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Zero-waste technologies: formation of multilevel structures of environmental protection systems

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Abstract. Zero-waste technologies are technically and technologically based mainly on environmental protection systems (EPS). Such systems help to arrange waste recycling into the technosphere rather than polluting the environment. The article gives a brief review of the methods and technologies of ferrous metallurgy waste recycling. Simple patterns in which the interrelations between devices for environmental protection against solid, liquid and gaseous wastes are not arranged, cannot provide the necessary level of zero-waste production. Only integrated multistage, multilevel systems of raw materials processing and waste recycling, including devices and technologies for processing of waste flows in various phase states, can create a high degree of zero-waste production. The design of such systems startswith the description of outgoing substances and energy flows from process plants, the formation of structural variants, operating principles (technologies) and equipment (devices) of system components. It is from these that the optimal variant will be chosen. The purpose of optimizing a protection system is to minimize the mass of waste sent into the environment. This provides for environmental and industrial safety, and takes into account the technical and economic constraints on the possibility of implementing the selected EPS structure. The study proposes a procedure for forming the structure of the system, including production, environmental protection devices, and the natural environment. Interrelations between the system components are represented by energy flows and masses of substances. The study also proposes an example of arranging the system structure including interrelated subsystems for processing (treatment, decontamination, etc.) of gases, wastewater and solid waste. EPS devices in general can form outgoing flows of substances, which, depending on their properties (hazard, usefulness and phase state), can be directed to the environment, to the next level (stage) protection devices, as well as to production for replacing raw materials or obtaining products. An example of organizing the structure of an integrated multistage and multilevel system of environmental protection against emissions, including subsystems for treating secondary waste in gaseous, liquid and solid states, is considered. The proposed procedure for forming the environmental protection system structures can be applied to other industries.

Keywords: zero-waste production, environmental safety, integrated environmental protection system, system analysis, structure formation, relations, substance flow processing

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Оригинальная статья

Безотходные технологии: формирование многоуровневых структур систем защиты окружающей среды

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Аннотация. Техническую и технологическую базу безотходных технологий в основном представляют системы защиты окружающей среды (СЗОС), которые позволяют организовать рециклинг отходов в техносферу, а не загрязнять ими окружающую среду. В статье дан краткий обзор работ, посвященных методам и технологиям утилизации отходов черной металлургии. Показано, что простые схемы, в которых не организованы взаимосвязи между устройствами защиты окружающей среды от твердых, жидких и газообразных отходов, не могут обеспечить необходимую степень безотходности производства. Высокую степень безотходности в общем случае могут создать только комплексные многостадийные, многоуровневые системы переработки сырья и утилизации отходов, включающие устройства и технологии обработки потоков отходов в различных фазовых состояниях. Проектирование таких систем должно начинаться со стадии описания выходных потоков веществ и энергии из технологических установок и формирования вариантов структур, принципов действия (технологий) и оборудования (устройств) элементов системы, из которых будет выбираться оптимальный вариант. Цель оптимизации системы защиты – минимизация массы отходов, направляемых в окружающую среду, обеспечивая экологическую и производственную безопасность с учетом технико-экономических ограничений на возможность реализации выбранной структуры СЗОС. Предложена процедура формирования структуры системы, включающей производство, устройства защиты окружающей среды, природную (окружающую) среду. Взаимосвязи между элементами системы представлены потоками энергии и масс веществ. Приведен пример организации структуры системы, включающей взаимосвязанные подсистемы обработки (очистки, обезвреживания и др.) газов, сточных вод и твердых отходов. Отмечено, что на выходе устройств СЗОС в общем случае могут сформироваться выходные потоки веществ, которые в зависимости от их свойств (опасности, полезности и фазового состояния) могут быть направлены в окружающую среду, в устройства защиты следующего уровня (ступени), а также в производство для замещения сырья или получения продукции. Рассмотрен пример организации структуры комплексной многоступенчатой и многоуровневой системы защиты окружающей среды от выбросов, включающей подсистемы отработки вторичных отходов в газообразном, жидком и твердом состояниях. Предложенная процедура формирования структур систем защиты окружающей среды может применяться для других отраслей производства.

