Mazilov Aleksey  
Candidate of Physical and Mathematical Sciences, Head of Laboratory,  
National Science Center Kharkov Institute of Physics and Technology, Ukraine

Mushnikov Valeriy  
Leading Research Engineer,  
National Science Center Kharkov Institute of Physics and Technology, Ukraine

Skorobagatko Dar’ya  
Candidate of Biological Sciences, Scientific Researcher,  
National Science Center Kharkov Institute of Physics and Technology, Ukraine

Yaremko Olga  
Leading Research Engineer,  
National Science Center Kharkov Institute of Physics and Technology, Ukraine

SOME QUESTIONS OF BETA-RADIATION PROTECTION  
BUILDING FOR OVERALLS

Abstract: The issues of beta-radiation protection building are considered in order to select the optimal materials for overalls for work with sources of ionizing radiation. The electrons passage through assembly consisting of fabric layers of various types with addition of protective shielding materials has been studied. The attenuation coefficients of an electron beam from $^{90}$Sr-$^{90}$Y source in fabrics were experimentally determined. Computer simulation of the passage of electrons through heterogeneous media has been carried out, and recommendations have been given on the materials composition for protective overalls.  

Keywords: beta-radiation, radiation protection, protective materials, $^{90}$Sr-$^{90}$Y source.

INTRODUCTION

The production of nuclear fuel – the nuclear fuel cycle (NFC), as well as the nuclear weapons complex – is a continuous cycle of technological processes from uranium mining (mining uranium ore, process of cleaning it from impurities to
obtain uranium concentrate, the enrichment process – separation into U-235 and U-238), the manufacture and use of nuclear fuel until the final disposal of radioactive waste.

Each of these processes, as well as carrying out repair, dismantling and emergency recovery work at all enterprises of the nuclear industry and energy, entails the need for personnel to stay in a zone of increased radiation hazard – increased doses of gamma-radiation, external neutron radiation, as well as beta-radiation, which accompanies almost all production processes.

According to the requirements of the sanitary legislation [1,2], the reduction of the level of external and internal exposure of personnel during work with open sources of ionizing radiation should be ensured, among other things, by the use of personal protective equipment (PPE). The basic set of PPE consists of a jumpsuit or suit, cap, special linen, etc. Protective equipment for hands and body during work with radioactive substances must have high protective qualities:

– be impervious to radioactive substances in the liquid state and in the form of dust;

– be chemically resistant to aggressive environments, which include radioactive substances;

– protective gloves should be strong, elastic, comfortable and easy to clean from radioactive contamination.

To protect against electromagnetic radiation (EMR), metallized and non-metallized fabrics are produced. There are several types of such fabrics: synthetic fabrics that contain metallic copper or silver-plated threads; polyester and polyamide fabrics, which are sprayed with a copper or nickel coating, fabrics, on which nickel, copper, cobalt or silver coatings are applied by chemical deposition in a gaseous medium or solutions. Currently, nickel is the most commonly used metal coating. It is a ferromagnetic and well reflects the magnetic component of electromagnetic radiation. [3-5].

The search for materials that provide effective protection against ionizing radiation remains an important area of radiation physics [6]. In most practical problems, radiation protection is a heterogeneous mixture of different media. The
calculation of such protection by analytical methods is very difficult, since the accumulation factors of heterogeneous media depend on a large number of task parameters: the incident radiation energy, thickness, material, number and geometry of layers, as well as their relative position.

In papers [7-10], the features of gamma quanta and electrons passage through heterogeneous layers of materials are considered, computer simulation data and experimental results are presented. It has been shown that the radiation protection efficiency of a heterogeneous assembly is better in the case when a light material is facing the source.

Protection of personnel from external gamma and neutron radiation can be ensured by reducing the duration of work ("protection by time"), by performing work using remote devices ("protection by distance"), as well as by using protective walls, screens, etc. [1,2]. All attempts to create PPE against these types of radiation have not been successful, since these radiations have a large penetrating power.

However, for protection against external beta radiation, PPE is very effective. The thickness of the protective material should be from 0.3 to 0.7 g/cm², depending on the energy of beta radiation [11], which corresponds to a protective suit weight of ~7–18 kg. The classification of PPE from external beta radiation is presented in Table 1.

