

This paper reports an alternative technique for producing a source of hard gamma radiation with the ^{60}Co isotope for the proposed device for radioactive irradiation of birds, which is also innovative in providing for ornithological aircraft flight safety. However, the high cost of producing a ^{60}Co radionuclide source with activity sufficient to irradiate bird pests with a lethal or sterilizing dose poses a serious challenge. A solution to the problem of reducing the cost of a ^{60}Co radionuclide source can be an alternative technique of its production outside the reactor.

The results are characterized by the following features and distinctive peculiarities that make it possible to solve the problem under study:

– an irradiation device with the radioactive isotope ^{60}Co causes a lethal or sterilizing effect. This is much more effective in ensuring ornithological safety of aircraft flights compared to known methods of scaring away birds of prey, but is harmless to humans;

– the production of ^{60}Co radionuclide for the irradiation installation is carried out by thermal diffusion heating, which significantly reduces the cost of the source compared to the well-known methods of its production in a reactor and accelerator.

The results obtained could find practical application in the field of civil aviation for ornithological flight safety, subject to compliance with national and international legislation. In addition, the proposed technique of manufacturing a ^{60}Co radionuclide source, in addition to aviation ornithology, may find application in other sectors of industry, economics, and agriculture

Keywords: aviation ornithology, civil aviation, ionizing radiation, radionuclide source, radiation dose

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DEVISING AN ALTERNATIVE TECHNIQUE TO MANUFACTURE A RADIOISOTOPE SOURCE OF ^{60}Co FOR IRRADIATION DEVICE TO ENSURE ORNITHOLOGICAL SAFETY OF AIRCRAFT FLIGHTS

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1. Introduction

Under modern conditions, scientific research into effective ways to combat birds that pose a danger to aircraft must be carried out for several reasons. First of all, the volume and intensity of air transportation are dynamically increasing; the threat of collision between aircraft and feathered pests is growing proportionally. At the same time, existing passive techniques of bird control demonstrate a certain effectiveness only the first few times, which is fully confirmed by the practice of any enterprise faced with this issue.

The results of the research may find application in aviation ornithology if the proposed method of radiation control of bird pests is adopted by airport airfield services. A radionuclide source produced outside the reactor and intended for lethal radurization of birds could find application in other areas of nuclear energy use.

According to the International Civil Aviation Organization, more than 5,000 bird strikes occur worldwide each year. This leads to various aviation accidents, including aircraft crashes due to engine failures, fuselage depressurization, or pilot injuries incompatible with aircraft control. To combat feathered pests, bioacoustics devices and repellents, laser and ultrasonic repellents, gas guns and many other devices are

used that do not lead to a lethal result visible to the birds. Modern techniques providing for ornithological safety of aircraft flights have now proven to be ineffective. Already for the second time, feathered pests cease to respond to the thunder of a gas gun, bioacoustic and ultrasonic vibrations. Laser repellents cause only short-term panic, which does not force birds to leave even the glide path zone, but at the same time they pose a threat to the life and health of aviation personnel and aircraft passengers when pilots are blinded.

If there is a suspicion of terrorist use of trained birds carrying explosive charges to commit acts of unlawful interference at an airfield, aviation security services may use lethal firearms. However, this also has a number of disadvantages, such as the impossibility of live firing at a civil aviation object on an ongoing basis, and a threat to the life and health of aviation personnel and aircraft passengers. In addition, it becomes difficult to identify the bone-feather remains of shot birds to analyze possible collisions and prevent them in the future.

Given the above, ornithological support and flight safety through the use of sources of ionizing radiation against bird pests in the take-off and landing zones of aircraft has undeniable technical advantages over traditional methods of bird control:

– the possibility of exposure to lethal or sterilizing doses, which actually reduces the number of birds and their nest-

ing sites within the required limits from the control point of the airfield;

- targeted exposure to high-energy radiation from a radionuclide source as a result of beam collimation based on the recognition signal of birds that pose a danger to aircraft by their silhouettes in flight and soaring;

- safety and integrity of the carcass of a bird of prey irradiated with a lethal dose, for less complex and more accurate identification compared to the analysis of bone and feather remains after the use of firearms or a collision with an aircraft.

The mechanism of action of the proposed radioactive irradiation device on birds is similar to a food radurizer [1]. It is supposed to be installed at the flight altitude of birds of prey above the airfield, up to 150 meters in the direction of aircraft takeoff, and about 60 meters along the direction of their landing. However, the most obvious disadvantage of using the proposed irradiation device is the high cost of the radionuclide source of hard ionizing radiation. In the practical application of a gamma ray source in industry, it is necessary to ensure that it emits a single (unsplit) gamma line with a width as close as possible to the natural one, while also having a high Debye-Waller factor (emission without recoil).

The issue of using an irradiation installation for ornithological flight safety should be tackled first by solving the problem of reducing the cost of manufacturing a radionuclide source of high-energy gamma radiation. A more accessible radionuclide source will find application not only in civil aviation but also in a number of other industries, economics, and agriculture, which is very relevant. In order to ensure reproducibility of the results, a detailed development of the technology for producing an industrial radionuclide source of ^{60}Co is necessary. The process of its out-of-reactor production includes the manufacture of a target, its irradiation in a cyclotron, electrochemical separation and purification of the radioactive drug, preparation of the substrate, electrolytic deposition of radioactivity onto the substrate, and cleaning the substrate surface from non-diffused ^{60}Co .

2. Literature review and problem statement

Scientists and aviation safety experts are tracking the dynamics of bird pest collisions with various types of aircraft and examining the details of aircraft accidents involving birds. Thus, in [1] an assessment was made of the damage to the survivability of the aircraft from damage to the engine, wing, windshield, tail, nose, and other parts of the fuselage as a result of bird strikes. In addition, the authors of [1] deeply studied the vulnerability of aircraft engines of different types and manufacturers affected by birds. Taken together, the results of their work will serve as the basis for further research aimed at increasing the reliability of aircraft through design changes that can increase the resistance of aircraft to bird attacks. However, such passive methods of aviation protection from bird predators are rather passive, very expensive, and only possible in the long term.

