Запропонована технологія утилізації радіаційно забрудненого металу методом плавлення, яка основана на ефекті самодезактивації. Розроблена методика розрахунку кількості забруднюючих шихту гамма-випромінюючих радіонуклідів, яка забезпечить необхідний рівень гамма-випромінювання на поверхні виплавленого металу. Показано, що критерієм оцінки радіаційної безпеки металу є потужність дози гамма-випромінювання на його поверхні. Представлена технологія характеризується високими техніко-економічними показниками

Ключові слова: технологія утилізації, радіаційно забруднений метал, радіонукліди, самодезактивація, плавлення

Предложена технология утилизации радиационно загрязнённого металла методом плавления, основанная на эффекте самодезактивации. Разработана методика расчета количества загрязняющих шихту гамма-излучающих радионуклидов, которое обеспечит требуемый уровень гамма-излучения на поверхности выплавленного металла. Показано, что критерием оценки радиационной безопасности металла является мощность дозы гамма-излучения на его поверхности. Представленная технология характеризуется высокими технико-экономическими показателями

Ключевые слова: технология утилизации, радиационно загрязненный металл, радионуклиды, самодезактивация, плавление

UDC 621.039.736:621.745
DOI: 10.15587/1729-4061.2016.74847

TECHNOLOGY OF RECYCLING RADIOACTIVELY CONTAMINATED METAL BY THE METHOD OF MELTING

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1. Introduction

In the process of using atomic energy, an enormous amount of radioactive waste is formed, part of which is radioactively contaminated metal (RCM). Contaminated metal forms in the course of repair, modernization or dismantling of equipment during decommissioning of the objects of nuclear industry. A large amount of metal wastes contaminated by natural radionuclides is also created in other industrial areas, for example, at gas- and oil-refining enterprises. Large volumes of RCM that were formed as a result of accident at the Chernobyl AES (Ukraine) and in the process of elimination of its consequences are located in the exclusion area of the Chernobyl AES.

The radionuclides located on the surface of contaminated metal are the source of ionizing radiation (IR), which is potentially dangerous for biological objects. For this reason, contaminated metal products are unfit for the use according to their purpose.

In practice, for the return of radioactively contaminated metal to the industrial applications, decontamination of its surface is conducted by different methods [1]. But it is not always possible to reach the required degree of cleaning of the articles of complex configuration and large volumes of new radioactive wastes are formed. This way is economically expensive, labor-consuming and unsafe for the production staff.

A more efficient approach to the recycling of RCM is decontamination by the method of smelting, which is based on the melting of metal and removal of radioactive materials to slag. Melting of radioactively contaminated metal is conducted in the electric steel melting furnaces with addition of decontaminating slags, which facilitate a more active transfer of radio nuclides from the molten metal to the slag.

At present, RCM melting is widely applied with the purpose of decreasing the amount of radioactive wastes, which should be buried, and the recycling of contaminated metal [2].

Introduction of fluxes and additives to the composition of slags in many cases leads to the necessity to complicate the technology of melting and to install additional equipment, complex as a rule. All this substantially reduces efficiency of the process of recycling contaminated metal and, as a result, leads to substantial rise in costs.

At present, the volumes of contaminated metal, from which radionuclides are removed, to the level when it is possible to re-use it, amount to only several percent of the amount of produced steel [2].

2. Analysis of scientific literature and the problem statement

In Ukraine and in many industrially developed countries RCM are recycled by its decontamination by smelting with the purpose of transfer of radio nuclides from metal to slag. In comparison with the “classical” methods of decon-

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tamination, a substantially smaller volume of radioactive wastes is sent to burial by this approach and conditions are created for the return of metal to the industry. For example, the [3] demonstrates that by a special selection of slags and application of the method of dual smelting of radioactive metallic wastes in the induction furnaces, ingots of steels were obtained with radioactivity not exceeding background values (lower than 20 mR/hr). However, this method is fairly complex for implementation since it requires conducting the process in two different melting units, it is technologically complicated, energy intensive and it requires introduction of additional alloying elements to the process of smelting.

