viable and the amount of nickel released is small. Another way to dispose of nickel-cadmium batteries is to end up in a landfill, where the process of corrosion of the outer part of the battery occurs. Then, cadmium flows into the soil and water, polluting the environment. In addition, the process of formation of explosive substances - hydrogen and oxygen in the course of hydrolysis reactions is possible. In addition, harmful chemicals from the battery enter the environment - alkali, cadmium, nickel, zinc, mercury, lead.

Eco-indicator 99

The implementation of the tasks set and the development of the life cycle is based on the processing of information and the performance of some calculations. It is quite difficult to manually assess the impact of products or processes. SimaPro software was used to simplify the data analysis process. SimaPro version 9.1.1 was used for this study.

The name field contains the name "nickel-cadmium battery". The Inputs from Technosphere materials/fuels column indicated the data required for the production of a nickel-cadmium battery. One functional unit is one nickel-cadmium battery. ‘Amount’ stands for quantity, and ‘unit’ stands for the unit of measurement.

Columns that include used materials - Name, Amount and Unit. Parameters and used materials are shown in Figure 10. Figure 10 includes the main chemical substances such as potassium hydroxide, cadmium. Moreover, Ni electrode, battery separator, anode were used as electronical components for research.

Figure 10. Parameters and used materials

Figure 11 shows the initial data. The name field contains the name of the nickel-cadmium battery. The Inputs from Technosphere materials/fuels column indicated the data required for the production of a compact fluorescent lamp. One functional unit is one nickel-cadmium battery. ‘Amount’ stands for quantity, ‘unit’ stands for the unit of measure.

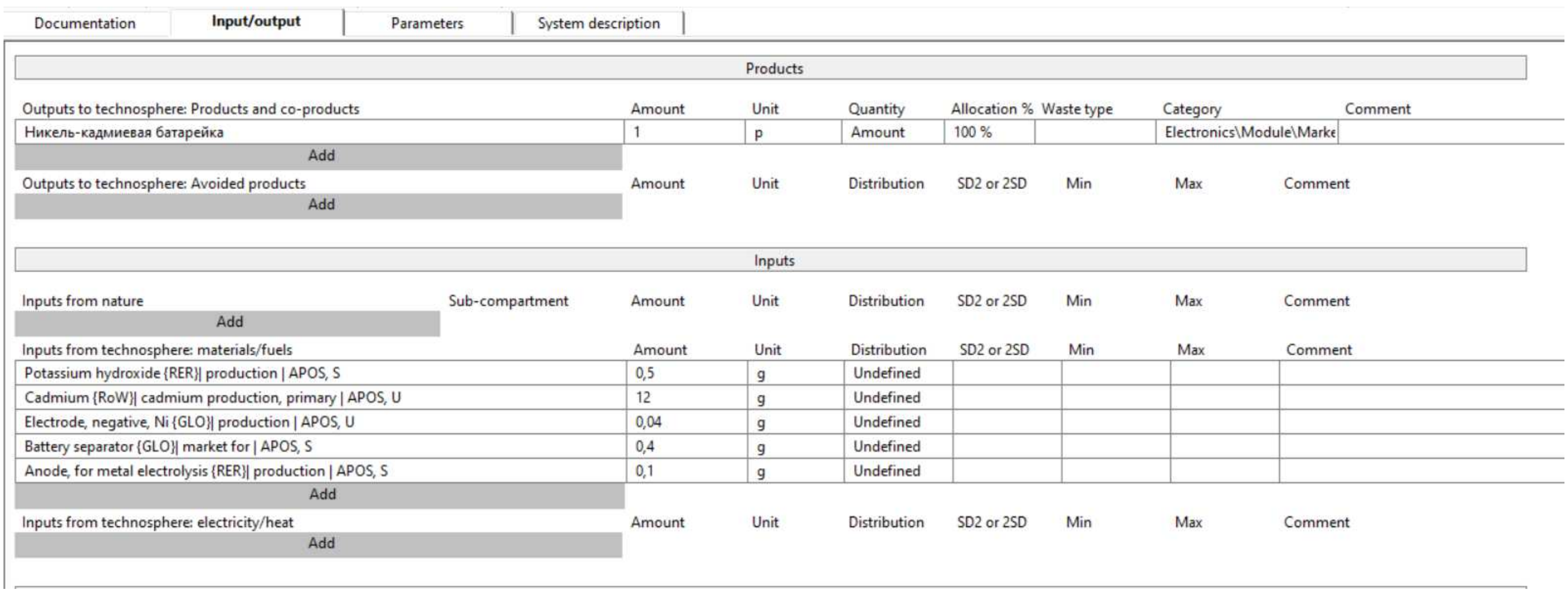


Figure 11. Used materials

The results of calculations for a nickel-cadmium battery using the Eco-indicator 99 method are shown in Figure 12. The performed analysis showed that according to four indicators, nickel-cadmium battery has an impact on the environment. Eco-indicators have a score of about 99%, create increased damage from the production of all battery.