Active methods of bird control, such as the use of thunder guns, bioacoustic, laser and other repellents not only in aviation but also in food enterprises, go back decades and have repeatedly proven their ineffectiveness. However, the alternative use of repellents not at airfields but directly on aircraft, as proposed in [2], can show higher effectiveness. The on-board thermal imaging system proposed by the authors for the detection of birds and their ultrasonic irradiation with electromagnetic waves with a frequency of 20–45 kHz, and then with a laser

device, really involves targeted and timely repelling of feathered pests. This is an absolute advantage over traditional techniques of periodically generating irritating factors automatically according to a given program. On the other hand, short-term exposure to electromagnetic waves with a frequency of 20–45 kHz, coupled with laser radiation, will be neither lethal nor sterilizing in nature, so the probability of a one-time effectiveness of the proposed on-board repellent system is high.

The idea of irradiating birds with ionizing radiation of corpuscular or electromagnetic origin arose on the basis of the food radurizer described in [3]. The authors confirmed that the collimated effect of ionizing radiation at various stages of growing raw materials, storing and procuring final food products significantly increases their yield, nutritional value, and shelf life. This suggests that radiation exposure of birds will cause reproductive sterilization or death. The duration of targeted irradiation of birds will depend on the activity of the radionuclide source, its distance from the irradiated object, and the magnitude of the lethal dose of radiation for it.

The use of a radiator similar to that described in [3] in the field of ornithological support for aircraft flights exclusively against birds not included in the Red Book requires their precise taxonomic identification by feather pattern or silhouette in flight and soaring. For this, the YoloV4 neural network presented in [4] or dense network models can be used.

Widespread use of a radioisotope device for ornithological support of aircraft flights will become possible if the price and technological availability of a radionuclide source improves, the choice of which will most likely fall on ^{60}Co . This radioisotope has a sufficiently high energy gamma radiation (1.3 MeV) to create a large, absorbed dose or kerma in a short period of time. The relatively short half-life of ^{60}Co (5.27 years) will necessitate periodic maintenance and recharging of the device with a radionuclide source. This will reduce the risk of radiation accidents caused by gate jamming, container or collimator falling out of the structure, and other reasons.

The most common technique for producing ^{60}Co is its production in nuclear reactors, as described in [5–7].

Thus, in [5], it was proposed to obtain ^{60}Co by the technique of neutron activation of the stable isotope ^{59}Co in a research reactor of the ETRR-2 type with a neutron flux trap built into the core. The trap, in turn, contains space to accommodate an irradiation chamber with a variable beam configuration. Despite the fact that the ETRR-2 reactor allows the production of ^{60}Co with a specific activity of more than 3 GBq/g, its induction time is very long (263 ± 14 days) and causes a high production cost for an ornithological irradiation installation.

Paper [6] reports improved production of high-level ^{60}Co with a more durable and trouble-free design in the ATR research reactor. The design of the DOE-IP capsule for cobalt production developed by the authors and manufactured at Oak Ridge National Laboratory (ORNL) can be adopted in the future if the radionuclide source matrix requires increased strength characteristics.

In [7], an innovative scheme for producing ^{60}Co in CANDU6 reactors (Canada) was proposed, which makes it possible to triple the operating time compared to earlier production methods. However, the disadvantage of the new scheme is an increase in the maximum power of the channel and a decrease in the safety margin of the reactors, which in turn again leads to an increase in the cost of production of the final radionuclide.

Thus, the prospects for using a radioisotope device for ornithological support of aircraft flights depend on simplifying the technique of producing the working radioisotope ^{60}Co

and reducing its cost. These questions remain open, however, without their solution, a detailed study of the design of an irradiation ornithological installation and a study of lethal radiation doses of various bird species are of dubious feasibility. Based on the foregoing, it is permissible to assert that devising an alternative technique of ^{60}Co production is a priority task in finding a solution to the problem of controlling feathered pests in the airfield area.

3. The aim and objectives of the study

The purpose of this study is to devise a simplified technique that is cheaper than traditional ones to obtain ^{60}Co for a radioisotope device for ornithological support of aircraft flights in the airfield area. This will make it possible to increase the effectiveness of the fight against feathered pests that pose a threat of collisions with aircraft in the glide path zone of the airfield.

To achieve the goal, the following tasks were set:

- to build a diagram of a radioisotope device for ornithological support of aircraft flights;
- to obtain a ^{60}Co radionuclide source of the required activity without using a nuclear reactor.

4. The study materials and methods

The object of our study is an out-of-reactor technique for manufacturing a radionuclide source of hard gamma radiation with the ^{60}Co isotope for establishing radioactive irradiation of birds over the airfield. Feathered pests threaten to damage engines, radar radomes, cockpit windshields, and other parts of aircraft, leading to aviation accidents.

The research hypothesis assumes that the radiation method of controlling birds in the glide path zone of an airfield should be more effective and safer compared to the use of traditional means of repelling them. This requires a radionuclide source that generates hard gamma radiation, such as ^{60}Co . The traditional production of ^{60}Co in a nuclear reactor is characterized by high cost, long duration, and technological inaccessibility, so the bird radiator requires ^{60}Co produced in a less expensive, faster, and more easily reproducible way.