The paper [4] described the experience of melting metallic wastes, contaminated by the radioisotopes ^{54}Mn, ^{60}Co, ^{65}Zn, ^{90}Sr, ^{137}Cs, ^{63}Ni, in the furnace of alternating current in a special mode and with the use of decontaminating slags.

It was established that all ^{60}Co and its chemical analog ^{63}Ni are evenly distributed in the metal. The remaining radionuclides pass into slag or evaporate and precipitate on the filter.

The experience of recycling a radioactively contaminated steam generator of a reactor is presented in [5]. The metal, obtained after dismantling of the steam generator, which contained radionuclides ^{60}Co, ^{90}Sr, ^{238}Pu, ^{240}Pu, after chemical decontamination was smelted in the furnace. Residual specific activity of the ingots of stainless steel amounted to 1–4 Bq/kg with predominance of ^{60}Co. The ingots are sent for a temporary storage with the prospect of their return to steelmaking enterprises in 5–12 years as nonradioactive metal.

In [6], the results are given of the studies of deep decontamination of metallic radioactive wastes by the method of smelting in a vacuum–induction furnace. For cleaning metal from radionuclides, the slag of a special composition was used. The measurements displayed that in some ingots the amount of radionuclides of cobalt-60 and ruthenium-106 exceeded the norm. But the gamma radiation power from their surface did not exceed the background values.

The results of the first experiments on smelting metallic radioactive wastes are presented in [7]. The studies revealed that with the use of oxidizing slag, the metals contaminated by transuranic radio nuclides can be efficiently decontaminated by smelting. However, this scheme of recycling is characterized by great complexity and it did not lead to proper development.

A continuously operating fuel-oxygen melting unit "MAGMA" is proposed in [8]. A technology of pyrometallurgical decontamination of large masses of metallic radioactive wastes is used. The project is characterized by complex technology and the melting unit is equipped with numerous additional systems. It has not been put to practice until now.

The [9] presents a method of complex recycling of solid radioactive wastes, including metallic, by the method of melting in the electric furnace of direct current. Partial decontamination of metal is achieved by using special features of the furnace and by physical-chemical properties of the main radionuclides.

At the enterprise "EKOMET-S" (Sosnovy Bor, Russia), a method of smelting is used at the final stage of the process of recycling metallic wastes, contaminated by radioactive substances [10]. An obligatory element of the recycling technology is preliminary decontamination of metallic raw materials before the melting. The end product is ingots, which are sent to metallurgical enterprises for the manufacture of products as the second raw material.

This technology is argued to make it possible to return a larger part of the contaminated metal after cleaning to industrial application for unlimited use. The resulting second radioactive wastes, whose amount do not exceed 10 % of the initial amount of contaminated metal, are transferred to ecologically safe form, suitable to transport and bury.

The main stages of the technology in question are radiation control, sorting, fragmentation, decontamination and smelting. This technology requires mandatory preliminary decontamination of metallic raw materials by classical methods, the application of refining fluxes that facilitate the transfer of radionuclides to slag, special mode of melting. All this decreases the efficiency of the process of recycling contaminated metal and makes it economically unprofitable.

As can be seen from this survey, existing difficulties of technological and economic nature do not make it possible to successfully solve the problem of reducing the volumes of accumulated radioactive wastes.

In the analysis of existing technological solutions, based on the method of smelting, and the experience of operation of melting furnaces, the following fact is worth attention: with all this variety of proposed approaches, the removal of radionuclides from melting metal is always present. More to the point, as shown in the works [11, 12], in blast furnaces natural radionuclides, put to the furnace with the charge materials, are concentrated essentially in such products of melting as slag and gas-aerosol emissions, increasing by this the radiation purity of smelted cast iron. In this case, a gamma radiation level from the surface of ingots of cast iron is always substantially lower than the forecast. This testifies to the fact that the known approaches do not fully take into consideration the influence of effects that occur during melting of metallurgical raw material, contaminated by radionuclides.