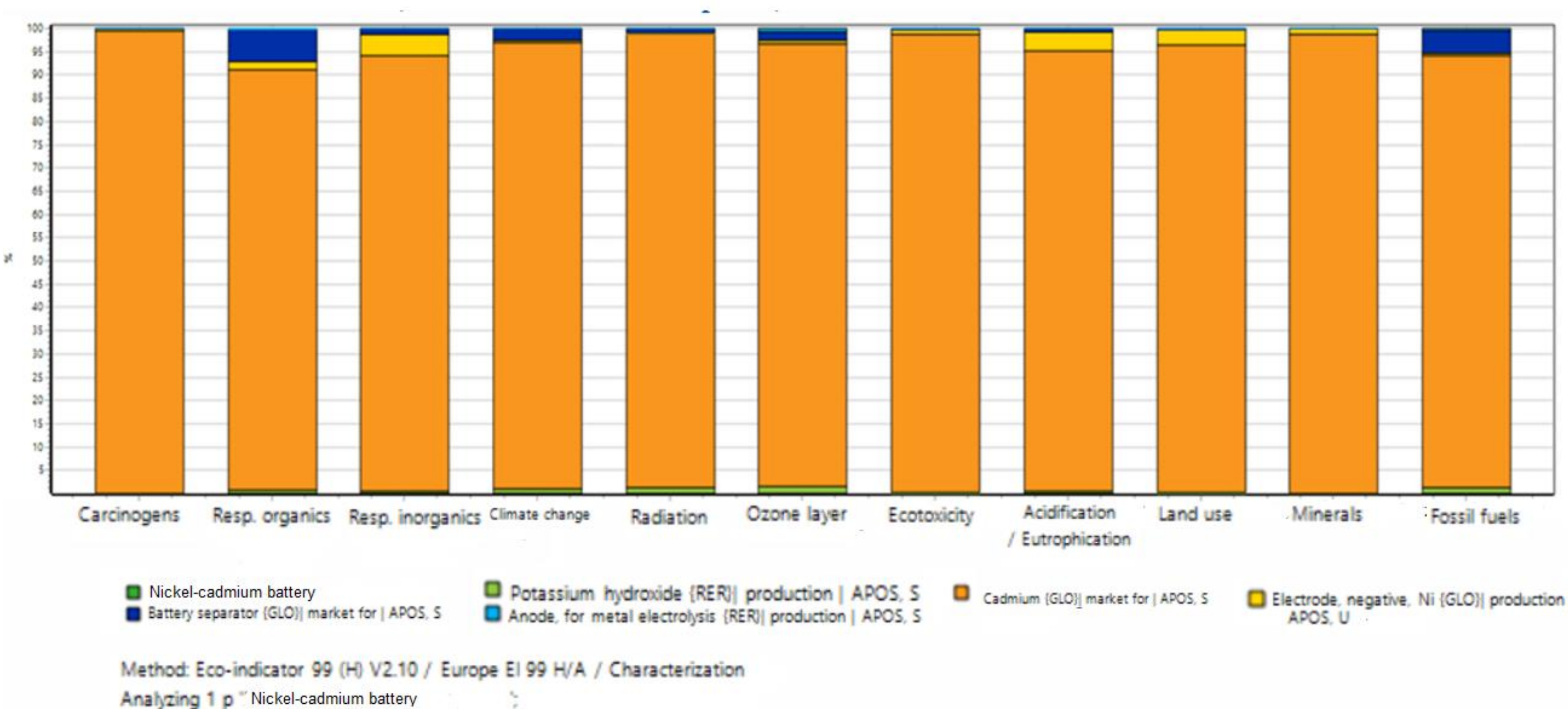


Figure 12. Results of calculations by the Eco-indicator 99 method for the production of a nickel-cadmium battery

SFA method

Based on the life cycle assessment, a material flow analysis diagram for cadmium was constructed. The diagram is shown in Figure 13.

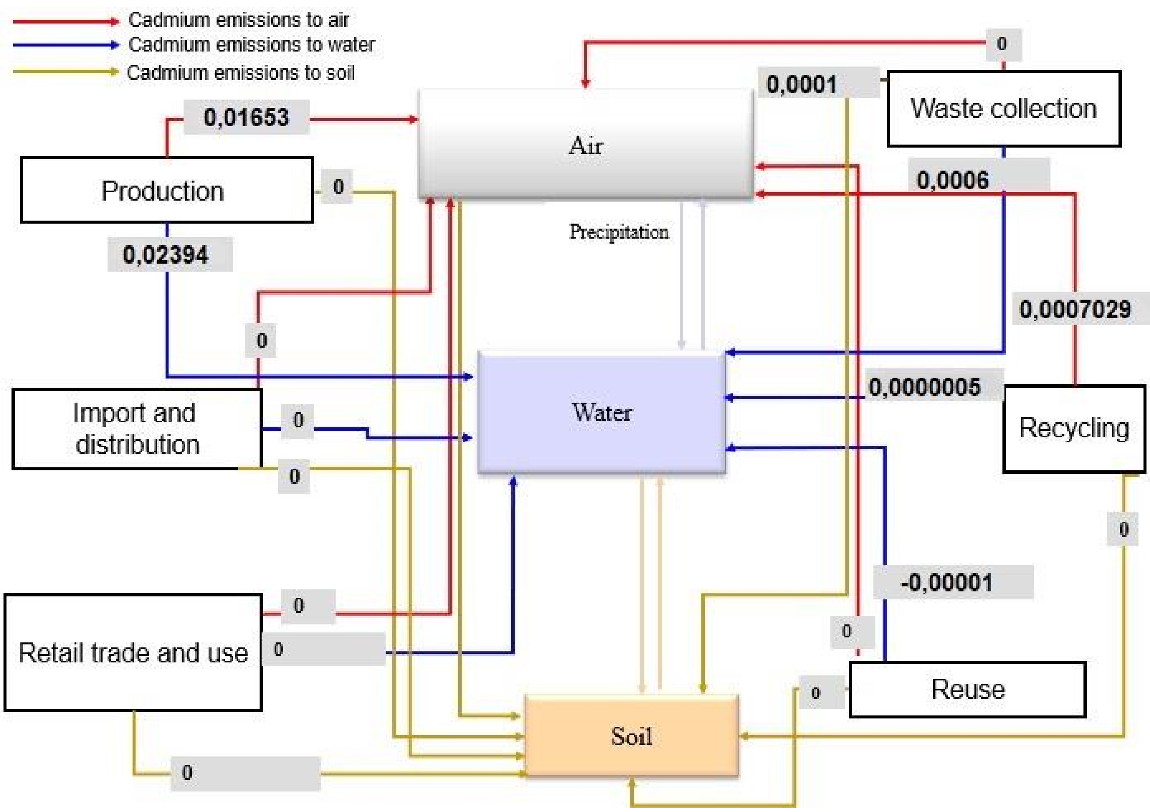


Figure 13. Diagram of the analysis of cadmium flows (the number of emissions - mcg, 700 cycles of work)