During the research, the following assumptions and simplifications were accepted:

- the choice of radionuclide source was made in favor of ^{60}Co since this radioisotope has high gamma radiation energy (1.3 MeV) to create a large, absorbed dose or kerma in a short period of time. The short half-life of ^{60}Co (5.27 years) will necessitate periodic maintenance and recharging of the device with a radionuclide source. This will reduce the risk of radiation accidents caused by gate jamming, container or collimator falling out of the structure and other reasons;

- the off-reactor technique of producing ^{60}Co should begin with the electrolytic deposition of a nickel layer on a copper substrate for subsequent in-chamber irradiation in a cyclotron. A resonant cyclic accelerator of non-relativistic heavy charged particles in a high-frequency electric field is no more accessible equipment than a nuclear reactor. However, its use is necessary only for one intermediate stage of alternative production of ^{60}Co , which is supposed to be delegated to a specialized organization;

- separation of carrier-free quantities of ^{60}Co from gram quantities of nickel in the irradiated target is most appro-

priately accomplished by dissolving the nickel layer in an electrolytic bath using extraction chromatography;

- the use of thermal diffusion heating of a nickel plate with palladium foil deposited on it will make it possible to obtain a radionuclide source in the form of a matrix into which ^{60}Co will diffuse from a drop of electrolytic solution deposited on it.

The study was carried out using a theoretical model of an irradiation installation for ensuring the ornithological safety of aircraft flights, as well as experimental equipment for alternative production of a radionuclide source of ^{60}Co .

We also used in the study:

- an installation for radiochemical processing of irradiated nickel target;
- a chromatographic column for separating carrier-free amounts of ^{60}Co from gram quantities of nickel;
- electrolytic bath for isolating the ^{60}Co radioisotope and depositing it onto metal palladium foil;
- a device for thermal diffusion heating of a nickel plate with palladium foil to diffuse ^{60}Co into the substrate.

The experiments described provide in vitro reproducibility and validation of the proposed solutions. A certain technological complexity is only the intra-chamber irradiation of a nickel target on a cyclotron, and therefore a detailed description of this stage is not given in this paper.

A radioisotope device for ornithological support of aircraft flights will allow irradiating birds with a lethal dose of ionizing radiation, the time of receipt of which depends on the activity of the ^{60}Co radionuclide source and the distance from it to the bird.

The most common non-reactor technique for producing ^{60}Co is a method based on irradiation of nickel with protons accelerated in a cyclotron. As a result of nuclear reactions with protons on a nickel target of natural isotopic composition, in addition to ^{60}Co , the following radionuclides are also formed: ^{56}Co , ^{57}Co , ^{58}Co , ^{65}Zn , ^{56}Ni and ^{57}Ni .

The process of obtaining radioactive ^{60}Co from an irradiated nickel target consists of the following steps:

- production of nickel targets by electrolytic deposition of nickel onto copper substrates;
- intra-chamber irradiation of the target on a cyclotron. Irradiation of electrolytically deposited nickel targets in the internal chamber of a cyclotron using a target holder should be carried out in order to increase the specific and volumetric activity of the resulting radionuclide ^{60}Co ;
- exposure of the target to reduce radioactive trace impurities: ^{56}Co and ^{58}Co for 30 days;
- electrolytic anodic dissolution of the activated target layer;
- radiochemical separation of microquantities of produced ^{60}Co from chemical and radiochemical impurities;
- diffusion of ^{60}Co from a drop of electrolytic solution into the palladium matrix due to thermal diffusion heating of a nickel plate with palladium foil deposited on it.

5. Results of investigating an alternative technique for producing the ^{60}Co radioisotope for use in aviation ornithology

5.1. Construction of a circuit diagram for a radioisotope bird control device

The constructed diagram of a radioisotope bird control device is shown in Fig. 1. This device is intended for instal-

lation on the territory of an airfield at an altitude of up to 150 meters along the direction of aircraft takeoff and about 60 meters along the direction of their landing.

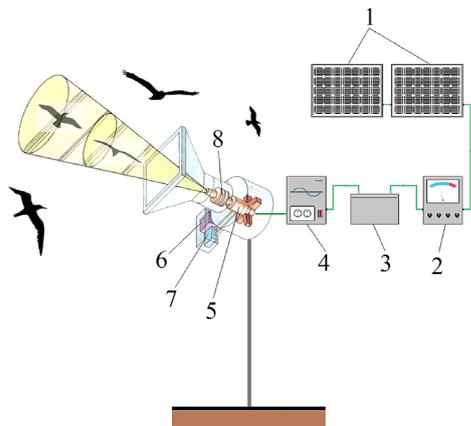


Fig. 1. Diagram of an irradiation installation for ornithological ensuring the safety of aircraft flights:

- 1 – solar panels, 2 – battery charge controller,
- 3 – battery, 4 – inverter - voltage converter, 5 – container with a radionuclide source, 6 – digital reader-identifier,
- 7 – electronic information processing and control unit,
- 8 – collimator

The energy coming from solar panels 1 is accumulated in battery 3 for use at night and on cloudy days, the charge level of which is determined by controller 2 and is supplied to inverter 4. In inverter 4, solar energy is converted into electric current, which powers and drives rotation an irradiation installation with container 5 containing a ⁶⁰Co radionuclide source. Digital reader-identifier 6, which has recorded the bird, transmits an image of its silhouette in flight or soaring to the electronic information processing and control unit 7. Unit 7 identifies the bird, the distance between it and the radionuclide source, and the lethal value of the exposure dose from the database. After this, unit 7, through the built-in controller, sends a signal to collimator 8 to open the protective gate and focus the emitted beam of ionizing radiation on the bird. The time required for a bird to receive a lethal dose is automatically calculated using the formula:

$$T = [D \times R^2] / [A \times K_\gamma], \tag{1}$$

where T is irradiation time, hours (h); D – exposure dose of radiation, roentgen (R); R – distance from the installation with a radioactive source to the bird, centimeters (cm); A – activity of the radionuclide source, millicurie (mCi); K_γ – decay constant, $([P \times \text{mCi}] / [h \times \text{cm}^2])$ [8].

A bird irradiated with a lethal dose of ionizing radiation does not receive mechanical damage, and its carcass retains its physical integrity. This allows for easier identification than analysis of osseous feather remains from firearms or aircraft collisions.