Ключевые слова: безотходность производства, экологическая безопасность, комплексные системы защиты окружающей среды, системный анализ, формирование структуры, взаимосвязи, обработка потока веществ

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Introduction

Ensuring the environmental safety of Russia and the entire world community is one of the most important tasks of our times. Improving the level of environmental protection will delay the onset of inevitable ecological catastrophe. One of the main focus areas in reducing environmental impact is the design, formation and use of zero-waste (green) technologies. Such technologies allow part of waste to be returned to the sphere of production or consumption, thus reducing environmental pollution and the extraction of natural resources. Environmental protection systems (EPS) serve as a technical base of zero-waste, energyand resource saving technologies.

Analysis of waste processing technologies in ferrous metallurgy

The metallurgical industry is one of the largest consumers of resources and generators of waste polluting the environment. Therefore, activities aimed at improving the environmental friendliness of metallurgical technologies are especially relevant.

Studies [1 – 5] show the general characteristics of the adverse impacts of metallurgical enterprises and the analysis of environmental problems caused by the impacts on the natural environment and people. Research and recommendations on solving the environmental problems have been conducted in several areas.

Due to the diverse nature of waste from ferrous metallurgy and other industries, a complete analysis of methods of deep waste recycling to ensure zero-waste production cannot be carried out within the framework of a single scientific work or article. Therefore, a large number of known scientific works consider individual cases of using technologies for processing, neutralization of solid waste, gas and wastewater treatment, as well as measures for resources and energy saving.

All ferrous metallurgy waste is divided into three groups according to its phase state: solid, liquid and gaseous.

The methods and technologies of solid waste (mainly slag) recycling are suggested in works [1, 5, 6 – 15].

Works [6, 11, 15] provide reviews of publications on the assessment of environmental problems and waste recycling methods. The technologies of using steelmaking slag for the production of mortar are described in [7, 12, 13]. The use of ferrous metallurgy slag for the reclamation of industrial waste dumps is considered in [8, 9]. Article [10] presents the results of research on the development of a cyclic technology for recycling of solid waste from blast furnace, converter and open-hearth furnace production with zinc recovery and regeneration.

Article [14] presents the possibility of integrating mining and metal-processing wastes into a single whole. Measures to solve environmental problems caused by stationary and fugitive emissions are developed and described in works [16 – 21]. Recycling technologies and wastewater treatment processes in the metallurgical industry are consideredin publications [22 – 24].

Simple patterns in which the interrelations between devices for environmental protection against solid, liquid and gaseous wastes are not arranged, cannot provide the necessary level of zero-waste production. For example, “wet” purification of emissions from dust generates slime, requiring the disposal of water and sludge. In order to comply with the principle of zero-waste production, and the first stages of low-waste production, integrated waste recycling systems need to be developed.

The urgency of integrated recycling of wastes and man-made formations is highlighted in [1]. Article [25] indicates the need to observe the system principles of arranging the modern production. Naturally, the system solution of environmental problems requires the development and use of multiple technologies [1].

The integrated approach principleis used to assess the environmental aspects of a series of impacts of metallurgical enterprises [22], integrated prevention and control [24] of environmental pollution, as well as to recycle solid waste of ferrous metallurgy enterprises [6, 7, 10].

Generally, integrated zero-waste systems of raw materials processing and waste recycling aim to divide the flows of substances not only in terms of composition, properties, fractions and phase state of components, but also perform their subsequent processing. The devices for flows division use physicochemical, thermal, mechanical, chemical, biochemical and other methods and technologies. A description is provided in the European Union reference document [24] on the best available technologies for processing wastes with different physicochemical properties (solid and pasty, liquid and gas). An overview of some technologies and their application in ferrous metallurgy is presented in [2, 22, 26 – 28].

The optimal design of environmental protection systems with selection of the best technologies can be reasonably performed with the help of software tools. Article [28] substantiates the need to build an information support system for the application of the most efficient technologies. It also proposes the structure of the unified information and analytical system UIAS with the "Atlas of the Best Environmental Technologies".

Thus, the zero-waste principle in general can be implemented only in integrated multilevel raw materials processing and waste recycling systems, including devices and technologies of various purposes.