The purpose of conducting SFA for this substance is based on solving the main tasks of the study and is based on constructing a scheme of cadmium fluxes in the environment based on the life cycle of a nickel-cadmium battery. The selected time frame is 700 nickel-cadmium battery cycles. The functional unit is one nickel-cadmium battery. The number of emissions for the chart is presented in mcg (micrograms). The main processes in the diagram considered are: Production; Import and Distribution; Retail Trade and Use; Waste Collection; Recycling; Reuse.

The resulting diagram illustrates the main flows and releases of cadmium into the environment. The amount of cadmium released into the environment at the main stages of the life cycle of a nickel-cadmium battery is shown in Figure 14. The largest amount of cadmium enters the environment during the production of a nickel-cadmium battery - 0.04047 mcg of cadmium, since the nickel-cadmium battery consists of two electrodes - nickel and cadmium, and the production process involves the use of cadmium (the technological process is described above).

It should be noted that a working or used battery is not dangerous if there is no damage to its case and it is stored in low humidity and at room temperature.

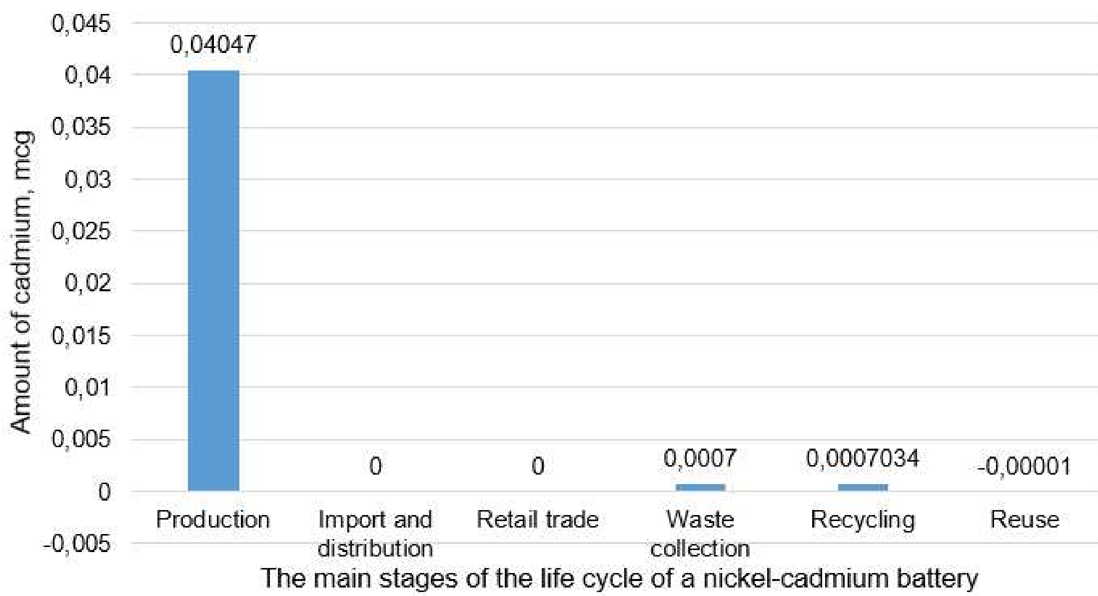


Figure 14. The amount of cadmium entering the environment at the main stages of the life cycle of a nickel-cadmium battery

Nickel-cadmium batteries are utilized by the hydrometallurgical method with subsequent production of secondary raw materials in the form of an alloy (iron with nickel) and cadmium based on BAT (Best Available Techniques) for use in steel production (BAT 2016). Information and technical guide to best available techniques. 2016). Another common method is vacuum distillation, which can produce cadmium oxide (low quality) and other waste products. Their use in various industries is difficult for various reasons.

The technological process of the hydrometallurgical method (sulfuric acid method) of processing cadmium-containing batteries is based on the use of ammonia, salt compositions and sulfuric acid. The first stage of recycling involves immersing used batteries in a container. Next, the batteries are transported to a concrete well, above which there is an electric magnet that attracts unnecessary scrap metal. The concrete well has a mesh bottom, below which there is a container. The liquid electrolyte from the batteries gets into this container. The next step involves crushing the batteries. The process of separating materials is carried out for concentration.

The main disadvantages of the method are the difficulty in extracting cadmium and the release of sulfur dioxide into the atmosphere, the difficulties in regenerating ammonia.

5.4 The principle of operation and life cycle of a compact fluorescent lamp

The fluorescent lamp is made in the form of a tube. The inner surface of the tube is covered with a phosphor, and filaments are installed at the ends of the flask. The inside of the lamp is filled with inert gases (eg argon) and mercury vapor. Mercury reacts with phosphor (powdered phosphorus). The glow occurs due to the discharge of electric current in an inert gas. This process is facilitated by an electric current that flows through the tungsten wire, and thermal energy along with emitters. The potential difference between the filaments and the mercury vapor provide the energy for the current to flow. The phosphor contributes to the creation of a glow. The electrical processes of the lamp proceed through the electronic ballast (electronic ballast).