The method of smelting is used in them for decreasing the amount of radionuclides in the volume of metal. This respectively leads to the decrease in intensity of IR, emitted by the metal. However, it is necessary to take into account that during the melting, the conditions of transfer of this emission to humans also change. The metal itself, in which IR created by the remaining radionuclides spreads, is the medium that substantially decreases its intensity. This also increases the safety level of smelted metal and creates conditions for its repeated use.

Thus, there appears a need for a more in-depth research of the processes that occur during the melting of RCM. This will make it possible to use the obtained results for further development of the technology of RCM recycling, suitable for its efficient large-scale practical application.

3. The purpose and objectives of the study

The purpose of the presented study is development of the technology of recycling of radioactively contaminated metal by its melting.

To achieve the set goal, the following tasks were to be solved:

– to conduct the analysis of behavior of radionuclides in the furnace during the RCM melting;

– to examine the nature of ionizing radiation on the surface of the metal that contains radionuclides;

– to develop for practical application a method of the calculation of gamma radiation power on the surface of the metal that contains radionuclides;

– to develop for practical application a method of the calculation of permissible amount of the gamma emitting radionuclides, which can be loaded to a melting furnace.

4. Methods of the study of influence of melting radioactively contaminated metal on the efficiency of its recycling

At the National Metallurgical Academy of Ukraine (Dnepropetrovsk) they conduct theoretical studies of the possibility of recycling radioactively contaminated metal by its melting in metallurgical furnaces [13–15].

4. 1. Analysis of behavior of radionuclides in molten metal

The melting of metal in a furnace is carried out at the temperature around t_m=1600 °C and with intensive stirring of metallurgical raw material. Besides the metal, the products of melting are also slag and gas-aerosol emissions.

Molten metal is a liquid that contains nonmetallic inclusions. Those inclusions, whose density is below the density of metal, and the radioisotopes contained in them, float and pass to slag. The results of the studies, given in [15], show that a substantial part of the radioactivity contained in the charge passes to slag.

Along with the charge, those radionuclides can be loaded to the furnace, the boiling point of which is lower than the temperature of the melt (for example, potassium-40, strontium-90, cesium-137, iodine-131). These radionuclides can evaporate from the melt.

The [15] demonstrated that a substantial part of radionuclides of natural origin, which are found in the furnace, in the process of melting pass to a powder-gas phase, thus decreasing their amount in the smelted cast iron.

Therefore, the process of melting leads to partial removal of the radionuclides that contaminated the metal. The radionuclides that remained in the metal are distributed evenly in its volume. First of all, cobalt-60 [2], whose boiling point at 2255 °C exceeds the temperature in the furnace while its density is higher than the density of iron, remains in the metal.

4. 2. Characteristic of ionizing radiation on the surface of the metal that contains radionuclides

The presence of radioactivity in a metal does not indicate the magnitude of the danger connected with it. Dangerous is the ionizing radiation, created at the decay of radionuclide that directly contacts a human. Each radionuclide can be represented as an elementary source, which creates one of the types of IR: gamma radiation, the flow of alpha-particles and the flow of beta-particles. In metal, electromagnetic gamma radiation can spread to a distance of several centimeters. Consequently, the limits of metal products can be exceeded by gamma radiation only of those radionuclides, which are located in the near-surface layer of the metal. Since the path length of beta-particles in metal is not longer than the units of millimeter, and of alpha particles – tens of micrometers, then these forms of ionizing radiations are completely absorbed in metal and do not exceed its limits [16].

Being located inside the metal products, which are a solid substance with high density, radionuclides are rigidly fixed. This excludes the possibility of their output into environment and, therefore, they no longer can be the source of internal irradiation of people. Thus, a metal with the radionuclides located in its volume is a gamma-ray emitter. Therefore, for biological objects it can be dangerous only as the source of external irradiation and all protecting measures must be carried out taking into account this circumstance.