If we assume that the activity of the ⁶⁰Co radionuclide source is 600 curies, the distance between it and the identified bird (for example, an eagle, peregrine falcon, or kestrel) is 0.2 m, and the lethal radiation dose for it is 100 R, then the required collimated exposure time is calculated by (1) will be 19 seconds:

$$T = [D \times R^2] / [A \times K_\gamma] = [100 P \times 20^2 \text{ cm}] / [600 \times 10^3 \text{ mCi} \times 12.853 (P \times \text{mCi}) / (h \times \text{cm}^2)] \approx 0.0052 \text{ h} \approx 19 \text{ s}.$$

where $K_\gamma = 12.853 (R \times \text{mCi}) / (h \times \text{cm}^2)$ for radionuclide ⁶⁰Co according to [8].

The above-described method of controlling feathered pests in the glide path zone of an airfield is currently theoretical since it requires the determination of lethal radiation doses for various birds and a technologically accessible technique for producing a ⁶⁰Co radionuclide source.

5. 2. Devising an alternative technique to obtain a ⁶⁰Co radionuclide source of the required activity without using a nuclear reactor

A nickel target is made by electrolytically depositing a layer of nickel onto a copper substrate with an area of 8 cm². Preparation of the substrate surface includes abrasive treatment, thorough washing with distilled water, degreasing the surface with acetone, repeated washing with distilled water, and drying with filter paper.

The application of a nickel layer on a copper substrate for intra-chamber irradiation is carried out electrolytically from an electrolyte of the following composition: NiSO₄ × 7H₂O (300–330 g/l), NiCl₂ × 6H₂O (45–60 g/l) and H₃BO₃ (30–40 g/l) at a pH of the environment 2.5–4.5.

After dissolving the salt in 600 ml of hot bidistilled water, boric acid is added, and the entire contents are kept in the container until cooled. Then the prepared electrolyte is treated with an electric current of density 3–4 mA/cm² on the electrodes to remove electropositive impurities.

The prepared copper substrate is weighed with precision on an analytical balance and fixed in the electrolytic bath. The substrate, which acts as a cathode, is connected to the negative pole of the power supply, and a platinum wire with a diameter of 1 mm serves as the anode. A voltage of 25 V is applied to the bath at a cathode current density of 70–100 mA/cm², an electrolyte heated to 65–70 °C is poured in, after which the mixing device is activated with a rotation speed of 150–200 rpm. To maintain the galvanostatic mode of electrolysis, or constant current density, a power supply with output voltage stabilization by current is used.

The electrolysis time is calculated based on the selected current density and the specified thickness of the nickel film (200–220 μm) on the substrate, according to the formula:

$$t = m_{Ni} / (W \times I), \text{ h}, \tag{2}$$

where m_{Ni} is the mass of nickel deposit at a given thickness; W – electrochemical equivalent of nickel under given deposition conditions, mg/mAh; I is the total current supplied to the substrate, A.

The mass of nickel sediment, in turn, is calculated using the formula:

$$m_{Ni} = S \times d \times \rho \times 10^{-1}, \text{ mg}, \tag{3}$$

where S is the area of nickel deposit on a rectangular substrate, cm² ($S = 2 \times 4 \text{ cm}^2$); d – specified thickness of the nickel layer, μm ($d = 200\text{--}220 \text{ μm}$); ρ – density of natural nickel, g/cm³ ($\rho = 8.91 \text{ g/cm}^3$).

The electrochemical equivalent of nickel is determined empirically based on several test deposition data (within 1 hour) under the conditions under which electrolysis of the working target is carried out, and is calculated using the formula:

$$W = m / (I \times t), \text{ mg} / (\text{mA} \times \text{h}), \tag{4}$$

where m is the average mass of nickel deposited within 1 hour, mg; I – current strength at which deposition occurs, mA; t – test precipitation time, h (1 h)

The procedure is used to obtain a given thickness of the nickel layer on the substrate, and the value of the electrochemical equivalent of nickel (W) averages 0.0713 mg/mAh.

After electrolysis for the estimated time, the voltage supply to the electrolytic bath is stopped, the mixing device is turned off, the electrolyte is drained, and the finished target is washed with distilled water, thoroughly dried, and weighed. As the metal gradually cools, nickel precipitates. The nickel deposit on the finished target has a matte, smooth, steel-gray tint and has no visible defects (pitting, foreign inclusions, and craters).

The thickness of the nickel layer on the finished target is calculated by the formula:

$$d = [\Delta m \times 10] / [\rho \times S], \mu\text{m}, \tag{5}$$

where Δm is the difference in target masses before and after electrolysis, mg; ρ – nickel density, g/cm³ ($\rho = 8.91$ g/cm³); S – deposit area on the substrate, cm² ($S = 2 \times 4$ cm²).

Subsequently, the finished target with a thickness of 200 microns and a substrate area of 8 cm² is irradiated in a cyclotron, where its reliable fixation inside the chamber, sufficient heat removal during irradiation, and rapid removal from the chamber for discharge into a protective container are ensured. Irradiation is carried out in the internal beam of a cyclotron with a proton energy of 22 MeV and a current of 250 μ A for 36 hours. The activity of the irradiated target is 15 mCi.

After irradiation at the cyclotron, the nickel target is subject to radiochemical processing in the installation schematically shown in Fig. 2. The equipment intended for assembling the installation is thoroughly washed with a chrome mixture, washed with distilled water until the wash water is neutral, and dried in an oven.