Life cycle of a compact fluorescent lamp

Production. At the stage of collecting raw materials for production, mercury, phosphorus, sodium, and aluminum are mined. Other raw materials used are glass, steel and paper.

CFL consists of a base, lamp housing, fuse, control board, tube holder. To produce such a lamp, the inside of a glass lamp is covered with a layer of an activated substance. Such substances can be oxides of barium, calcium and strontium. The lamp itself is filled with liquid metal - mercury. A lamp contains approximately 5 mg of mercury. During the operation of the lamp (the operation of the electrodes at the ends of the tube), mercury from a liquid state turns into vapor. In this part of the lamp, ionization occurs. For the process of glowing a lamp, after ionization of an inert gas and mercury vapor, ultraviolet affects the phosphor. A phosphor is a chemical substance whose main property is the conversion of energy into light. Phosphorus is used as the phosphor. It is the composition of the phosphor that determines the color of the lamp, so the color temperature is measured in kelvins, K.

One of the important parts of the lamp in its production is the electronic ballast (electronic ballast), which is located between the discharge tube and the base. The electronic ballast consists of a capacitor, a capacitive filter, a current-limiting choke, bipolar transistors, and a fuse.

The capacitor is made and serves to ensure the start of the lamp. A capacitive filter prevents flickering in the lamp. The current-limiting choke controls the current in the lamp, and limits it within certain limits. Bipolar transistors perform the function of switching current. The fuse provides protection against short circuits and network overload and prevents ignition.

The package indicates the code, nominal service life, power, base type, voltage, luminous flux and frequency of the power supply.

Product use. Fluorescent lamps are used where it is necessary to save energy. The main parameters that affect the choice of lamp are color temperature, color rendering index, lamp holder, bulb shape, power. CFL lamps have the following advantages: lack of blinking light; high level of light output; small power losses; long service life; possibility of work of a lamp from a network with a direct current.

Product disposal (waste collection, recycling, reuse). Waste lamps are disposed of by specialized enterprises that also keep records of lamps. These organizations process mercury-containing substances and transport these substances to consumer organizations.

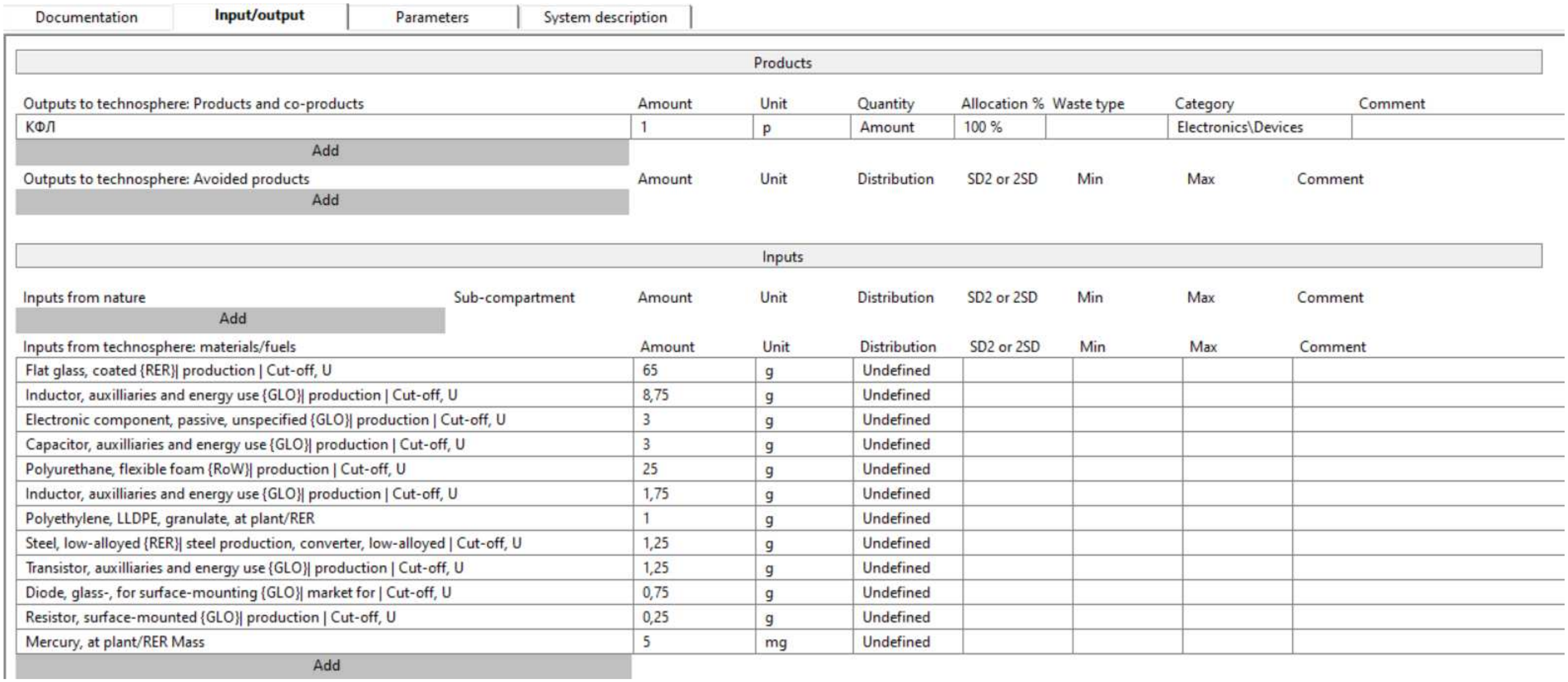
Eco-indicator 99

An assessment of the impact of CFLs on the environment was also made using the SimaPro 9.1.1 software.