Table 1

Classification of PPE from external beta radiation with a boundary energy of 2.27 MeV

| PPE class | Protection factor |
|-----------|------------------|
| 1 class   | ≥ 3              |
| 2 class   | ≥ 10             |
| 3 class   | ≥ 30             |
| 4 class   | ≥ 100            |

Protection against external alpha radiation is not relevant due to the low range of alpha particles in air (~5 cm), and the presence of PPE that provides protection against beta radiation fully provides protection against alpha radiation.

The aim of our work is to determine the attenuation coefficients of β-radiation
from a $^{90}$Sr-$^{90}$Y source in tissues and try to give recommendations on the composition of materials for protective overalls.

**MATERIALS AND METHODS**

All works were carried out in the metrological certified Laboratory of Radiation Research and Environmental Protection of the National Science Center Kharkov Institute of Physics and Technology (www.rrep.kipt.kharkov.ua). In the experiments we used:

- calibration source $^{90}$Sr-$^{90}$Y;
- dosimeter-radiometer DKS-96 with a detection unit BDKS-96s, (registration range of $\beta$-particle energies 0.12 MeV – 3 MeV);
- dosimeter-radiometer MKS-08-01 with detection unit BDKS-96b, (registration range of $\gamma$-particle energies 15 keV – 10.0 MeV).

The energy spectrum of electrons from the $^{90}$Sr-$^{90}$Y source [12] is shown in Fig. 1. Beta-decay chain of $^{90}$Sr has the form:

$$^{90}\text{Sr} \rightarrow^{\text{decay}}_{T_{1/2}=27.7 \text{ years}}^{90}\text{Y} + \beta^{-};$$

$$^{90}\text{Y} \rightarrow^{\text{decay}}_{T_{1/2}=64 \text{ hours}}^{90}\text{Zr} + \beta^{-} \text{ (90Zr stable)}.$$  

![Energy spectrum of electrons from $^{90}$Sr-$^{90}$Y source](image)

Fig. 1. **Energy spectrum of electrons from $^{90}$Sr-$^{90}$Y source**

Samples of materials were made in a circle form with a diameter of 6 cm.

The following materials were used as samples: Jeans (cotton 98%, elastane 2%); Silk; Fleece (100% polyester); Flannel (cotton 100%); Chintz (cotton 100%); Velour (cotton 100%); Linen 100%; Dermantine; Leather; Silicone; Tungsten powder; special fabrics (rubberized PVC).
RESULTS AND DISCUSSION

In the experiment, the source of ionizing radiation was located at a distance of ~1 cm from the detection unit. Protective materials were alternately placed between the source and the detection unit, and the flux density of β-particles was measured. The attenuation of β-radiation is described by the formula:

\[ I = I_0 e^{-\mu d}, \]

where \( I_0 \) is the flux density of β-particles without protection;

\( \mu(\rho, Z, E) \) – linear attenuation coefficient of β-radiation, cm\(^{-1}\) – depends on the density \( \rho \), the serial number of the substance \( Z \), and also on the electron energy \( E \);

\( d \) is the thickness of the protective layer.

Let us introduce the mass attenuation coefficient \( \mu_m = \mu/\rho \), then:

\[ I = I_0 e^{-\mu_m P}, \]

where \( P = d \cdot \rho \) is the surface density of the protective material, g/cm\(^2\).

\[ \mu_m = \ln(I_0/I)/P. \]

The results of measurements of radiation passage through fabrics are presented in table 2. The surface activity of the source of β-radiation \(^{90}\)Sr-\(^{90}\)Y is \( I_0=1775 \) particles/cm\(^2\)·min.

From Table 2, it is obvious that the use of classic fabrics without additional fillers (screens) for the manufacture of protective suits is inappropriate. Based on the requirements for overalls [11], the protective screen should be thin and elastic enough so as not to hinder the movement of personnel by more than 30%.