According to GOST R 57702 – 2017 [29] the principles of systematicity and integrity need to be implemented, while "the ultimate goal should be to optimize production simultaneously in terms of energy, economic and environmental parameters".

Methodology of formation of multilevel structures for environmental protection systems

We shall limit ourselves to considering the systems of production wastes recycling, usually referred to environmental protection systems.

The design of such systems should begin with the description of the outgoing flows of substances and energies from technological and thermal power plants.

Depending on the properties of flows, which can have an inadmissible impact on the environment, structural variants and principles of action (technologies), equipment (devices) of system components should be designed, from which the best option will be selected. An example of solving such a problem is the algorithm for five-level optimization of structures, principles of operation, design values and standard parameters for the optimal design of the heating furnace compartment [30].

The system approach to the design of waste processing technologies will allow for waste hazard reduction problems to be resolved more effectively and for secondary energy (SER) and material (SMR) resources to be used more widely. Integrated, multilevel and deeper processing of substance flows, taking into account changes in their phase state in environmental protection systems, will increase the degree of zero-waste production. By setting a broad optimal design problem, greater effect can be obtained in the implementation of the purpose. On the other hand, the greatest damage to nature and society is caused by system errors preconditioned by the absence of aholistic analysis of system relations of production – environmental protection systems – and the environment.

System representation is important for a general understanding of the structures and functional purpose of environmental protection system components. It also serves to identify the opportunities for more comprehensive waste recycling.

The article proposes a procedure for forming the system structure, including: production, environmental protection devices, and the natural environment.

It is advisable that an integrated structure of such a system be designed based on the principle "top to bottom" or "general to specific", representing the interrelation between the system components by substances and energy flows.

The following terms will be used for the convenience of describing the integrated structure of the environmental protection system: "processing", "stage" and "level" of processing.

Processing will be understood as any process operation [24]: purification, roasting, deposition of substances, etc.

Processing stages are commonly referred to as functions of devices through which the flow of substances, without a change in the phase state, passes sequentially. For example, a mixer, an aerotank and a settling tank, which carry out processing stages for wastewater.

A processing level can be considered as a function of the device into which the flow enters in a different phase state of the substance to the main flow processed in the previous device. For example, slime processing after the aerosol "wet" purification device is the next level of flow processing.

Let us consider the purpose of the main material and energy flows which connect the environmental protection subsystems with production and the natural environment (Figure 1). Each protection subsystem can include elements that perform stages or levels of flow processing. Atmosphere, hydrosphere and lithosphere protection subsystems process flows of gases, liquids and solid substances accordingly.

Production and consumption (part of the technosphere) uses natural resources (solid lines) from the atmosphere, lithosphere and hydrosphere and returns flows