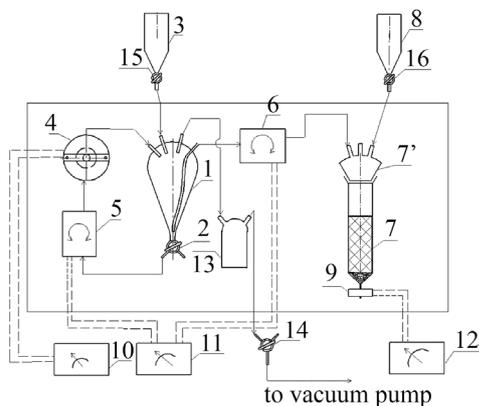


Fig. 2. Diagram of the installation for radiochemical processing of an irradiated nickel target: 1 – intermediate vessel; 2, 14 – two-way valves; 3, 8 – vessels for supplying inactive solutions; 4 – electrolytic cell; 5, 6 – peristaltic pumps; 7 – chromatographic column; 7' – chromatographic column cover; 9 – solenoid valve; 10 – electrolytic cell control unit; 11 – control unit for peristaltic pumps; 12 – solenoid valve control unit; 13 – Wulff's flask; 15, 16 – one-way valves

A Wulff flask 13 is installed on the vacuum line to vessel 1. Vessels for supplying inactive solutions 3 and 8 with one-way valves 15 and 16, vacuum valve 14, control panels 10, 11, and 12 are brought to the operator area. Electrolyzer 4 for electro-

lytic removal of the nickel layer with activated ⁶⁰Co is made of organic glass and is placed on a metal stand together with an intermediate vessel 1 and a chromatographic column 7. Uniform mixing in intermediate vessel 1 and pumping the solution into a Wulff flask 13 and into chromatographic column 7 through lid 7' is carried out using peristaltic pumps 5 and 6 through two-way valves 2 and 14. Control of peristaltic pumps 5 and 6, electrolytic cell 4, as well as supply and voltage regulation is carried out through control units 10 and 11.

The target is inserted into electrolyzer socket 4 with its back side facing the operator and pressed tightly with a screw clamp. With tap 15 closed, vessel 3 is filled with bidistilled water (30 ml). When valve 2 is closed, valve 14 opens to connect vessel 1 with the vacuum pump, after which valve 15 is turned on. When liquid from vessel 3 is pumped into vessel 1, the vacuum pump is turned off, valve 14 opens, and valve 15 closes. Valve 2 opens to connect vessel 1 and peristaltic pump 5, which for 5 minutes sets the liquid in motion in a circle: vessel 1 – pump 5 – electrolyzer 4 – vessel 1. The optimal voltage value supplied to the pump is 16–18 V. The fluid flow rate is controlled by remote control panel 11.

With tap 15 closed, vessel 3 is filled with a solution of 8 M HCl (25 ml). Dissolution of the deposited active nickel layer of the target is carried out in electrolytic cell 4 using 8 M HCl coming from vessel 3 after opening tap 15, at a current density of 42 A/dm² at a speed (v) of 10 μ m/min. A voltage of 29 V is supplied to electrolyzer 4 from power supply 10. Dissolution of the target lasts 1 minute, and over the next 3 minutes the solution washes the target to remove salts deposited on it during the dissolution process. The operation is repeated until a layer of nickel with a thickness (d) of 50 μ m remains on the copper target substrate to prevent copper from entering the solution and then into the chromatographic column. The total dissolution time is calculated using the formula:

$$t_{\text{diss}} = d/v, \tag{6}$$

where d is the thickness of the nickel layer on the copper substrate, μ m ($d = 50$ μ m); v – nickel dissolution rate, μ m/min ($v = 10$ μ m/min).

Due to the high activity of the irradiated target (15 mCi), creating an ambient gamma radiation dose equivalent rate of about 50 μ Sv/h [9, 10], the dissolution of the deposited nickel layer is carried out under constant radiometric control. When the target dissolves, the following are formed:



The hydrochloric acid mixed solution of nickel and cobalt after dissolution of the deposited nickel layer has a green color due to the predominant concentration of nickel. The green color of nickel chloride solutions is due to the presence of complex anions: $[\text{Ni}(\text{H}_2\text{O})_6]^{2+}$; $[\text{NiCl}_3]^-$ and $[\text{NiCl}_4]^{2-}$.

Along with nickel chlorocomplexes, chlorocomplexes of trace amounts of cobalt are formed. A detailed study of the absorption spectra of aqueous solutions of cobalt chloride revealed that in 0.1–4 M HCl solutions the hydrated ion $[\text{Co}(\text{H}_2\text{O})_6]^{2+}$, predominates, and at higher HCl concentrations $[\text{CoCl}_3]^-$ and $[\text{CoCl}_4]^-$ ions are formed, the content of which increases with further increase in HCl concentration. The transition from aqua ions to the $[\text{CoCl}_4]^-$ complex occurs in steps.

Separation of carrier-free quantities of ^{60}Co from gram quantities of nickel is carried out by extraction chromatography. This method for separating these elements is based on the strength of the resulting complexes of cobalt and nickel, as well as their different extractability with tri-*n*-octylamine from hydrochloric acid solutions of various concentrations.

During chromatography, chlorine complexes of the separated metals are sorbed on the column and then successively washed out with HCl of various concentrations. Nickel ion complexes are most easily washed out because they are practically not sorbed from 8 M HCl, while at the same time cobalt chloro complexes are firmly retained by tri-*n*-octylamine at a given acid concentration. The wash solution (8 M HCl) is periodically analyzed for nickel content. If there is no nickel in the washing solution (^{56}Ni), ^{60}Co is washed out of the column with 3 M hydrochloric acid. The chromatographic column is subsequently subject to regeneration, which is carried out with 1 M nitric acid.

Controlled chemical micro impurities in the ^{60}Co radioisotope are Ni, Fe, Cu, Cr ions, the concentration of which should not exceed $0.02 \mu\text{g}/\text{mCi}$ for each element. The total activity of radionuclide impurities ^{56}Co , ^{57}Co , ^{58}Co and ^{65}Zn in the final product ^{60}Co should not exceed 1 %, and ^{56}Ni , ^{57}Ni and other radionuclides should not be detected at all.

At the end of the dissolution of nickel, which lasts no more than 5 minutes, the peristaltic pump 5 is turned off, and the stroke of its engine through unit 11 is changed in the opposite direction so that all the liquid enters vessel 1. Opening tap 2 to air leads to the drainage of water into the waste container, after which tap 2 is closed. Then pump 6 is turned on by supplying a voltage of 16–18 V through unit 11, the solution is pumped into chromatographic column 7.

