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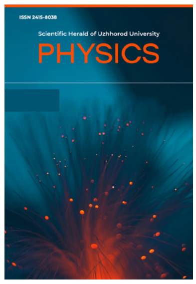

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Cobalt application in repair tools for maintenance and modernisation of NPP equipment

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Abstract

Relevance. The research discusses the actual risks that can arise from the formation of the radioisotope cobalt ^{60}Co from the stable isotope ^{59}Co during radiation neutron capture, which is specific to repair work at a nuclear power plant, but these risks are poorly understood.

Aim. The research aims to analyse the possibility of additional exposure to ionising radiation for the repair personnel of a nuclear power plant due to the use of a repair tool that may contain cobalt.

Methodology. The physical-theoretical and analytical approaches are used in the study.

Results. A certain risk has been identified as a result of the use of drills or other tools for cutting metal containing cobalt among the repair tools. The calculation (analysis) of the activation of a cobalt-containing drill bit showed that a drill bit weighing 500 g containing 8% of ^{59}Co in the tool steel acquires a partial activity (i.e., only cobalt activity) of 5.397×10^{-8} Ci, which leads to gamma radiation with an exposure dose rate of 0.024 mSv/year. The

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calculations of dose rates did not consider gamma radiation from the nuclear isomeric transition $^{60m}Co \rightarrow ^{60}Co$, which could only worsen the radiation risk picture (when considering other examples).

Conclusions. The use of a drill bit with the cobalt content specified in the calculations (or the location of the drill bit in the vicinity of the personnel), one way or another, contributes to the personnel exposure. It is proved that the calculation was not conservative, but rather liberal, because gamma radiation from the ^{60m}Co isomer was not considered, otherwise, the obtained numerical values would have been higher. A practical recommendation to prohibit or reduce the use of tools containing cobalt during repairs on nuclear power plant equipment was made, theoretically, given that the analytically justified need to study the issue of radiation safety is relevant and vital for the safety of NPP maintenance personnel

Keywords: radiation safety; ionising radiation; collective dose; exposure dose rate; gamma photons; drills; neutron energy

Introduction

When installing new equipment at a nuclear power plant (NPP), for example, installing new measuring instruments (including sensors) or additional process equipment (during modernisation), it is inevitable that a locksmith tool is required, and it is the choice of this tool that not everyone currently pays attention to.

At the same time, it is known that the bulk of the collective effective dose of ionising radiation is received by NPP personnel during scheduled and unscheduled outages. Therefore, radiation safety measures to reduce radiation doses should cover the organisation of work during scheduled outages (hereinafter referred to as SOC) (this applies to planning, preparation, execution and control) [1].

To this end, before the start of the outage, dose quotas for personnel involved in repair activities are established for each Ukrainian NPP unit [2; 3]. Preliminary forecasts of collective doses are developed based on the analysis of the radiation state of equipment of a particular nuclear reactor unit during previous outages, with future labour costs for outages to be considered.

Scientists and engineers in practical nuclear power plant operations around the world are finding cobalt in reactor room equipment and trying to reduce its impact on personnel. H. Ocken [4] discusses the feasibility of reducing the cobalt content in the metal of NPP equipment. This issue is also the subject of a joint study conducted by the Nuclear Energy Institute, Electric Power Research Institute and Nuclear Reactor Operations Institute (all US institutions), which resulted in recommendations and a strategy to reduce cobalt content in NPP equipment [5]. The team of authors of the Scientific and Technical Complex "Nuclear Fuel Cycle" of the National Science Centre of the Kharkiv Institute of Physics and Technology (KIPT) [6] proposes to use the Zn additive in the composition of the VVER-1000 primary coolant to reduce corrosion and delay diffusion of cobalt through the oxide film, reduce its release into the coolant medium, and thus reduce the level of radiation in the primary circuit and premises serviced during NPP operation, which demonstrates the urgency of the problem. Castiella Villacampa also considers the process of degradation of cobalt alloys in NPP equipment [7]. In its study, the Electric Power Research Institute (USA) also aimed to reduce radiation exposure to NPP personnel and identified cobalt in the first circuit equipment as one of the main sources of personnel exposure [8]. A team of Egyptian scientists generally suggests the use of cobalt-free steel [9]. However, it should be noted that almost all authors of publications in their studies do not pay attention to the issue of cobalt appearance due to the use of locksmith tools containing cobalt.