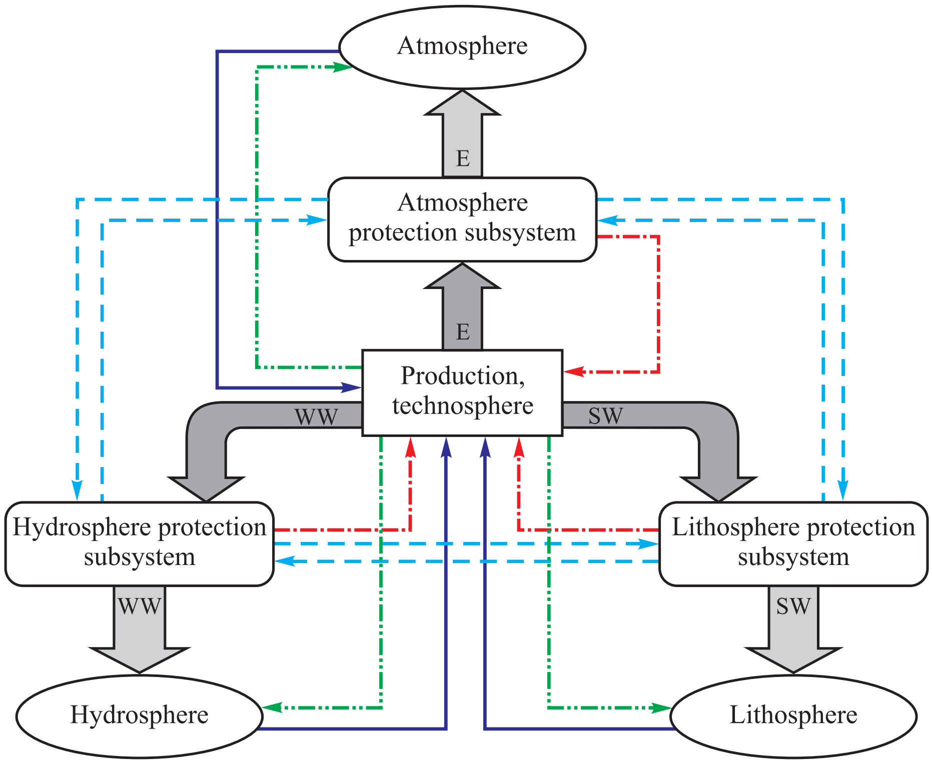

Figure 1. Structure and interrelations in the production – environmental protection devices – natural environment system:
E — emissions; WW — wastewater, SW — solid waste;
– – – – secondary waste; –··–·– primary nonhazardous waste; —— – resources; –·–·– – secondary material and energy resources; ⇦ – EPS treated and neutralized flows; ⇦ – harmful and hazardous substances waste flows

Рис. 1. Структура и взаимосвязи в системе производство – устройства защиты окружающей среды – природная среда:
В – выбросы; СВ – сточные воды; ТО – твердые отходы;
– – – – вторичные отходы; –··–·– первичные безопасные отходы; —— – ресурсы; –·–·– – вторичные материальные и энергетические ресурсы; ⇦ – очищенные и обезвреженные потоки СЗОС; ⇦ – потоки отходов вредных и опасных веществ

of primary "safe" waste (dashed line with two dots) which do not require special treatment for the natural environment. Such waste is dispersed in the atmospheric air, discharged into water reservoirs, and disposed of, for example, in dumps.

Flows of primary production wastes (emissions, wastewater, solid wastes) which require special treatment are directed to the corresponding atmosphere, lithosphere and hydrosphere protection subsystems (incoming flows of the EPS, dark arrows). In addition to primary wastes, secondary wastes (second level or stage of protection) allocated by other types of protection subsystems (dashed lines) can enter protection subsystems. For example, the atmospheric protection subsystem can receive gases from lithosphere and hydrosphere protection subsystems, which can be formed during thermal treatment of liquid and solid wastes.

Outgoing flows of protection subsystems (see Figure 1, light arrows) include flows of purified or treated waste sent to the atmosphere, lithosphere, and hydrosphere, respectively (main flows of treated waste). They also include flows of secondarywaste sent to production in the form of secondary energy and material resources (SER and SMR, dashed lines) and/or to the next level of waste treatment (dashed lines).

Figure 2 shows in more details the incoming and outgoing flows of environmental protection subsystems and gives a description of their functional purpose. The flow into the environment, which can bypass the EPS, is not shown conventionally. This flow may include useful and/or non-hazardous substances the treatment of which is not feasible. The diagram shows that the structure of the EPS outgoing flows is formed in relation to the amount and properties of substances included in the primary waste (the EPS – *I* incoming flow). Incoming flows of protection subsystems (primary wastes in the form of gases, liquids, solids of metallurgical enterprises or other technospherefacilities) may include (see Figure 2):

– hazardous and harmful substances;

– useful substances;

– non-hazardous substances.

In environmental protection subsystems division of substances shall occur in relation to their properties: the degree of danger, quantity and phase state. After the primary waste flow division, in general, four outgoing flows of substances from the first-level or stage protection subsystems (EPS – *I*) may form.

I – the first (main) flow, which has passed purification or treatment and has not changed the phase state, is sent into the environment. This flow may include environmentally non-hazardous substances:

– hazardous and harmful substances, but in safe quantities (e.g., emissions not exceeding the maximum permissible values;

– useful substances;

– non-hazardous substances which, for technical or economic reasons, cannot feasibly be separated from the flow into the environment.