In chromatographic column 7, carrier-free ^{60}Co is separated from gram quantities of nickel. To begin with, column 7 is prepared and the flow rate of the solution flowing from it is adjusted. To do this, with valve 16 closed, vessel 8 is filled with three column volumes of 8 M HCl solution, then valve 16 is opened, and the liquid flows into column 7 by gravity, after which valve 16 is closed and solenoid valve 9 is turned on through control panel 12. The rate of liquid flow through valve 9 also controlled by remote control 12 and maintained at 1 ml/min.

After the working solution has expired, 70 ml of 8 M HCl is fed through vessel 8 and tap 16 into column 7 to remove associated radioactive and inactive impurities. Then, 50 ml of 3 M HCl is supplied through vessel 8 and tap 16 to elute ^{60}Co . The working solution after the column, the washing liquid and the eluate are collected in separate waste containers. The volumetric activity of the eluate is 10–12 Ci/l.

Details of chromatographic column 7 are shown in Fig. 3.

PTFE with a fraction of $0.5\pm 1.2 \mu\text{m}$ is used as a stationary phase carrier. The column is filled with a pre-prepared stationary phase (fluoroplastic-4) with tri-*n*-octylamine fixed on its surface in benzene or xylene in a ratio of 6:1:1. A small amount of glass wool is placed at the bottom of the column, thoroughly washed with bidistilled water to avoid the ingress of fluoroplastic particles.

The inactive column after regeneration with a 1M HNO_3 solution is filled with 0.1M HCl.

From the compound $^{60}\text{CoCl}_2$, formed as a result of dissolving the nickel target (7), in the electrolytic bath shown in Fig. 4, the radioisotope ^{60}Co is released and deposited on a metal palladium foil 10 microns thick. Palladium, which is a paramagnetic metal with a cubic lattice and a Debye temperature of 245 K, is easily rolled into foil, the diffusion depth

in which is limited, which does not create strict requirements for the heating mode since the small diffusion depth determines shallow atomic absorption in the matrix and a better amplitude g-spectrum.

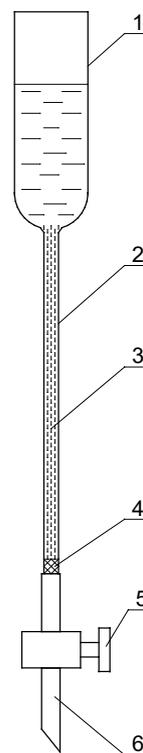


Fig. 3. Diagram of a chromatographic column for separating carrier-free amounts of ^{60}Co from gram quantities of nickel: 1 – reservoir; 2 – packing part of the column; 3 – carrier; 4 – glass wool (quartz); 5 – clamping screw; 6 – PVC hose

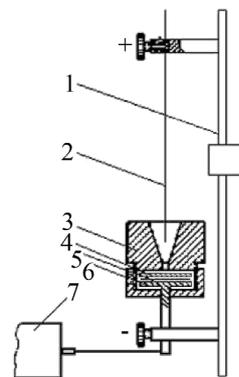


Fig. 4. Electrolytic bath for isolating the radioisotope ^{60}Co and depositing it on metal palladium foil 10 microns thick: 1 – plexiglass bath holder; 2 – platinum anode wire; 3 – conical Teflon cup; 4 – Teflon washer; 5 – palladium foil; 6 – copper disk; 7 – vibrating mixer

Palladium foil 5 in the form of a rectangular plate measuring $20\times 55 \text{ mm}^2$ is pressed against copper disk 6 with a Teflon washer 4. Its internal diameter of 3 mm determines the size of the active spot. In turn, washer 4 is pressed against a conical Teflon cup 3, into which up to 1 cm^3 of electrolyte is poured. Platinum wire with a diameter of 1 mm is used as anode 2. The electrolyte is obtained by adding concentrated ammonia to a brine solution of $^{60}\text{CoCl}_2$ until the pH of the medium is 11–12 mol/l. During electrolysis of the solution,

it is necessary to maintain the alkaline environment of the solution in order to avoid self-dissolution of the deposited ^{60}Co . The bath is powered by a 6 V battery, the current is controlled by a rheostat, and the current density is maintained at 140 mA/cm^2 . The solution is stirred by vibrator 7, mechanically connected to the bath body. The plexiglass bath holder 1 is flexible enough to allow vibration. Stirring the solution, which ensures normal electrolysis, also helps release the resulting gas bubbles that interrupt the current. The electrolytic deposition of ^{60}Co continues for 2–3 hours, during which time up to 80 % of the activity is recovered. At the end of electrolysis, without interrupting the current, the solution is removed from the bath with a pipette, and the bath is washed with distilled water. The surface activity of ^{60}Co will be about 4 mCi/mm^2 , so the work is performed in a fume hood under constant radiometric control.

Diffusion of radioactive nuclei into the palladium matrix is carried out in a vacuum under a pressure of 10^{-3} torr in an inert or reducing environment under the influence of high temperature created in a thermal diffusion heating installation shown in Fig. 5.