4. 3. Methods of estimation of gamma radiation power on the surface of the metal that contains radionuclides

The gamma-emitting radionuclides, which passed during the process of melting from the surface of contaminated metal inside it, form a homogeneous volumetric source of ionizing radiation. Each of such a radionuclide is an elementary isotropic emitter. The totality of all such radionuclides forms a radiation field both inside and on the surface of a molten metal. In this case, the source of IR is a semi-infinite radiating space, the boundary of which is one of the surfaces of the metal. In accordance with [16], the power of IR on this surface is determined by the activity of gamma-emitting radionuclides that are contained in the metal.

Metal is the absorbing medium for gamma radiation. The further from the surface the elementary emitters are, the smaller part of radiation energy created by them reaches the surface. Thus, radiation of not all radionuclides participates in the creation of field on the surface of metal. The gamma radiation of only a small part of the radionuclides located in the smelted metal is beyond its border. The gamma radiation of the remaining radionuclides, as well as alpha radiation and beta-radiation, are fully absorbed by metal. As a result, the process of melting led to a considerable decrease in the power of ionizing radiation on the surface of metal. That is why this effect can be named the self decontamination of metal during its melting.

A quantitative assessment of the power of gamma radiation on the surface of metal can be performed based on the approach, presented in [17]. Let us assume that a melt has the form of parallelepiped of the length l, with the area of one of the sides S (Fig. 1).

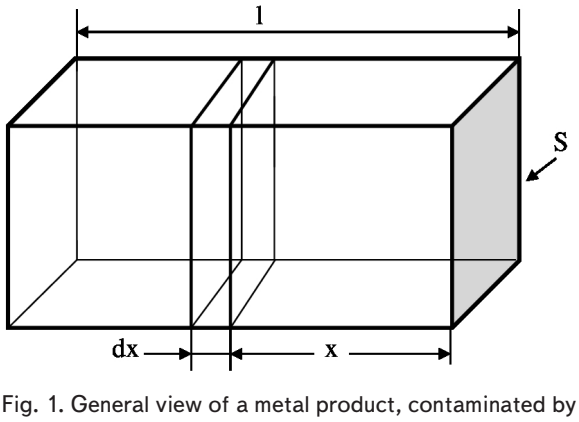

Fig. 1. General view of a metal product, contaminated by radionuclides: l is the thickness of the product; dx is the thickness of elementary layer, m; S is the surface area of the front plane, m^2; x is the distance from the plane S, m

Let us highlight elementary layer dx in the thickness of the product at the distance x from its front plane S. The contribution of this layer to the radiation power on the plane S with regard to the attenuation, caused by radiation ab-

sorption in the volume of the product, is determined by the expression:

$$dP = P_i \cdot \exp(-\mu x)dx, \quad (1)$$

where $P_i = \frac{P_0}{l}$ is the power, radiated by elementary source, Gr/s; P_0 is the power, created by all elementary sources, Gr/s; μ is the coefficient of attenuation of radiation in metal, 1/m; l is the thickness of the product, m; dx is the thickness of elementary layer.

The total power of radiation P_t on the plane S, taking into account attenuation of radiation in metal, is determined by the expression:

$$P_t = \int_0^l \frac{P_0}{l} \cdot \exp(-\mu x)dx = \frac{P_0}{l} \cdot \frac{1-\exp(-\mu l)}{\mu}. \quad (2)$$

Taking into account the exponential character of the dependence of the level of absorption of radioactive radiation in the thickness of metal, the coefficient of attenuation μ can be written down in the form:

$$\mu = \frac{\ln 2}{l_{0,5}} = \frac{0,693}{l_{0,5}}, \quad (3)$$

where $l_{0,5}$ is the half-value layer of radioactive radiation, m.