Substances in this flow, depending on the phase state, are dispersed into the atmospheric air (gases), diluted with water of water bodies (discharges), sent to dumps, landfills, storage facilities and other facilities for solid waste storage.

II – the second flow, which includes environmentally non-hazardous substances captured by the first-level protection subsystems (EPS – *I*), can also be sent to the environment. Unlike the first flow, this flow has a different phase state. For example, solid particles from devices for gas cleaning from dust, or from biochemical wastewater treatment devices, etc.

III – the third flow consists of hazardous and noxious substances captured by the first-level protection subsystems (EPS – *I*). This flow or flows shall be sent to the second-level or second-stage protection subsystems (EPS – *II*).

IV – the fourth flow is formed by hazardous, harmful and useful substances captured by EPS – *I*. They can be used to obtain products in the production, where the primary waste was formed (for example, metal or cement dust), or other production (for example, sediment from wastewater treatment from organics, red mud – waste from non-ferrous metallurgy, which is used as raw material in ferrous metallurgy).

The EPS secondary wastes in general can have a different phase state when compared to primary wastes. Thus, subsystems for environment protection against gaseous, liquid and solid wastes in the general case should be interconnected, i.e. they represent a uniform system including several levels of protection. An example of the structure of such an integrated protection subsystem is shown in Figure 3. This demonstrates a pattern of arranging multistage and multilevel protection of the environment from emissions (primary waste) only.

Polluted emissions are sent into the atmospheric air protection subsystem, where the gas flow from process plants (sintering machines, oxygen converters, etc.) is purified using energy, chemical reagents, water or other resources (EPS incoming flows). At the outlet of the atmospheric protection subsystem in general four more flows (secondary waste and secondary material and energy resources) can be formed. They are briefly described above (see Figure 2).

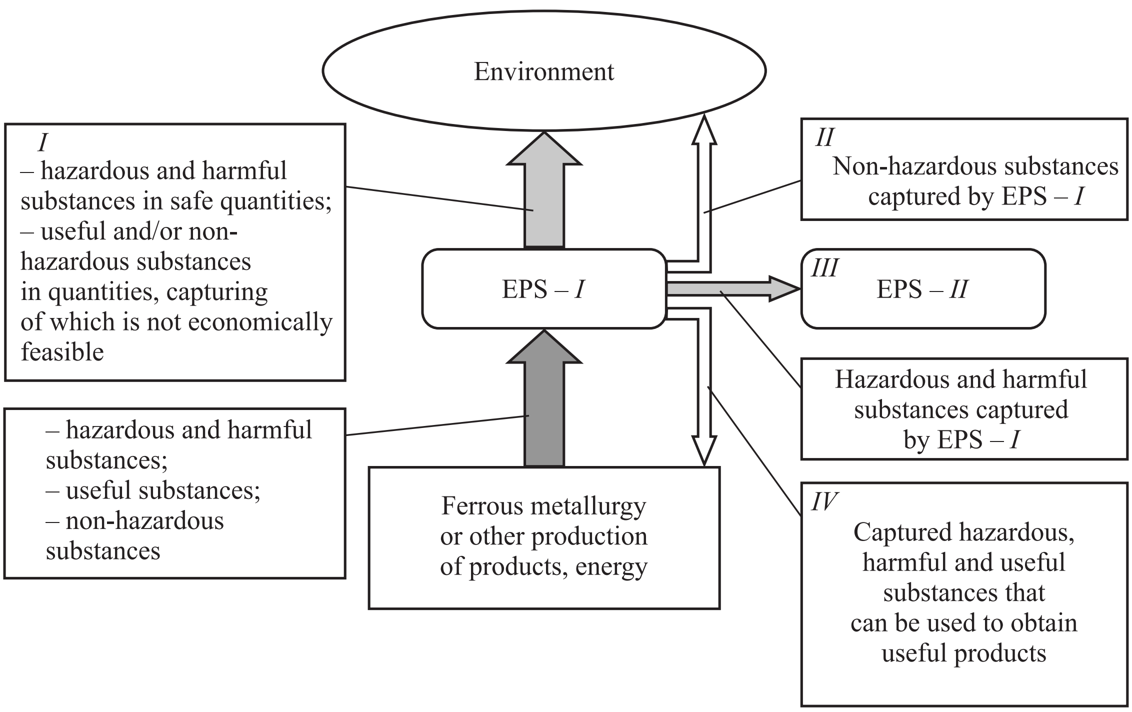

Figure 2. Incoming and outgoing flows of environmental protection subsystems and their properties determining their scope of application