Columns that include used materials are Name, Amount and Unit. Parameters and used materials are shown in figure 15. Figure 15 includes the main electronic devices such as 2 inductors, passive electronic component, capacitor, transistor, diode, resistor. An inductor is used to excite a discharge in a gas. Passive electronic components include groups of capacitors, transformers, inductive coils, resistors.

Figure 15. Parameters and used materials

Figure 16 shows the initial data. The name field contains the name of the CFL. The Inputs from Technosphere materials/fuels column indicated the data required for the production of a compact fluorescent lamp. One functional unit is one lamp (120 g).



Documentation | **Input/output** | Parameters | System description

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
КФЛ	1	p	Amount	100 %		Electronics\Devices	

Add

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment

Add

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Flat glass, coated {RER}| production | Cut-off, U	65	g	Undefined				
Inductor, auxilliaries and energy use {GLO}| production | Cut-off, U	8,75	g	Undefined				
Electronic component, passive, unspecified {GLO}| production | Cut-off, U	3	g	Undefined				
Capacitor, auxilliaries and energy use {GLO}| production | Cut-off, U	3	g	Undefined				
Polyurethane, flexible foam {RoW}| production | Cut-off, U	25	g	Undefined				
Inductor, auxilliaries and energy use {GLO}| production | Cut-off, U	1,75	g	Undefined				
Polyethylene, LLDPE, granulate, at plant/RER	1	g	Undefined				
Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Cut-off, U	1,25	g	Undefined				
Transistor, auxilliaries and energy use {GLO}| production | Cut-off, U	1,25	g	Undefined				
Diode, glass-, for surface-mounting {GLO}| market for | Cut-off, U	0,75	g	Undefined				
Resistor, surface-mounted {GLO}| production | Cut-off, U	0,25	g	Undefined				
Mercury, at plant/RER Mass	5	mg	Undefined				

Add

Figure 16. Used materials

The results of calculations for CFLs using the Eco-indicator 99 method are shown in Figure 17. The performed analysis showed that according to four indicators, CFL has an impact on the environment. Eco-indicators - respiratory organic effects, respiratory inorganic effects, climate change, acidification/eutrophication have a score of about 99%, create increased damage from the production of all CFL. The rest of the indicators have little damage from other components of the lamp.

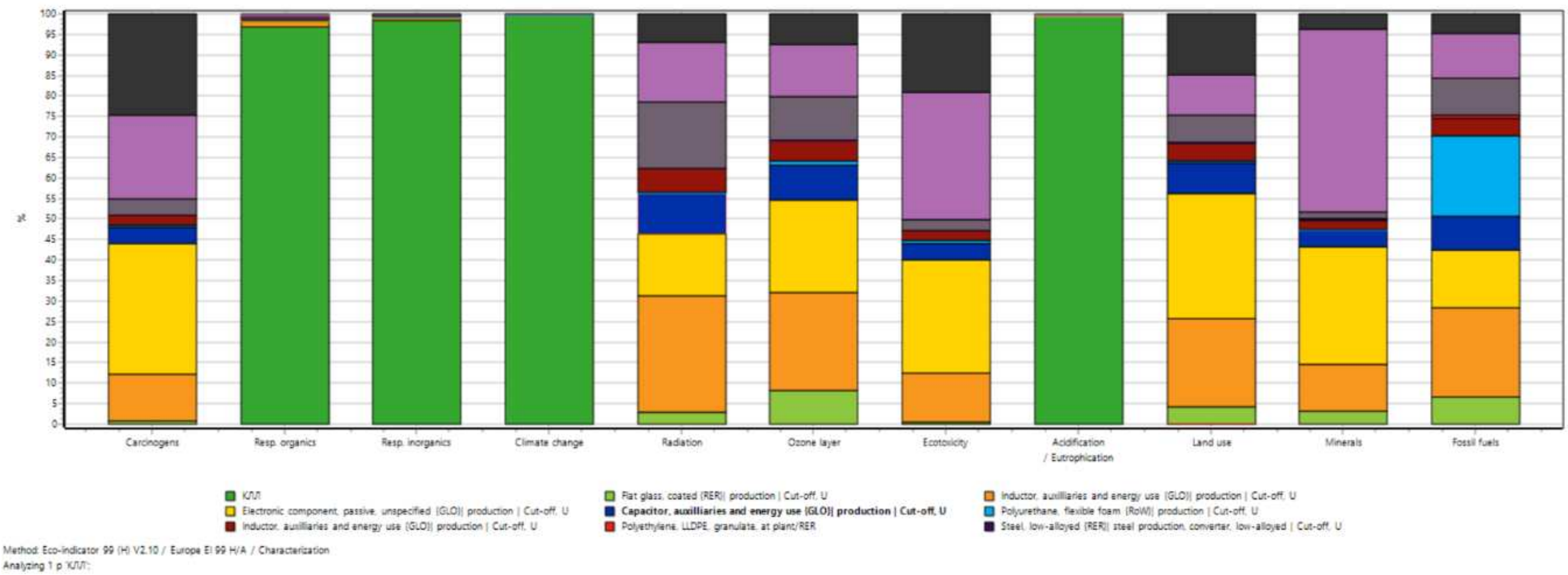


Figure 17. Results of calculations by the Eco-indicator 99 method for the production of CFLs

SFA method

Based on the life cycle assessment carried out, a substance flow analysis diagram for mercury was constructed. The diagram is shown in Figure 18.