Taking into account (3), the expression (2) takes the form:

$$P_t = \frac{P_0 \cdot l_{0,5}}{0,6931} \cdot \left(1 - \exp\left(\frac{-0,6931}{l_{0,5}}\right)\right). \quad (4)$$

The expression (4) acquires maximal value when the length of the product l considerably exceeds the half-value layer $l_{0,5}$:

$$P_t max = P_0 \cdot \frac{l_{0,5}}{0,6931}. \quad (5)$$

Fig. 2 displays a calculated dependence of the radiation power on the surface on the length of the product l.

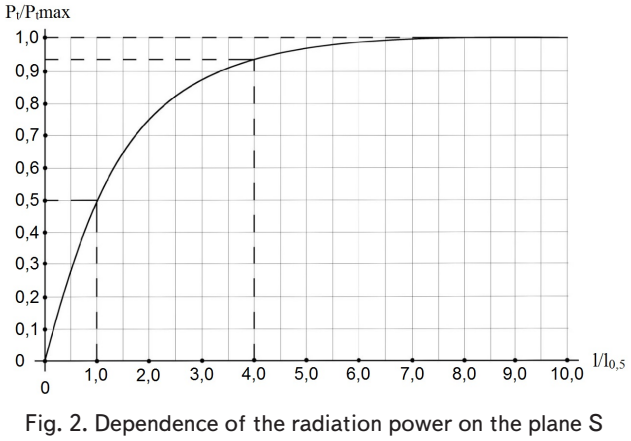

Fig. 2. Dependence of the radiation power on the plane S of the product on its length l: $P_t/P_t max$ is the power of radiation P, related to its maximal value $P_t max$; $l/l_{0,5}$ is the length of the product l, related to the thickness of half-value layer of the metal $l_{0,5}$

In Fig. 2 we see that whatever the dimensions of the product are, the radiation power on the surface S cannot exceed the value $P_t max$. Moreover, the main contribution to its value is added by those radionuclides, which are located in the near-surface layer of the thickness approximately $4l_{0,5}$.

Applying the expression (5), let us introduce into consideration the concept of "coefficient of self decontamination" K_{sd}:

$$K_{sd} = \frac{P_0}{P max} = \frac{0,6931}{l_{0,5}}.$$

This coefficient shows by how many times the power of gamma radiation on the surface of the product of the length l is less than the total power of radiation of all radionuclides, which are found in this product.

4. 4. Methods of calculation of permissible amount of activity of the gamma-emitting radionuclides, loaded in a melting furnace

The total activity of the gamma-emitting radionuclides put to the furnace must be such that the power of gamma radiation from the surface of the finished metal products does not exceed a certain value P_{adm}.

A quantitative connection between the power of gamma radiation on the surface of the metal P_t and the activity of the gamma-emitting radionuclides evenly distributed by its volume V takes the form [16]:

$$P_t = \frac{2\pi \cdot A_0 \cdot K\gamma}{\mu \cdot V}, \quad (7)$$

where A_0 is the total activity of gamma-emitting radionuclides in metal, GBq; Kγ is the ionizing gamma-constant of radionuclides, (mkSv·m^2)/(h·GBq).

Hence, by the known power of gamma radiation on the surface of the metal P_t, it is possible to determine the activity of the metal product:

$$A_0 = P_t \cdot \mu \cdot \frac{V}{2\pi \cdot K_\gamma}. \quad (8)$$

This is the total activity of the gamma-emitting radionuclides, which were located on the surface of the contaminated metal and were put to the melting furnace. Consequently, to provide the desired value P_{adm}, the activity put to the melting furnace must not exceed the value:

$$A_{adm} = P_{adm} \cdot \frac{\mu \cdot V_s}{2\pi \cdot K_\gamma}, \quad (9)$$

where V_s is the volume of the metal molten in the furnace, m^3.