It should be noted that to date, there is no complete understanding of the processes of cobalt isotope ^{60}Co occurrence at the sites of repair work on the first circuit equipment, which is found among metal cutting waste since cobalt is not a component of alloys used in the flow part of the reactor equipment.

Based on the Law of Ukraine "On the Use of Nuclear Energy and Radiation Safety", radiation protection during the use of nuclear energy is based on the principle that the magnitude of individual doses, the number of people exposed and the probability of exposure to any type of ionising radiation should be the lowest that can be practically achieved, considering economic and social factors and based on the basic principle of state policy in the field of nuclear energy use and radiation protection: the priority of protection of people and the environment [10]. These two principles confirm the importance of this study.

In other words, a hypothesis was proposed that metal cutting tools with a significant cobalt content could lead to additional exposure of personnel during repair.

The research aims to investigate the possibility of additional (partial) risks of gamma photon exposure from the radioisotope ^{60}Co during repair at NPPs using metal cutting tools containing cobalt.

To achieve this goal, the following tasks were set and solved: analyse the ways of formation of the radioisotope ^{60}Co in the metal of the first circuit equipment; investigate the possibility of formation of the radioisotope ^{60}Co in metal cutting tools during repair work; quantify the possible additional radiation risk arising from repair work when using metal cutting tools containing cobalt.

Materials and Methods

The research object is a variety of metalworking tools (containing cobalt) used during scheduled maintenance of equipment in the reactor compartment of a nuclear power unit.

The study used publicly available data on the neutron-physical characteristics of the cobalt isotope ^{59}Co and public technical information on its content in some modern high-speed alloys.

To solve the tasks set and achieve the above goal, the physical and theoretical approach and analytical and computational methods of information processing were used.

The calculation was performed using the formulas listed below in the following order.

1. Concentration of cobalt atomic nuclei at the initial (zero) moment of ^{59}Co transformation into ^{60}Co according to the formula:

$$N_{59}^{\langle 0 \rangle} = \frac{N_A}{A_{59}}, \tag{1}$$

where N_A – Avogadro number, $\frac{1}{\text{mol}}$; A_{59} – molar mass ^{59}Co, $\frac{g}{\text{mol}}$.

2. The number of cobalt nuclides in the cutting tool by the formula:

$$N_x = m \times N_{59}^{\langle 0 \rangle}, \tag{2}$$

where m – bore mass, g.

3. The rate of formation of ^{60}Co in the tool is calculated by the formula:

$$I = N_x \times \sigma \times \Phi\,, \tag{3}$$

where σ – microscopic cross-section of activation of a stable cobalt isotope, barn; Φ – neutron flux density, which irradiates the contact element of the tool (drill bit), $\frac{neutr}{cm^2 \cdot s}$.

4. The number of cores formed during working hours according to the formula:

$$N_1 = t \times I\,, \tag{4}$$

where t – time during which the acquired activity of the cutting tool is exponentially reduced due to the decay of ^{60}Co accumulated during the contact of the tool with the equipment, s.

5. Activity of ^{60}Co at decay by the formula:

$$\mathrm{A} = \lambda_{\mathrm{p}} \times N_1\,, \tag{5}$$

where λ_p – constant isotope decay ^{60}Co.

$$\lambda_{\mathrm{p}} = \frac{\ln 2}{T_{1/2}}, \tag{6}$$

where $T_{1/2}$ – half-life, sec.

6. Exposure dose rate from gamma radiation by the formula:

$$P_\gamma = \frac{K_\gamma \times A}{R^2}, \tag{7}$$

where K_γ – ionisation gamma-ray constant. For ^{60}Co K_γ=2.5·10^{-18} $\frac{Cl \cdot m^2}{kg \cdot s \cdot Bq}$ or 12.9 $\frac{\mathrm{P} \cdot cm^2}{year \cdot mCi}$; A – activity, Ci; R – the distance of a person to the gamma-ray emitter source (worker – to the drill), (arm's length) is R=50 cm. Formal and logical methods of cognition, modelling methods, and methods of formal and logical interpretation of the content of scientific and regulatory categories and concepts were used to formulate conclusions. The potential risks of using locksmith tools at NPPs were identified using formal logistic methods and should be considered whenever it is possible to change the tools (negation and transition from quantity to quality – according to Hegel, general logistics). In this case, theoretically known variables were used, according to the above formulas, following professional knowledge in the field of nuclear energy.