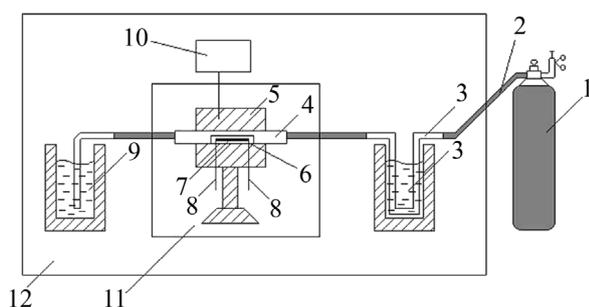


Fig. 5. Diagram of installation for thermal diffusion heating of a nickel plate with palladium foil for diffusion of ^{60}Co into the substrate: 1 – gas cylinder, 2 – vacuum hose, 3 – nitrogen trap, 4 – quartz tube, 5 – oven, 6 – ceramic boat, 7 – $^{60}\text{Co}+\text{Pd}$ foil, 8 – thermocouple, 9 – water valve, 10 – power supply, 11 – lead glass protection, 12 – fume hood

All operations for thermal diffusion heating of a nickel plate with palladium foil for the diffusion of ^{60}Co into substrate 7 are carried out in a stainless-steel fume hood 12, equipped with exhaust ventilation and a lead glass screen 11. Drops of a solution previously removed from the electrolytic bath and containing ^{60}Co using a pipette transferred to metal substrate 7 and dried under an infrared lamp. Then substrate 7 is transferred to a ceramic boat 6 and annealed using induction heating from thermocouple 8 in furnace 5 mounted in fume hood 12. Furnace 5 is powered from unit 10 in a stream of hydrogen coming from cylinder 1 through vacuum hose 2 into nitrogen trap 3, or in an inert atmosphere at temperatures up to $1000\text{ }^\circ\text{C}$. The nitrogen trap 3 serves to prevent the penetration of vapors from vacuum hose 2 into quartz tube 4, the condensate from which enters water valve 9.

The thermal diffusion annealing time of a nickel plate with palladium foil and drops of a solution containing ^{60}Co deposited on it is 2 hours, after which the sample is slowly cooled to room temperature at a rate of about $100\text{ }^\circ\text{C}$ per hour.

After thermal diffusion annealing, the foil on the nickel plate must be cleaned with dilute hydrochloric acid to remove ^{60}Co that has not diffused into the palladium. The plate,

cleared of removed ^{60}Co deposits, becomes a closed source of ionizing radiation with a given activity.

To establish the actual activity and exact radioisotopic composition of the resulting source, it is sent for spectrometric studies for the purpose of quality control, then packaged, processed, and used for its intended purpose. According to experimental data, the following relationship is established between the volumetric activity of ^{60}Co in a solution diffusing into the palladium matrix as a result of thermal diffusion heating and the specific activity of the ^{60}Co contained in it:

$$A_{Pd}=0.77\times A_{sol}, \quad (9)$$

where A_{Pd} is the specific activity of ^{60}Co in the palladium matrix, Bq/kg; A_{sol} – volumetric activity of ^{60}Co in a diffusing solution, Bq/l.

6. Discussion of results of investigating an alternative technique for producing the ^{60}Co radioisotope for use in aviation ornithology

Before introducing the developed scheme of a radioisotope device for ornithological support of aircraft flights (Fig. 1) into the aviation infrastructure, it is necessary to experimentally determine the lethal radiation doses of various bird species that pose a danger to aircraft. The corresponding values of the required exposures (D) must subsequently be entered into the electronic information processing and control unit. The time of lethal irradiation of feathered pests will be inversely proportional to the dose generated by the radionuclide source, which in turn directly depends on its energy and activity, which is described by formula (1).

An alternative production of a ^{60}Co radionuclide source of the required activity without the use of a nuclear reactor was implemented in 4 stages.

At the first stage, by electrolytically deposition of a nickel layer on a copper substrate, a target for intra-chamber irradiation in the accelerator was fabricated. The thickness of the nickel layer on the copper substrate is directly proportional to the time of its deposition, calculated by formula (2). The thickness of the nickel layer also depends on the difference in target masses before and after electrolysis, and on the current supplied to the substrate.

In-chamber irradiation of a nickel target at a cyclotron is the second stage, which is carried out in a specialized organization using generally accepted technology, so its description is not included in our paper. At the third stage, radiochemical processing of the irradiated target was carried out and the nickel layer deposited on it was dissolved in an electrolytic bath to separate carrier-free quantities of ^{60}Co from gram quantities of nickel using extraction chromatography. The separation of carrier-free quantities of ^{60}Co from gram quantities of nickel occurs due to the binding of cobalt and nickel molecules by chlorine contained in a solution of hydrochloric acid in the electrolytic bath shown in Fig. 4. Subsequently, cobalt and nickel, which have different extractability, are easily separated from chlorine by extraction chromatography.

At the final fourth stage, the ^{60}Co radionuclide source was diffused from the electrolytic solution into the palladium matrix by thermal diffusion heating of a nickel plate with palladium foil deposited on it. Diffusion of ^{60}Co from an electrolytic solution into a palladium matrix on a nickel plate occurs as a result of its microstructural expansion under

the influence of thermal diffusion heating in the installation shown in Fig. 5. After cooling the plate, it contracts with the absorbed active carrier. The efficiency of diffusion was established experimentally and amounted to 77 % of the volumetric activity of ^{60}Co in an electrolytic solution. Changing thermal diffusion heating modes can affect this indicator.

For the radiation device for ornithological support of aircraft flights, a high-energy radioisotope ^{60}Co is required. At the same time, the resulting radionuclide source of ionizing radiation is not subject to increased requirements for mechanical strength and purity from impurities, so it can be generated using the alternative (out-of-reactor) method described above.

The features of the proposed method are the greater technological and price accessibility of the necessary production capacities compared to a nuclear reactor. In addition, the advantage of the proposed method is obvious in the time it takes to obtain ^{60}Co , the production of which requires no more than 32 days:

- 1 hour – for deposition and determination of the electrochemical equivalent of nickel on a copper substrate;
- 36 hours – for irradiation of a nickel target at a cyclotron;
- 30 days – for exposure of the irradiated target to reduce radioactive trace impurities ^{56}Co and ^{58}Co ;
- 2 hours – for thermal diffusion annealing of a nickel plate with palladium foil and drops of a ^{60}Co solution deposited on it. For comparison, the time of induction of ^{60}Co in the reactor is at least 263 days.