Рис. 2. Входные и выходные потоки подсистем защиты окружающей среды и их свойства, определяющие направление их использования

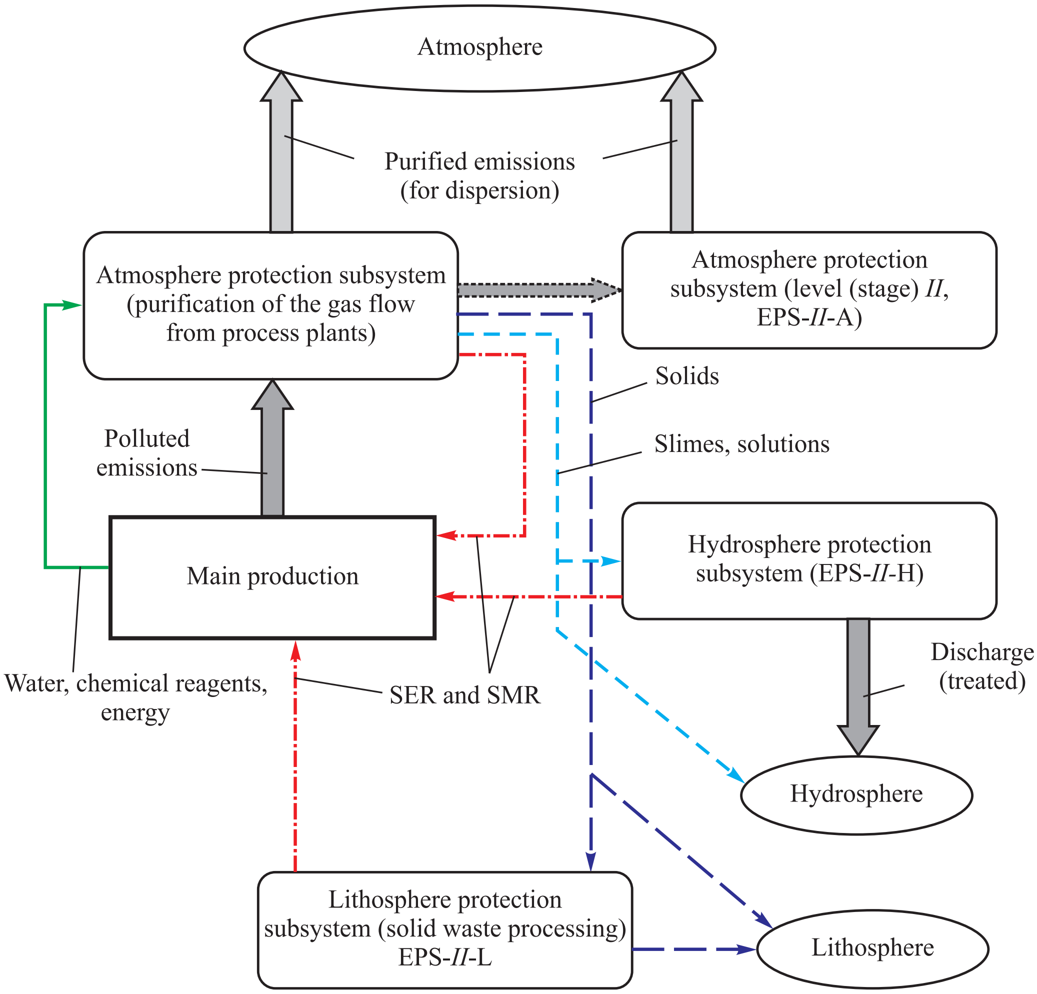

Figure 3. Structure and interrelations in multistage and multilevel environmental protection subsystems (primary waste – emissions)

Рис. 3. Структура и взаимосвязи в многоступенчатых и многоуровневых подсистемах защиты окружающей среды (первичный отход – выбросы)

Substances removed from the mixture of gases can be gaseous (products of thermal processing (after-burning)), solid (dust), or liquid (solutions) or in the form of slime (concentrated suspended solids in liquid).