Results and Discussion

At all stages of preparing and conducting the emergency response, dosimetric monitoring and radiation surveys are carried out on radiation-hazardous equipment following the recommendations[11].

Radiation exposure to maintenance personnel includes:

– radiation contamination;

– ionising radiation.

Radiation contamination can be both external and internal. It is the internal contamination of personnel that requires special attention, as it is the most dangerous for human health. When radioactive material enters the human body, it can be transferred to different areas (for example, to the bone marrow), where it continues to emit radiation. And even a small number of radionuclides inside the body exposes an employee to danger. One of these hazardous materials is the cobalt isotope ^{60}Co [12-14].

To further investigate the problem, it is necessary to assume that the radioisotope ^{60}Co is formed as a result of nuclear transformations in both the equipment of the first circuit and the metal cutting tool used in repairs at NPPs.

The contribution of radiation exposure of individual groups of the main equipment to the total collective dose received by personnel during NPP unit outages, for example, during outage 2020, on average at the State Enterprise "National Nuclear Energy Company (SE NNEGC) "Energoatom" was (approximately) 23% from the reactor unit, 6% from the main circulation pipeline, 4% from the main circulation pump, 17% from the steam generator, 1% from the pressure compensator, 11% from the cooling system, 6% from auxiliary systems of the reactor compartment, 4% from the SSC-1.2, and 2% from nuclear fuel (during overload) [15]. It is not difficult to calculate that the contribution of exposure from the main equipment during an outage is approximately 74%. The question arises as to what causes the remaining 26% of the collective dose.

The theoretical analysis, for the first time, unlike other scientific sources, confirmed that a component of radiation hazard is the risk associated with the radioactive cobalt isotope ^{60}Co, which can be formed by irradiation of the stable isotope ^{59}Co, which in turn occurs in the materials of the first circuit equipment as a result of nuclear transformations of iron and nickel, which are part of the 08(10)X18H10T steel:

– $^{58}Ni(n,p)^{58}Co$; $^{58}Co(n,g)^{59}Co$;

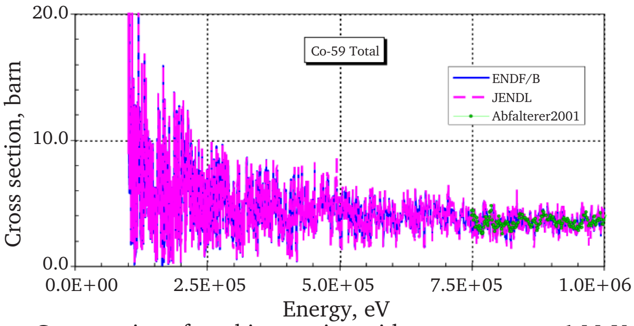
– $^{58}Fe(n,g)^{59}Fe$, ^{59}Fe (β-decay $T_{1/2}$=47 days)→ ^{59}Co.

This explains the appearance of the stable isotope ^{59}Co in the first circuit.

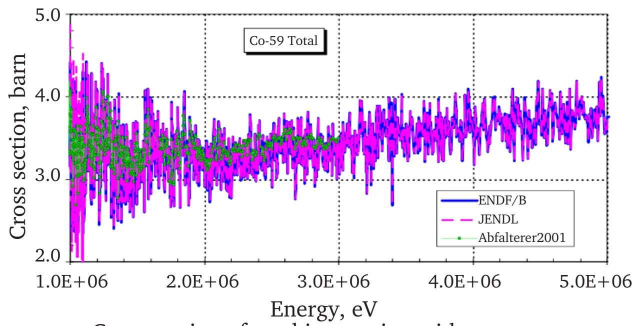
Due to the erosive wear of metal in the flowing part of the first circuit equipment, the coolant carries cobalt through the equipment and leads to its accumulation on the surfaces.

Neutron activation of ^{59}Co leads to the formation of ^{60m}Co and ^{60}Co isomers: $^{59}Co(n,g)^{60m}Co \rightarrow ^{60}Co$.