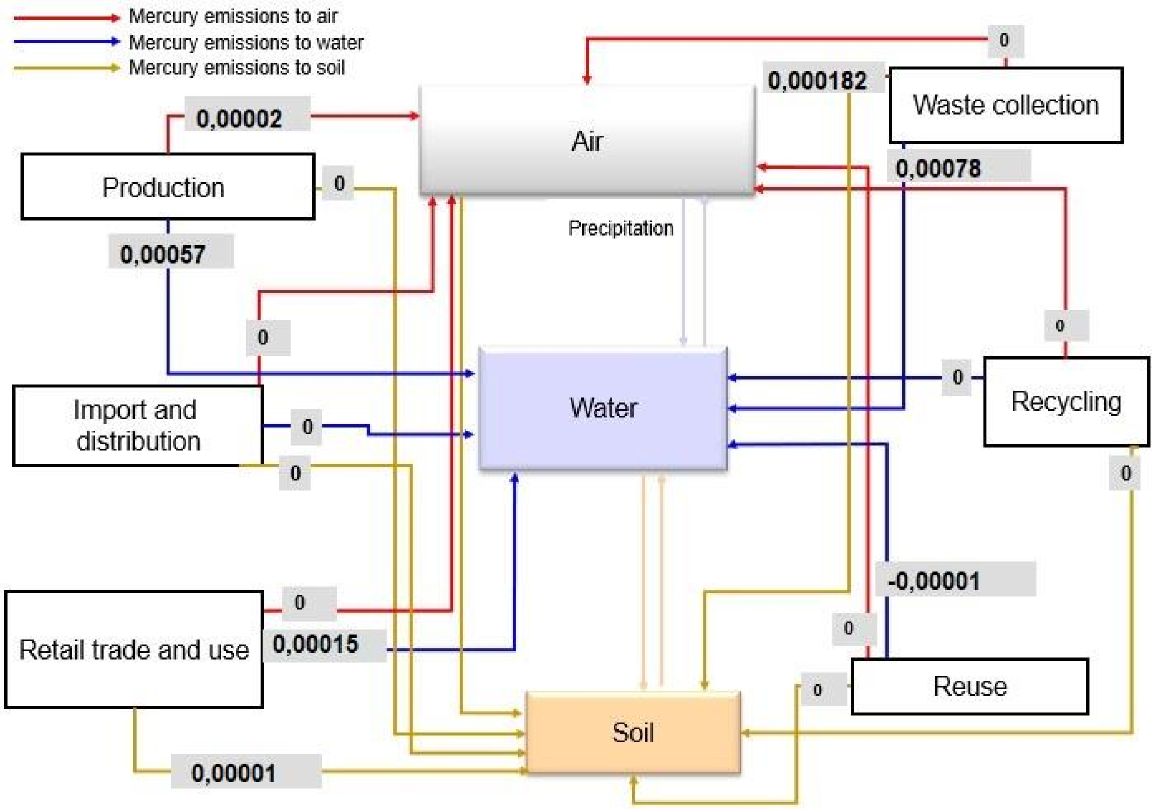


Figure 18. Diagram of mercury flow analysis (number of emissions - mcg, 100,000 hours of operation)

As shown in Figure 18 the purpose of conducting SFA for this substance is based on the solution of the main research objectives and is based on the construction of a scheme of mercury flows in the environment based on the life cycle of the lamp. The selected time frame is 100000 hours of CFL operation. The functional unit is one compact fluorescent lamp. The number of emissions for the chart is presented in mcg (micrograms). The main considered processes of the diagram are Production; Import and distribution; Retail trade and use; Waste collection; Recycling; Reuse.

As shown in Figure 19 the resulting diagram illustrates the main flows and releases of mercury into the environment. The amount of mercury released into the environment at the main stages of the life cycle of CFLs is shown in Figure 19. The largest amount of mercury enters the environment during the production of the lamp - 0.00059 mcg of mercury. Because elemental mercury is used to be introduced into the tube during the manufacturing process and serves to create ultraviolet light when an electric current is passed. During the manufacturing process, about 50 micrograms of mercury are added to the lamp. Mercury itself is either in its divalent form or in its vapor phase elemental form. At the end of its life, only the divalent form of mercury is present in the lamp. Therefore, mercury emissions at this stage are due to the processing of mercury and adding it to the lamp tube. The most common situations of substance release during production are the release of mercury vapor during operations of interaction with mercury (repair of parts of the lamp, cleaning, introduction of mercury into the lamp, random situations associated with a change in the integrity of the lamp, etc.).

Another significant environmental pollution is waste collection, which releases 0.000962 mcg of mercury into the environment. Indeed, if mercury is not included in the circulation process at the enterprise, then the exiting flows of mercury will be significant. When disposing of lamps, mercury may be released when used lamps are placed in an oven. Mercury vapors are released under the influence of high temperatures. Mercury is obtained in the form of a stupa (mercury, soot, dust and water). Upon repeated firing, finely dispersed mercury is obtained. As a result, operations are performed with mercury and bottled.