Gaseous secondary wastes which do not meet safety requirements are transferred to stage II of the subsystem of atmospheric protection from hazardous gases (EPS – *II*A).

Captured solid and liquid wastes, if they meet environmental safety requirements and do not relate to SMR and SER, are sent (dashed line) directly into the hydrosphere or lithosphere. Otherwise, they are directed to devices for processing (purification, recycling) of solid and liquid wastes, i.e. to second-level lithosphere and hydrosphere protection subsystems (EPS – *II*L and EPS – *II*H).

In general, the atmosphere, lithosphere and hydrosphere protection subsystems shown in Figure 3 can form wastewhich requires the appropriate protection subsystems of the third, fourth and more levels. Four kinds of flows can leave these subsystems (see Figure 2).

Note that different variants of technologies described, for example, in [24] shall be considered as implementing the means of protection. The variety of protection system variants thus formed will improve the efficiency of optimal design.

The volume (mass) of waste transferred to the next processing level or stage is usually reduced. At the same time, the subsequent purification stages may in some cases require more sophisticated devices. For example, large particles in aerosols are well captured by simple purification devices, while in order to catch fine particles in EPS – *II* (the second stage) more sophisticated devices with higher gas velocities and water spraying (for example, high-speed gas washers with Venturi tubes) will be required.

In general, an atmospheric protection subsystem (see Figure 1) can be used as the next level of purification of gases coming from hydrosphere and lithosphere protection subsystems, in which gas formation as secondary waste is possible.

Wastewater treatment processes can be accompanied not only by the formation of treated discharges, but also the formation of secondary solid wastes and gases (e.g., during thermal decontamination).

The recycling and disposal of solid waste in lithosphere protection subsystems (see Figure 1) can also generate secondary waste in the form of gases (combustion or decomposition products) or wastewater. Thus, the emission purification subsystem can receive gas flows from discharge and solid waste processing subsystems (they are not shown in Figure 3). Note that the hydrosphere and lithosphere protection subsystems shown in Figure 1 can have essentially similar multilevel and multistage structures shown in Figure 3 foremissions.

Integrated EPS can include several industries. For example, ferrous metallurgy slag is used for the production of construction materials and even crystal products. Consumers of waste can be searched for by means of information subsystems, comparing information about production and consumption wastes with data about the properties of raw materials and materials of resource consumers.

Protection systems should ideally minimize the mass of waste sent to the environment, thus ensuring ecological and industrial safety. Naturally, when choosing the variants of EPS structures, the following limitations should be taken into account:

– technical ability to implement the selected structure of the environmental protection system (availability of technologies and waste processing devices in the market);

– technical and economic feasibility of the adopted environmental protection system.

In conclusion we should note that the formation of structures and the optimal design of EPS are only a part of a more common task. GOST R 57702 – 2017 (item 5.4.1) [29] states that “the consistency principle underlying the creation of zero-waste production shall take into account the existing and increasing interrelation and interdependence of production, social and natural processes”.

Conclusion

Simple patterns, in which the interrelations between devices for environmental protection against solid, liquid and gaseous wastes are not arranged,cannot provide a high level of zero-waste production. In general, the zero-waste principle can be implemented only in integrated multilevel systems of raw materials processing and waste recycling, including devices and technologies for different purposes. In resolving the problem of optimal design of zero-waste systems,a necessary stage is the formation of EPS structures variants. The proposed general description of the system structure includes: production, subsystems of environmental protection devices, natural environment and their interrelation in the form of substance and energy flows. EPS devices in general can form the outgoing flows of substances, which, depending on their properties, will be directed into the environment, to the nextlevel (stage) protection devices. They can also be directed to production for replacing raw materials or obtaining products. The system approach to designing variants for implementing environmental protection systems will improve the efficiency of their optimal design and the degree of zero-waste production.

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