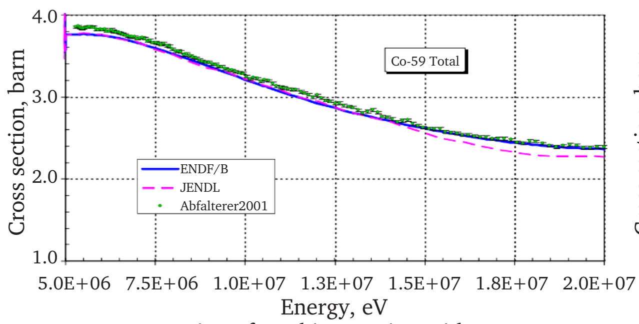
The physics and quantitative indicators of these nuclear transformations can be considered in detail. To date, two independent estimates are available: the estimates of the Smith and Desassières group (ENDF/B-VII) and the Watanabe estimate (JENDL-3.3). For example, Figure 1 shows the neutron-physical characteristics of radiative neutron capture by stable cobalt with its conversion into an unstable radioisotope [16; 17].



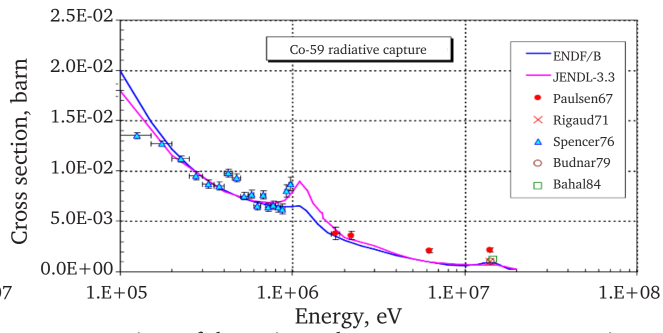
Cross section of total interaction with neutrons up to 1 MeV



Cross section of total interaction with neutrons from 1 MeV to 5 MeV



Cross section of total interaction with neutrons from 5 MeV to 20 MeV



Comparison of the estimated neutron capture cross sections at Co-59 in the energy sector above 100 keV

Figure 1. Neutron-physical characteristics of cobalt isotope ^{59}Co

Source: compiled by the authors based on [16; 17]

The neutron-physical characteristics indicate a significant microscopic cross-section of the activation reaction for low-energy neutrons [18].

The processes of activation of stable cobalt by neutrons occur both in the reactor (to a greater extent, due to the high fission neutron flux density) and in off-reactor equipment (to a lesser extent, due to the relatively low neutron flux density from radioactive contamination of the surfaces of the flowing part of the equipment). However, for fast and thermal (slow) neutrons, the reaction cross section is smaller than for thermal neutrons.

^{60}Co in the process of β-decay (half-life of 5.27 years) with transformation into ^{60}Ni is characterised by powerful non-monochromatic gamma radiation. Moreover, the ^{60}Co isomer is also a gamma emitter (its nuclear half-life is about 10 minutes).

These processes of ^{60}Co formation should be known in the practice of NPP operation, as they pose certain radiation risks, but no clear description of them could be found in the NPP literature. However, the study of the design and principle of operation of the so-called cobalt bomb [19] has led to what seems to be a more complete understanding of the formation of the ^{60}Co isotope. In other words, ^{60}Co in the first circuit, even after the reactor unit is shut down for a time-out, makes a significant contribution to the gamma background around the equipment being repaired. This is unavoidable, but radiation protection equipment for personnel performing repairs helps to reduce the collective dose.

At the same time, the study revealed that high-speed electromechanical tools are used to mechanise and accelerate repair operations with radioactive equipment at NPPs. The use of such tools is regulated, but the analysis did not reveal any prohibitions or restrictions on the use of replaceable (consumable) elements of high-speed tools (drills, mills, cutters, etc.) at NPPs.

The scientific and technical developments of new modifications of tool high-speed steels that have emerged in recent years strongly recommend increasing the cobalt content in steel, where it was not previously present in previous years’ designs [20-22].

Modern developments in metal cutting tools indicate that the cutting ability of martensitic steels is proportional to their cobalt content [23; 24]. Modern industry has mastered the production of appropriate tools in an attempt to improve the mechanical characteristics of tool steels, but the change in the neutron-physical properties of these steels was not considered.