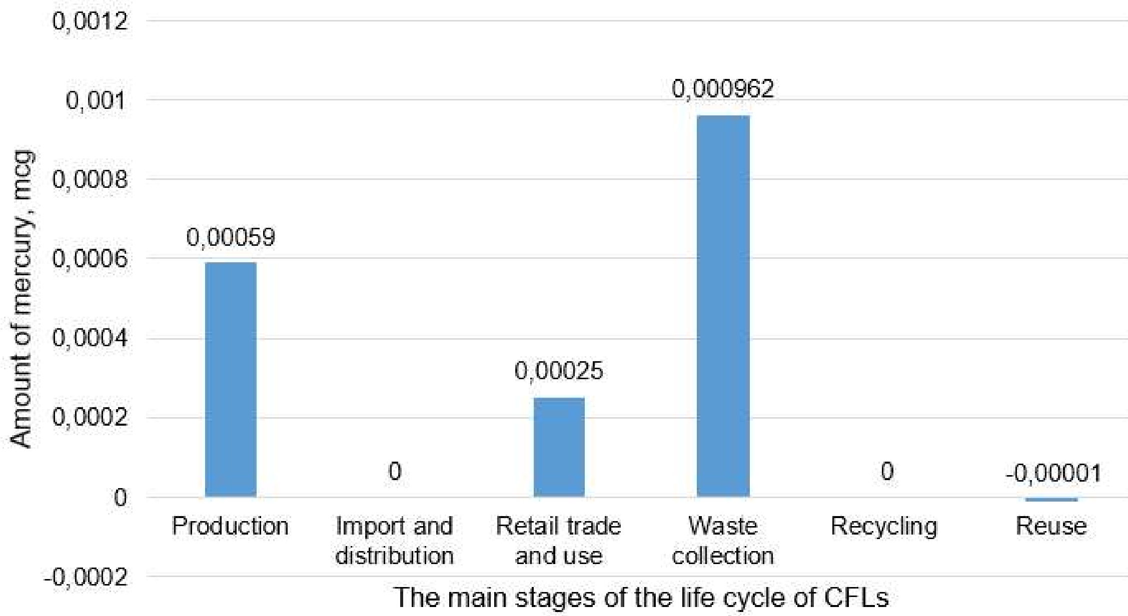


Figure 19. The amount of mercury released into the environment at the main stages of the life cycle of CFLs

Lamps containing mercury are disposed of by chemical, physicochemical or thermal methods, followed by the production of secondary raw materials in the form of mercury for reuse based on BAT (BAT 2016). Chemical disposal methods for CFLs include the following:

1. Hydrometallurgical method (wet chemical demercurization method)

The method is based on the conversion of mercury into very insoluble compounds (for example, mercury sulfide) using a demercurization process. The demercurizer is a solution of calcium or sodium polysulfide.

To clean CFLs from organic substances, caustic alkali solutions, organic solvents, etc. are used. To implement the method, an Ecotrom-2U installation is used. A demercurizer is applied to the surface of the crushed lamps. During the course of chemical reactions, hydrogen sulfide, calcium oxide, highly active sulfur, and heat are released. After drying, the mercury that has been sorbed by the phosphor is converted to mercury sulfide. The content of hydrogen sulfide and sulfur with activated carbon saturates the sorbent, and the content of mercury decreases (0.0003 mg/m^3).

2. Thermochemical technology of periodic action

Lamps containing mercury are kept at a temperature that allows the mercury to desorb. This is followed by rapid cooling by contacting the hot lamp with a reagent solution containing sulfur. Thermal destruction of the flask occurs, mercury is bound by the Salt technology.

Physical and chemical methods of CFL disposal include:

Separation of CFLs into components

This method is used to separate CFLs into metal bases, glass and mercury-containing phosphor. The capture of mercury vapor occurs in adsorbers.

The lamp is sent to the crusher, where the crushing process takes place. After this stage, the glass enters Ecotrom-2, where the glass is cleaned from the phosphor, which contains mercury. The base is placed in a special container, then in a crushing and separating device, where mechanical cleaning takes place.

With the use of a physical process - vibration, the phosphor is separated from the glass. The mercury-containing phosphor is sent to the cyclone along with the air stream. Residues of this substance are captured in a bag filter and collected in a receiving tank. Neutralization of a phosphor containing mercury is carried out by converting mercury into a non-hazardous insoluble compound (mercury sulfide).

Thermal methods for CFL disposal include:

1. Heat treatment in a screw tube furnace using the UDM-3000 unit

The method is based on the demercurization of CFLs and includes the sublimation of mercury from crushed CFLs, the condensation of mercury vapor, and the removal of processing waste. In this case, the heat treatment process takes place in a screw tube furnace at a temperature of about 360 °C. Mercury turns into a gaseous state, together with organic compounds, the phosphor is delivered to the afterburner filter. At this stage, the combustion of organic compounds to H_2O and CO_2 is carried out at a temperature of about 800 °C. The next stage includes cooling the gas in the condenser to a temperature of about 35°C and the process of mercury condensation. After condensation, mercury mixed with mortar contains 70% mercury. Then, after the precipitation of mercury, the gas enters the adsorber. The purified gas enters the filter-ventilation module, where it is purified to a concentration of <0.0003 mg/m^3.

After the sublimation of mercury and the combustion of the organic components of the lamp, metals and crushed glass are sent for demercurization. Demercurized cullet contains less than 0.0001% mercury, 1% non-ferrous metals, 3% phosphor, 97% glass (BAT 2016). Information and technical guide to best available techniques. 2016). This percentage of mercury content does not exceed the MPC of mercury in the soil, so demercurized cullet is sent to a landfill or added as a building material to expanded clay concrete blocks.

2. High temperature firing.
The method involves heating waste to 500 ^{O}C, concentrating mercury by distillation and trapping it, and condensing mercury vapor.

3. Thermal vacuum technology at the URL-2m facility.
Thermal vacuum technology is carried out in a stationary demercurization chamber. The dependence of saturated mercury vapor on temperature is taken into account when implementing the method. CFLs are destroyed in the chamber, and the mercury vapor formed under the influence of temperature is pumped out using a low-temperature trap. Thawing the trap facilitates the assembly of mercury in the liquid state.

6 DISCUSSION

The rational use of chemically hazardous substances involves activities that are based on the prevention of hazards, risks, consequences of human activities, maintaining the safety of technological systems associated with chemicals. Based on the study, in order to control and rationally use chemicals at the enterprise, it is recommended to carry out a preliminary assessment of the mining process for the purpose of rational management; keep records of the amount of chemicals used for their rational use and effective management; identify emissions of chemicals into the air, discharges into water sources, ways of utilizing cadmium and mercury; introduce the best available technologies in the main production and for wastewater treatment; and rovide a process for identifying business risks.