RCM is, in accordance with the classification, the source of open type IR, the radioactive substances (RS) from which can enter the environment. These RS are located on the surface of a metallic object. Attaching RS on this surface usually happens by confinement of the particles on the rough, porous, uneven surface, and also owing to physical-chemical interaction with the metal, diffusion inside its surface, etc. This surface contamination is extremely uneven due to the action of numerous and diverse factors. All this substantially hampers, with the use of RCM as the charge, a possibility of loading a controlled amount of activity to the melting furnace. In practice, quantitative

measurement and identification of radioactive elements is conducted by the intensity of radiation [17]. The only accessible method of evaluating the contamination of open surfaces is the measurement of power of exposure dose P, (mSv/h), with subsequent determining the density of radioactive contamination of the surface A_s, (GBq/m^2), since these values are interconnected by a linear dependence, on the indicative ratio [17]:

$$A_s = K_r \cdot P, \quad (10)$$

where K_r is the conversion factor, (GBq/m^2)/(mSv/h).

The metal intended for recycling is divided into fragments before transportation and loading to a melting furnace. The level of contamination of different fragments by radionuclides differs significantly from each other. During the arrangement of fragments in a transportation vehicle or at their storage, the IR created by them is mutually screened, which makes it practically impossible to determine a real amount of activity in the given batch of scrap metal.

Determining the value of general activity of the contaminated metallurgical raw material must be conducted before its fragmentation. The measurement is carried out of the radiation power P_i on the i-th section of the object intended for scrap metal, the activity A_{Si}, the area S_i of contaminated surface of this section and its mass M_i are evaluated. As a result, the activity of the i-th section:

$$A_i = A_{Si} \cdot S_i = K_r \cdot P_i \cdot S_i. \quad (11)$$

As a result, the total activity of the object divided by N identical in area ΔS sections is:

$$A_0 = \sum_{i=1}^{N} A_i = K_r \sum_{i=1}^{N} P_i \cdot \Delta S. \quad (12)$$

Taking into account that the total area of the surface contaminated by radionuclides is S=ΔS·N, the ratio (12) is represented in the form:

$$A_0 = K_r \cdot S \cdot \left(\sum_{i=1}^{N} \frac{P_i}{N} \right). \quad (13)$$

Bracketed expression is the mean value of the power of gamma radiation P_m on the surface of the contaminated metal with the area S.

Finally:

$$A = K_r \cdot S \cdot P_m. \quad (14)$$

Consequently, determining the amount of activity, put to a melting furnace, comes down to determining the mean value of the power of gamma radiation P_m on the surface of contaminated metal and the area of contamination S.

The mass of the charge M_c, contaminated by radionuclides, is defined in the same way:

$$M_c = \sum_{i=1}^{N} M_i, \quad (15)$$

which must not exceed the capacity of the melting furnace M_s.

5. Results of the study of influence of the process of melting of radioactively contaminated metal on the efficiency of its recycling

Let us examine potential of the proposed technology of RCM recycling on the example of using existing electrometallurgical furnaces operating in normal mode.

Let us accept that the mass of molten metal with the mass M_m=150 t. At the specific mass of metal ρ_M= =7,86 g/cm^3, its volume:

$$V_m = \frac{M_m}{\rho_m} = \frac{1{,}5 \cdot 10^8 \text{ g}}{7{,}86 \text{ g/cm}^3} = 19 \cdot 10^6 \text{ cm}^3. \quad (16)$$

Let the melt have a form of cube. Then its side:

$$l = V_m^{\frac{1}{3}} = \left(19 \cdot 10^6\right)^{\frac{1}{3}} = 2{,}7 \cdot 10^2 \text{ cm}. \quad (17)$$