It is known that at the end of the 20th century, drills were produced from high-speed steels of grades (e.g., P9; P18) (the number after the letter “P” determined the percentage of tungsten), while the amount of cobalt in those alloys was very small [25]. Such drills, which were designed to work with materials at nuclear power plants according to the projects of that time (due to the neutron-physical properties of the tool alloy), are almost impossible to find on sale today. Table 1 shows the content of some modern high-speed alloys.

Table 1. The content of some modern high-speed alloys, %

Steel grade / Contents	P9	P18	10X12K4V2DMFBR	10X9V2MFBR (P92)	P0M1F3	P6M5	P6M5F2K8	P9K5
C	0.85-0.95	0.73-0.83	0.1	0.07-0.1	1.10-1.25	0.82-0.90	0.95-1.05	0.9-1.0
Si	-	-	≤0.05	0.3-0.6	-	-	-	<0.5
Mn	-	-	≤0.05	0.54	-	-	-	<0.5
Cr	3.8-4.4	3.8-4.4	11.9	8.5-9.5	3.8-4.6	3.8-4.6	3.8-4.4	3.8-4.4
Co	-	<0.5	4.0	-	-	<0.5	7.5-8.5	5.0-6.0
Mo	<1.0	<1.0	0.59	0.51	2.3-2.9	4.8-5.3	4.6-5.2	<1.0
W	8.5-10.0	17.0-18.5	2.2	1.5-2.5	-	5.5-6.5	5.5-6.6	9.0-10.0
V	2.0-2.6	1.0-1.4	0.22	0.15-0.23	2.6-3.3	1.7-2.1	1.8-2.4	2.3-2.7
Nb	-	-	0.05	0.03-0.07	-	-	-	-
B	-	-	0.012	0.001-0.006	-	-	-	-
N	-	-	0.012	0.04	-	-	-	-
Al	-	-	≤0.05	≤0.013	-	-	-	-
Ni	-	-	0.065	0.21	-	-	-	<0.4

Source: compiled by the authors based on [25]

The data in Table 1 show that Ukrainian nuclear power generation companies are currently actively offering metalworking tools that contain cobalt in much higher amounts than traditional tools made of steel (e.g., P9; P18), which were intended for use in NPP repairs according to the design. Here is just one example of the actual situation regarding the possible use of a tool with significant cobalt content that may come into contact with equipment during NPP repairs.

For example, Ukrnichrome LLC lists Energoatom among its customer-consumers [26]. The product catalogue of this supplier of nuclear power plants includes products made of P9K5 tool steel, which contains an increased proportion of cobalt [27]. Sometimes, the grade of tool steel is unspecific or unclear, for example, foreign manufacturers mark drills with the abbreviation HSS (High-Speed Steel) and only the added letter "E" indicates that the steel contains cobalt [28; 29] or other markings, such as M42 [30]. In Ukraine, the technical specifications for tool steels harmonised with the European Union are in force and should be used as a basis for choosing a steel grade for industry [31]. Figure 2, for example, shows an image of drills made of HSS and HSS-E tool steel grades.

Figure 2. The appearance of modern drill bits with cobalt content markings. The letter "E" indicates that the steel contains cobalt

Source: [28]

For further computational analysis, derived data on the cross-section of the ^{59}Co radiative neutron capture reaction obtained mathematically from the Japanese Atomic Energy Agency, namely the above-mentioned JENDL-3, were selected and are selectively presented in Table 2.

Table 2. Cross section of the (n,γ)-reaction of ^{59}Co interaction with low-energy neutrons

Neutron energy, eV	$1.0\cdot10^{-5}$	$1.31\cdot10^{-5}$	$1.71\cdot10^{-5}$	$2.24\cdot10^{-5}$	$2.92\cdot10^{-5}$
intersection (n,γ) absorption, barn	1872.53	1634.54	1432.48	1250.41	1095.84

Source: compiled by the authors based on [17]

These calculated data complement the officially accepted graphical dependences shown in Figure 1 and show that for neutrons, the values of the microscopic activation cross-section of the stable cobalt isotope are large. An increase in neutron energy determines a relatively rapid decrease in the microscopic cross-section of the reaction. This situation is reflected in the calculated (extrapolated) graphical dependence shown in Figure 3.