The proposed method of out-of-reactor production of ^{60}Co has a number of limitations, primarily infrastructural ones. Laboratories with electrolytic, radiochemical, and thermal diffusion equipment do not require large expenditures to comply with construction, environmental, and sanitary standards and regulations, and can be created on the basis of an industrial or research enterprise. However, the presence of a cyclic accelerator is possible only in a specialized organization, so in-chamber irradiation of a copper substrate with a nickel layer will most likely be carried out separately from other stages of the technological process.

The main disadvantage of the proposed method for the out-of-reactor production of ^{60}Co is the complexity of its implementation and the associated difficulty in accurately reproducing the results. In addition, if it is necessary to produce the ^{60}Co radioisotope with high activity (more than 10 mCi), it will be necessary to equip workplaces according to radiation hazard class I [11] and carry out measures for radiation protection of personnel. The listed shortcomings can be eliminated in the future by increasing the level of automation of the described technology in order to minimize human work in contact with harmful and radiation-hazardous substances and production factors.

Our research can be further developed if experimental and then serial production of irradiation installations for ornithological support of aircraft flights begin. The proposed method of alternative (out-of-reactor) production of ^{60}Co may also arouse interest and find application in other sectors of the economy, science, industry, or agriculture. Various difficulties are inevitable in the implementation and development of this research. First of all, it is necessary to ensure

the accuracy of bird recognition by silhouettes in flight and soaring, as well as the empirical determination of lethal doses of their radiation. Problems with quality control of ^{60}Co radionuclide sources produced by the proposed method may lead to other difficulties, the reliable prediction of which is not possible at the current stage.

7. Conclusions

1. The built diagram of a radioisotope device for ornithological ensuring the safety of aircraft flights, containing a high-energy radionuclide source of ionizing radiation ^{60}Co , gives a clear idea of the principle of its operation to combat bird pests targeted with lethal doses.

2. Using the devised alternative technique, a ^{60}Co radionuclide source of the required activity was obtained without the use of a nuclear reactor. This technique includes production of a nickel target, its intra-chamber irradiation in a cyclotron, radiochemical processing, and subsequent diffusion of ^{60}Co from the electrolytic solution.

The technique devised for producing a target for intra-chamber irradiation makes it possible to set the thickness of the nickel layer applied to the copper substrate electrolytically and to determine the time of its deposition.

The developed technology for radiochemical processing of an irradiated target and subsequent dissolution of the nickel layer in an electrolytic bath made it possible to separate carrier-free quantities of ^{60}Co from gram quantities of nickel using extraction chromatography. This ensured the production of a nickel plate with palladium foil, ready for thermal diffusion of a ^{60}Co radionuclide source into it from a liquid solution.

As a result of the study of thermal diffusion heating of a nickel plate with a palladium foil deposited on it, ^{60}Co diffused from the solution extracted from the electrolytic bath into the palladium matrix. By thermal diffusion heating of two nickel plates with palladium foil and a drop of ^{60}Co solution between them, it is possible to obtain two radionuclide sources of ^{60}Co at once for a radioisotope device to provide for the ornithological aircraft flight safety.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

References

1. Juračka, J., Chlebek, J., Hodaň, V. (2021). Bird strike as a threat to aviation safety. *Transportation Research Procedia*, 59, 281–291. doi: <https://doi.org/10.1016/j.trpro.2021.11.120>

2. Akzigitov, R., Kuznetsov, E., Musonov, V., Timokhovich, A. (2023). Ensuring the Safety of Aircraft Flights in Ornithological Terms. *Transportation Research Procedia*, 68, 566–572. doi: <https://doi.org/10.1016/j.trpro.2023.02.077>
3. Kassenov, K., Kim, D.S., Zhmagulova, R. E. (2019). Some results and perspectives of the application of radiation treatment of agricultural products. *Research, results*, 3 (83), 354–360. Available at: <https://journal.kaznaru.edu.kz/index.php/research/issue/view/7/5>
4. Belko, A. V., Dobratulin, K. S., Kuznetsov, A. V. (2021). Classification of plumage images for identifying bird species. *Computer Optics*, 45 (5). doi: <https://doi.org/10.18287/2412-6179-co-836>
5. Judaibi, A., Soliman, A. Y. (2022). Simulation of cobalt-60 production in research reactors using OpenMC Monte Carlo code. *Kern-technik*, 87 (2), 230–236. doi: <https://doi.org/10.1515/kern-2021-1027>
6. Howard, R. H., Reichenberger, M. A., Urban-Klaehn, J. M., Peterson-Droogh, J. L., Brookman, J. V. et al. (2021). Overcoming challenges to support us resumption of high specific activity cobalt-60. *Applied Radiation and Isotopes*, 169, 109494. doi: <https://doi.org/10.1016/j.apradiso.2020.109494>
7. Lyu, J., Ryu, E. H., Park, J. H. (2020). Innovative core design using cobalt-equipped bundles for cobalt-60 production in CANDU6 reactors. *Annals of Nuclear Energy*, 142, 107384. doi: <https://doi.org/10.1016/j.anucene.2020.107384>
8. Delacroix, D., P. Guerre, J., Leblanc, P., Hickman, C. (2002). Radionuclide and radiation protection data handbook 2002. *Radiation Protection Dosimetry*, 98 (1), 1–168. doi: <https://doi.org/10.1093/oxfordjournals.rpd.a006705>
9. Kudryashev, V. A., Kim, D. S. (2019). Determination of the total effective dose of external and internal exposure by different ionizing radiation sources. *Radiation Protection Dosimetry*, 187 (1), 129–137. doi: <https://doi.org/10.1093/rpd/ncz170>
10. Kim, D. S. (2019). Methods of calculation of radiation protection for operational safety optimization at working with radionuclide photon radiation sources. *Eurasian Journal of Physics and Functional Materials*, 3 (4), 348–354. doi: <https://doi.org/10.29317/ejpfm.2019030407>
11. Giuffrida, D. (2018). Source of Radiation Exposure in the Workplace: Nuclear, Medical and Industrial Sources. *Physical Agents in the Environment and Workplace*, 227–245. doi: <https://doi.org/10.1201/b22231-11>