Energy of IR on the surface of metal is determined by the sum of gamma radiation energy of radionuclides in the volume of metal. The main contribution to the residual radioactivity of the ingots of metal is introduced by radioisotope cobalt-60, for which the half-value layer of gamma-radiation is $l_{0,5}$=1,6 cm [15]. In this case, in the considered example, the coefficient of self decontamination, determined by the expression (6), is:

$$K_{sd} = 0{,}693 \cdot \frac{270}{1{,}6} = 117. \quad (18)$$

Let us assume that the power of gamma radiation from the surface of the products made of steel, obtained after RCM melting, must not exceed the value P_{adm}=0,3 mSv/h. By using the expression (9), let us calculate the amount of activity of cobalt–60, which can be put to a melting furnace, for which μ=42 m^{-1}, K_γ=2·10^{-18} (Gr·m^2)/(s·Bq), then we will obtain:

$$A_{adm} = \frac{0{,}3 \cdot 10^{-6} \cdot 42 \cdot 19}{3{,}6 \cdot 10^3 \cdot 6{,}28 \cdot 2 \cdot 10^{-18}} = 5{,}3 \cdot 10^6 \text{ (kBq)}. \quad (19)$$

The specific activity of an ingot on the average comprises:

$$A_m = \frac{A_{adm}}{M_m} = \frac{5{,}3 \cdot 10^6}{150 \cdot 10^3} \cong 35 \text{ (kBq/kg)}. \quad (20)$$

The formula of connection between the mass of radionuclide and its activity takes the form [15]:

$$m = \frac{A_{adm} \cdot T_{0,5}}{0{,}693} \cdot \frac{M}{N_a}, \quad (21)$$

where m is the overall mass of radionuclide, g; M is the molar mass of radionuclide, g/mol; $T_{0,5}$ is the period of the half-life of radionuclide, s; N_a=6,02 · 10^{23}, mol^{-1} is the Avogadro number.

Taking into account that for radioisotope cobalt-60 M=59,93 g/mol, $T_{0,5}$=5,27 years, its mass will be:

$$m = 0{,}127 \cdot 10^{-3} \text{ g}.$$

It is necessary to indicate that this is the mass of the radioisotope cobalt-60, which was put to the furnace and remained in the smelted metal M_m=150 t.

6. Discussion of results of the research into the influence of the process of melting of radioactively contaminated metal on the efficiency of its recycling

The performed assessments of the possibilities of RCM recycling on the example of using electrometallurgical furnaces, operating in normal mode, indicate that due to the process of melting, the power of gamma radiation from the surface of metal decreases by tens – hundreds of times. During RCM melting, a substantial part of the radionuclides contained by it evaporates, and a part passes into slag, additionally removing radionuclides from the metal.

On the average, specific activity of RCM, used as the charge, lies within the range of values for the category of low-active solid radioactive wastes [18]. In the mass of all metallic radioactive wastes, the low-active wastes amount to 90 %, which offers possibilities for the recycling of enormous volumes of radioactive metal by the proposed technology.

The calculations, performed by the expression (21), display that in the smelted metal, the mass of radionuclides remained in it is vanishingly small and cannot influence physical-chemical and operation properties of the products made of this metal. In this case, the necessity to control the composition and specific activity of radionuclides, which are found in the metal, is also eliminated. No forms of processing of metal products (rolling, melting, cutting, etc.) can lead to the increase in the level of ionizing radiation from their surface.

The described processes are similar to how natural radiation background on the Earth's surface is formed. There is a large amount of natural radionuclides in the Earth's crust, which are the sources of all forms of ionizing radiation; however, the main contribution to the radiation background is introduced by gamma radiation of radionuclides, which are found in the upper layer of soil of the thickness to 0,5 m. The alpha- and beta-radiation, created by radionuclides, which are found in the soil, is completely absorbed by it. In contrast to metal, soil is not monolithic; therefore, radionuclides from it can enter atmospheric air (for example, gas radon), water, food, which can lead to the internal irradiation of people.

In the technologies, which use a method of smelting for obtaining production that can be used without limitations, from the metal contaminated by radionuclides, there are very rigid criteria. According to acting norms, established by the European Commission, residual specific activity in the smelted metal must not exceed the value of 0,4 kBq/kg [19]. That is why a preliminary decontamination of the surface of scrap metal is conducted before the smelting and the measures are taken to activate the transfer of radionuclides to slag. The control of residual specific activity in the melt is conducted obligatorily.