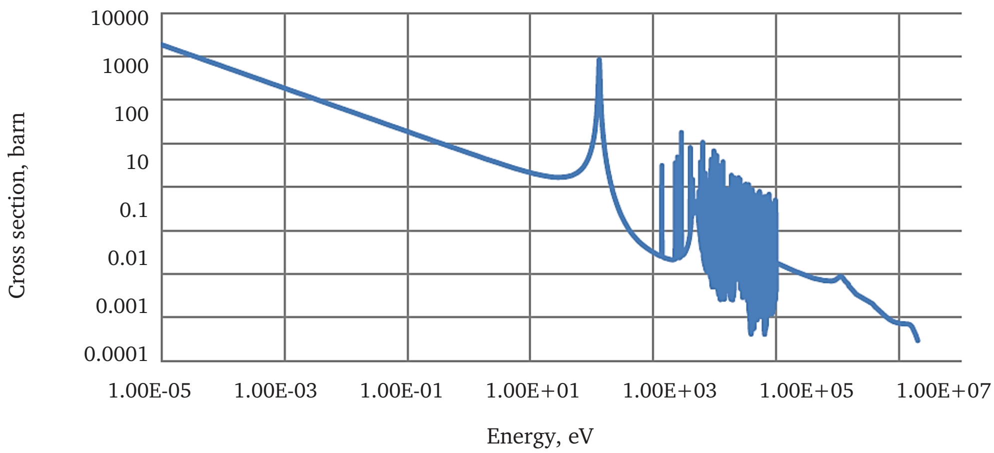


Figure 3. Dependence of the microscopic cross-section of neutron capture by isotope ^{59}Co from neutron energy

Source: compiled by the authors based on [17]

Thus, it can be considered appropriate to accept the value σ=1872 barn in further calculations. It should be noted that it would be desirable to accept the value based not on theoretical considerations but on field studies with empirical determination of the energy spectrum of neutrons coming from activated equipment under repair at NPPs.

The amount of stable isotope ^{59}Co nuclides in the volume of the drill bit element exposed to neutron irradiation with subsequent conversion to ^{60}Co was then determined. For this purpose, first, the mass of cobalt contained in a drill bit similar to those considered was approximately determined. We assume that the ^{59}Co content is 8%. If the mass of the drill is 500 g, then the mass of cobalt in such a drill is m=40 g.

The calculation was performed using formulas 1-7.

The concentration of cobalt atomic nuclei at the initial (zero) moment of ^{59}Co transformation into ^{60}Co is:

$$N_{59}^{\langle 0 \rangle} = \frac{6{,}022 \times 10^{23}}{58.993} = 1{,}021 \times 10^{22} \cdot 1/\text{gram}$$

Therefore, the cutting tool contains the following number of cobalt nuclides:

$$N_x = 40 \times 1{,}021 \times 10^{22} = 4{,}084 \times 10^{23} \cdot \text{nuclei}$$

Let us consider a hypothetical case of neutron irradiation of stable cobalt. In a shutdown reactor, the neutron flux density is estimated to be 10^{-9} of the nominal value. The average neutron flux density in the core is $5.8 \times 10^{13} \frac{neutr}{cm^2 \cdot s}$ [32]. Therefore, for further calculations, $F = 5.8 \times 10^4 \frac{neutr}{cm^2 \cdot s}$ is assumed. The refinement can be made by direct measurement. In this case, the rate of ^{60}Co formation in the tool will be:

$$I = 4{,}084 \times 10^{23} \times 1872 \times 10^{-24} \times 5.8 \cdot 10^4 = 4{,}434 \times 10^7 \ \frac{nuclei}{s}$$

For example, we calculated the activity that will be acquired during the use of the drill for 3 hours of working time. Thus, if the irradiation time of the drill is 3 hours (10800 s), then multiplying by the rate of nucleation of ^{60}Co, we will get the number of nuclei formed during 3 hours of working time:

$$N_1 = 10800 \times 4{,}434 \times 10^7 = 4{,}789 \times 10^{11} \text{ nuclei}$$

This number of nuclei corresponds to the decay activity of ^{60}Co:

$$\lambda_{\text{p}} = \frac{ln\,2}{1{,}663 \times 10^8} = 4{,}169 \times 10^{-9} \ \cdot c^{-1}$$

Thus, the activity of the drill, after substituting numerical values into formula (5):

$$A = 4{,}169 \times 10^{-9} \times 4{,}789 \times 10^{11} = 1{,}997 \times 10^3 Bq = 5{,}397 \ \times 10^{-8}\ Ci$$

The obtained numerical estimate is an approximate value of the activity, which characterises the amount of ^{60}Co isotope accumulated in the instrument during 3 hours of repairs using it.