Nickel-cadmium batteries should be replaced with more environmentally friendly lithium-ion and nickel-metal hydride batteries. It is desirable to replace the CFL-producing products with more environmentally friendly Incandescent light bulbs. For example, the brightness of a CFL with a power of 20 W corresponds to the brightness of an incandescent lamp with a power of 100 W, although the main negative point is the high energy consumption of incandescent lamps. However, incandescent lamps do not contain the hazardous chemical mercury.
In addition, an effective way to ensure the rational use of chemicals is to increase the productivity of the equipment used and reduce the period of work using chemicals (a short effective period of equipment leads to less emissions in the enterprise).

Table 5 contains 3 sections of the developed recommendations (Organization for Cooperation between Government, Industry and International Enterprises; Development of an informative base for the management of chemical waste, emissions and discharges from enterprises; Risk management, reducing the likelihood of risks in the handling of chemicals) for reduce the hazard level of chemicals. The complete list of these recommendations is given in Appendix 1 and is divided into two groups: for enterprises and for public administration (authorities).

7 CONCLUSION

Life cycle assessment of chemicals is an analysis tool for reducing the anthropogenic load of manufactured products on the environment at all stages of the production process and solving environmental problems based on the development of recommendations. LCA is aimed at identifying the main shortcomings in the technological processes of production and allows you to make management decisions and carry out environmental management of the enterprise.

Existing Russian legislation, conventions and agreements, and sustainable development goals are aimed at controlling the safe management of chemicals. The main policy documents in this area are Agenda 21, the Basel Convention on the Control of transboundary movements of hazardous wastes and their disposal, the Rio Declaration on Environment and Development, the Declaration of the United Nations Conference on the Human Environment, the Minamata mercury convention, Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, Protocol on Heavy Metals.

The life cycle assessment methodology for substances in products is an algorithm for conducting an LCA, which requires a large amount of information to achieve the goals and objectives of the process. There are a number of LCA methods, among which EIA, SFA and MFA are often used. The chosen method of the SFA study showed that most cadmium emissions occur during the production of nickel-cadmium batteries, the most mercury emissions occur during the production of compact fluorescent lamps and during the disposal of spent CFLs.

Based on the results of the life cycle assessment of battery cadmium and mercury in the CFL, recommendations are proposed for enterprises and for government bodies (authorities) on the basis of cooperation organization, industry and international enterprises; development of an informative base for handling chemical waste, emissions and discharges from enterprises; risk management, reducing the likelihood of risks occurring when handling chemicals. Thus, all the tasks set are fulfilled, the purpose of the study is achieved.

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APPENDICES

Appendix 1

Table. Recommendations for the rational use of chemically hazardous substances

For businesses	For government bodies (authorities)
1	2
Organization for cooperation between government, industry and international enterprises	
Creation of collaborative activities to reduce the hazard of substances and develop environmental criteria for the identification of chemicals	Development of measures aimed at strict control of the activities of enterprises in order to reduce pollution and assessment of the life cycle of chemicals
Creation of a unified system on the toxicity of substances (for example, using the database of the Federal Register of Potentially Hazardous Chemicals and Biological Substances)	Development of measures, guidance documents for industrial sectors in certain production cycles (for example, the manufacture of CFLs and nickel-cadmium batteries)
Implementation of the principles of replacing toxic substances with more environmentally friendly substances or a complete ban on the use of those substances that adversely affect the environment and public health	Creation of a system for supporting environmental decision-making, including economic support for enterprises
Creation of tools for the liquidation of dangerous situations, accidents, creation of a common system for information on the liquidation of accidents associated with the use of chemicals, as well as the introduction of measures to implement the liquidation of emergencies from each enterprise	Introduction of new principles and measures for the conduct of trade in chemicals, development of international standards that are aimed at controlling the functions of manufacturers, importers and other parties involved in relations with the LC of toxic chemicals

Table continued

1	2
Marking of manufactured products	Establishment of a program to encourage industry to engage in a collaborative process of international cooperation in the field of chemicals-related activities
Creation of the necessary centers for the constant monitoring of the health of workers who directly interact with toxic chemicals, and with the aim of timely prevention of shipment in case of its occurrence	Creation of a unified system for the export of chemicals based on strict control measures
Implementation of the principle based on the “responsible handling” of chemicals and products containing these substances	Identification of risks and implementation of new environmental methods based on the identification of obsolete substances
	Development of measures for the environmentally safe disposal of toxic substances that are converted into waste
	Creation of international mechanisms for the organization of safe production with environmental accounting of toxic materials or implementation of programs to replace such materials
Development of an informative base for the management of chemical waste, emissions and discharges from enterprises	
Share information between enterprises and at the regional level to reduce the level of chemical hazards	Creation of a unified program for access to information on emissions and emergencies for the population

Table continued

1	2
Creation of a unified information system with an assessment of the life cycle of all manufactured products	Collaborate with businesses to develop guidance documents on the dissemination of information to the public to create awareness of potential hazards
Risk management, reducing the likelihood of risks in the handling of chemicals	
Implementation of low-waste technologies at each enterprise by increasing the number of closed technological processes	Establishment of a unified register of cadmium and mercury emissions with quantitative indicators and quantification of emissions
Development and implementation of a unified investment program in production	Modification of the existing production system based on the guidance documents on labor protection
Provide or upgrade existing processes to reuse low reactivity products or components with low chemical activity	Implementation of rational risk management based on the System of Global Indicators for the Achievement of Sustainable Development Goals developed by ECOSOC (United Nations Economic and Social Council)
Development of effective methods for identifying and managing risks in the enterprise, Compliance with certain regulations (in particular, Decree of October 7, 2016 No. 1019)	