In the example examined earlier it was shown that the metal, safe in radiation sense, can be obtained by the activity of the gamma-emitting nuclides A_m=35 kBq/kg, which by many times exceeds the above-indicated criterion. Compliance with such an unjustifiably rigid norm forces to apply additional operations, which do not contribute to the increase in efficiency of the process of recycling.

As the products, made of RCM, are gamma-ray emitters, then the criterion of assessment of radiation safety of the smelted metal is the power of gamma radiation dose on its surface. For obtaining the metal, suitable for using without limitations, this power must not exceed the set standardized level.

It is proposed to melt RCM by this technology, excluding the stage of its preliminary decontamination and without application of additional measures, which facilitate the transfer of radionuclides from the melt to the metal. In the implementation of the examined approach, both the existing technologies of melting metal and the equipment of melting furnaces are not in fact complicated.

The proposed technology can also be used for recycling the constructions and elements of the nuclear reactors, whose operation term expired, that have high level of the induced activity under the effect of powerful neutron radiation. Along with the fact that the induced radioisotopes are the source of IR, the neutrons penetrating the metal can substantially change its properties.

The induced activity is created in the volume of metal; that is why usual methods of decontamination of its surface are not applicable in this case. Preliminary estimations reveal that the proposed technology of RCM recycling may not only secure the metal, activated in radiation sense, but also restore its mechanical and operating characteristics.

For the assessment of the possibility of technical realization of this approach to the recycling of RCM and the possibility of its large-scale implementation, presented theoretical positions require testing by conducting full-scale field experiments.

The main element of the complex for conducting the experiments is an induction steel-making furnace with the capacity of several tons, which has a number of advantages over other types of furnaces. Thus under the action of alternating current field, the warm-up of metallic fragments begins from their surface, which contributes to a more intensive evaporation of radionuclides and their removal into the gas path through the voids between the fragments of the charge. Under the action of alternating current field, the intensive stirring of the melt occurs. These processes help a more complete purification of metal from radionuclides.

The complex must have necessary radiometric instrumentation for conducting radiation monitoring at all stages of RCM recycling.

The section for the fragmentation of RCM down to the required mass-and-size parameters of the components of the charge must also be included in the set-up of the complex.

For the provision of radiation safety at all stages of RCM recycling and the prevention of possible additional radioactive environmental contamination, a number of measures must be executed. All necessary initial data for the evaluation of developing radiological situation are obtained by their measurements by radiometric instruments.

Along with metal, the melting products are the slag, contaminated by radionuclides, and gaseous emissions. To prevent the radioactive substances that accompany the production process from entering the atmosphere, a melting furnace must have reliable system of the filtration of emissions.

Preliminary analysis indicated that by obeying the rules for the treatment of RCM, the levels of exposure of production personnel do not exceed the norm.

7. Conclusions

1. The analysis of behavior of radionuclides in a melting furnace was performed. It was established that a part

of radionuclides contained by the melt of RCM passes into slag, some of them evaporate, and the remaining radioactive substances are distributed evenly in the volume of the furnace.

2. It was determined that of all types of ionizing radiation, created by radionuclides, which are located in the metal, its limits is exceeded only by gamma radiation.

3. During development of the method of estimation of the power of gamma radiation on the surface of metal, it was taken into account that metal is the absorbing medium for IR. As a result, beyond the limits of metal is the gamma-radiation of only a small part of the radionuclides contained by it.

4. The proposed method of calculation of permissible amount of activity of the gamma-emitting radionuclides, which can be loaded to a furnace, is based on the known quantitative connection between the power of gamma radiation on the surface of metal and the activity of the radionuclides contained in its volume. Consequently, determining the amount of activity on the surface of contaminated metal comes down to the measurement of the power of gamma radiation on this surface.

It was shown that the criterion of evaluation of radiation safety of the metal, smelted out of radioactively contaminated raw material, is the power of gamma radiation on its surface.

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