Next, let's estimate the exposure dose rate from gamma radiation, considering the ionisation gamma constant of ^{60}Co, based on the definition of the gamma constant and its physical meaning:

$$P_\gamma = 12.9 \times \frac{1000 \times 5{,}397 \times 10^{-8}}{50^2} = 2{,}785 \times 10^{-7} \ \frac{\text{P}}{year} = 0.024 \frac{mSv}{year}$$

The calculation of the activation of a cobalt-containing drill bit showed that a 500 g drill bit containing 8% ^{59}Co in the tool steel acquires partial activity (i.e., only cobalt activity) Ci, which leads to gamma radiation with an exposure dose rate of 0.024 mSv/year (with a limit of 20 mSv/year for category A personnel, according to NRBU-97/2000 [33]).

Receiving this dose may not seem significant but using a drill with the cobalt content specified in the calculations (or having the drill near personnel) also contributes to personnel exposure.

The calculation was not conservative; gamma radiation from the ^{60m}Co isomer was not considered, otherwise the values obtained would have been higher.

Nevertheless, the results obtained, although they should be considered approximate and preliminary, indicate the existence of a real (greater or lesser) risk due to the use of cobalt-containing drills among the tools. The results obtained can only be clarified by conducting full-scale experimental studies on NPP equipment. However, it is already possible to express concern and provide recommendations regarding the NPP repair work regulations – it is necessary to prohibit the use of drills, cutters, mills, etc. with cobalt in the steel in the tooling.

The issue of additional cobalt formation in NPP equipment is currently poorly understood, so the authors cannot rely on facts and studies on this problematic issue, but the assumption was made by NPP engineers during an oral discussion at the seminar of the NPP Department, National University "Odesa Polytechnic": that cobalt, which is a gamma-ray emitter and is present in cutting sawdust during repairs, is formed in the steel materials of circuit 1 equipment.

The emitter described in this study is formed as a result of neutron activation of iron (as well as cobalt and nickel) in steel structures.

Ukrainian physicist, expert in the field of radiation physics and nuclear safety, Doctor of Physical and Mathematical Sciences, Corresponding Member of the National Academy of Sciences of Ukraine V.M. Voevodin paid much attention to the study of radiation damage to structural materials in his studies [34; 35].

Analysing the studies of R. Rumbu and F. Crundwell, the results obtained in the study are consistent [36; 37]. The study [36] states that Cobalt is a hard, ductile, shiny bluish-grey metal, that belongs to heavy metals. Cobalt is an element of the side subgroup of the eighth group of the fourth period of the periodic table of chemical elements of D.I. Mendeleev, atomic number 27. It is denoted by the symbol Co (Latin cobalt). The name of the chemical element cobalt comes from it. Kobold means a housekeeper, a gnome. The burning of cobalt minerals containing arsenic releases volatile, poisonous arsenic oxide. The ore containing these minerals was named Kobold by miners as the mountain spirit. In 1735, Swedish mineralogist Georg Brand managed to isolate a previously unknown metal from this mineral, which he named cobalt. Cobalt has only one stable isotope, Co-59.

The study [37] proved that the “stellite” alloy, which is now used as a traditional metalworking tool alloy containing 35% cobalt, the same amount of chromium, 15% tungsten, 13% iron and 2% carbon, which has a high hardness, is used to make cutter tips, drills, bits, etc. Superhard alloys (“pobedit”, etc.) containing 78% to 88% tungsten, 5% to 6% carbon and 6% to 15% cobalt, which is cobalt-cemented tungsten carbide, which retains its hardness even at temperatures up to 1000°C.

A study [35] shows that cobalt alloys were developed in the early 1990s by Elwood Haynes in the United States in search of a material that was resistant to aggressive environments and had sufficient strength and hardness at high temperatures. The study also found that alloying P911 steel with cobalt significantly increases creep resistance. The time to fracture increases by 4 times at a test temperature of 650°C and applied stresses from 100 MPa to 200 MPa.

At the same time, the analyses presented in the study revealed that there are certain risks relevant to NPP maintenance activities when using tools containing cobalt. Further discussion of the published materials in the article will be useful for understanding the technological processes and physics of material behaviour to improve the safety of repair work at Ukrainian NPPs.

Conclusions

Based on the analysis and numerical results obtained, the possibility of additional (partial) risks of gamma photon exposure from the radioisotope ^{60}Co during repair work at NPPs was confirmed. The hypothesis put forward at the beginning of the study was confirmed analytically.

It is necessary to consider that, firstly, there is a likely risk associated with the radioactive cobalt isotope ^{60}Co, the formation of which is associated with the activation of materials of primary circuit equipment, and decay is associated with the formation of powerful cascade non-monochromatic gamma radiation from process equipment, in the steel of which this isotope can be formed. Secondly, in addition to primary circuit equipment, this isotope may be formed in metal cutting tools that may come into contact with activated primary circuit equipment during repairs of NPP equipment. Such tools include drills, cutters, milling cutters, etc., which may contain cobalt ^{59}Co, which, when activated in the process of contact with the equipment, is converted into radioactive ^{60}Co.

Based on the results of the study, recommendations can be made to ban the use of drills, cutters, milling cutters, etc. with cobalt in the steel alloy during repairs on the equipment of the first circuit NPP. At the very least, this should be understood as a wake-up call to the scientific community.

The obtained scientific results are the first step of the research and can be clarified and supplemented by the scientific community through further experimental studies.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgement

None.

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Використання кобальту в ремонтному інструменті при забезпеченні роботи та модернізації обладнання АЕС

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Анотація

Актуальність. У статті розглянуті актуальні ризики, що ймовірно виникають внаслідок утворення радіоізотопу кобальт ^{60}Co із стабільного ізотопу ^{59}Co при радіаційному захоплені нейтронів, що є специфічним під час ремонтних робіт на атомній електростанції, проте ці ризики є мало вивченими.

Мета. Метою проведеного дослідження був аналіз можливості додаткового впливу іонізуючої радіації на ремонтний персонал атомної електричної станції, внаслідок використання слюсарного інструменту, який в своєму складі ремонтного інструментарію, може містити інструментальний кобальт.

Методологія. У статті використаний фізико-теоретичний та аналітичний підхід для проведення дослідження з'ясованої проблеми.

Результати. Визначено наявність певного ризику внаслідок використання серед ремонтного інструментарію свердл чи іншого інструменту для різання металу із вмістом кобальту. Проведений розрахунок (аналіз) щодо активації свердла зі вмістом кобальту показав, що свердло масою 500 г, яке містить в інструментальній сталі ^{59}Co в кількості 8 % по масі, набуває парціальну активність (тобто лише активність кобальту) $5{,}397\times10^{-8}$ Ки, що призводить до гама-випромінювання, потужність експозиційної дози якого досягає 0,024 мЗв/рік. В проведених розрахунках дозових показників не враховувалося гама-випромінювання

при ядерному ізомерному переході $^{60m}Co \rightarrow ^{60}Co$, що могло б тільки погіршити картину радіаційного ризику (при розгляді інших прикладів).

Висновки. Було зазначено, що використання свердла зі зазначеним (в розрахунках) вмістом кобальту (чи знаходження свердла неподалік від персоналу), так чи інше, робить додатковий внесок в опромінення персоналу. Доведено, що проведений розрахунок був не консервативним, а скоріше ліберальним, бо гама-випромінювання від ізомеру ^{60m}Co не враховувалася, інакше отриманні числові значення розрахунків були б більшими. Була надана практична рекомендація щодо заборони чи зменшення використання при проведені ремонтних робіт на обладнанні атомної електростанції інструментів, у складі яких міститься кобальт, теоретично зважаючи на те, що аналітично обґрунтована необхідність вивчення питання радіаційної безпеки є актуальною і життєвоважливою для безпеки-ремонтного персоналу АЕС

Ключові слова: радіаційна безпека; іонізаційне випромінювання; колективна доза опромінення; потужність експозиційної дози; гама-фотони; свердла; енергія нейтронів