Heavy metals provide the best protection against ionizing radiation. However, an obstacle to their use in workwear is their toxicity. Let us evaluate the use of tungsten (tungsten carbide) for protection against β-radiation as part of PPE. Tungsten is in 1.7 times denser than lead, chemically resistant and belongs to low-toxic metals, unlike lead, nickel and copper.

Using the software package Geant, a computer simulation of β-radiation passage through a tungsten target was carried out. The \(^{90}\)Sr-\(^{90}\)Y source was a circle
2 cm in diameter with the coordinates of electron emission equally probable in area [13,14]. A tungsten target was located close to the source, behind which was a total absorption detector. Table 3 shows the results of the escape of $\beta$- and $\gamma$-particles from tungsten with a thickness of 0.1, 0.2, and 0.3 mm per $10^5$ events.

### Table 2

**Passage of $\beta$-radiation through factory fabrics**

| №  | Material   | $P$, g/m² | $I$  | Protection efficiency, % | Attenuation ratio, $I_0/I$ | $\mu_m$, cm²/g |
|----|------------|-----------|------|-------------------------|----------------------------|-----------------|
| 1  | Jeans      | 290       | 1332 | 25                      | 1,33                       | 9,90            |
| 2  | Silk       | 93        | 1616 | 9,0                     | 1,10                       | 10,10           |
| 3  | Fleece     | 235       | 1387 | 21,9                    | 1,28                       | 10,50           |
| 4  | Flannel    | 153       | 1526 | 14,0                    | 1,16                       | 9,88            |
| 5  | Chintz     | 139       | 1537 | 13,4                    | 1,15                       | 10,36           |
| 6  | Velour     | 288       | 1358 | 23,5                    | 1,31                       | 9,30            |
| 7  | Linen      | 364       | 1319 | 25,6                    | 1,35                       | 8,45            |
| 8  | Special fabric 1 | 255 | 1375 | 22,5                    | 1,29                       | 10,01           |
| 9  | Special fabric 2 | 221 | 1452 | 18,2                    | 1,22                       | 9,09            |
| 10 | Special fabric 3 | 134 | 1541 | 13,2                    | 1,15                       | 10,55           |
| 11 | Dermantine | 405       | 1205 | 32,1                    | 1,47                       | 9,56            |
| 12 | Leather    | 522       | 1053 | 41,5                    | 1,71                       | 10,00           |

### Table 3

**Output of $\beta$- and $\gamma$-radiation from tungsten of various thicknesses**

| d, μm | $N_\beta$ | $N_\beta$, % | $N_\gamma$ | $N_\gamma$, % |
|-------|-----------|---------------|------------|---------------|
| 100   | 39583     | 39,5          | 3530       | 3,5           |
| 200   | 10966     | 10,9          | 3783       | 3,7           |
| 300   | 3406      | 3,4           | 2906       | 2,9           |

Assuming that the total weight of the protective suit should not exceed 20 kg, the maximum thickness of the tungsten carbide should be 200 μm. Then, taking into account density $\rho$(WC)=15.63 g/cm³, the surface density is $P$(WC)=$d\cdot\rho$ =3126 g/cm²; and for density $\rho$(W₂C)=17.2 g/cm³, the surface density is $P$(W₂C)=$d\cdot\rho$ =3440 g/cm²;

In table 3 the data for solid sheet tungsten are presented. In protective suits, finely dispersed tungsten carbide powder should be used to ensure elasticity. Such a
fraction is difficult to simulate. Let us calculate the yield of β- and γ-particles from tungsten plates with a total thickness of 0.2 mm, located at a distance of 10-20 μm from each other. The results are presented in table 4 for 10^5 events.

Table 4

| Number of plates | Nβ  | Nβ, % | Nγ  | Nγ, % |
|------------------|-----|-------|-----|-------|
| 4                | 2100| 2,1   | 3502| 3,5   |
| 10               | 600 | 0,6   | 2954| 3,0   |

It should be taken into account that when β-particles pass through the protective material, bremsstrahlung arises (Fig. 2), the output of which increases with increasing atomic number Z of the shield. Fig. 2 shows a peak at an energy of 60 keV, which corresponds to the Kα1=59.3 keV line of the characteristic X-ray emission for tungsten.

According to computer simulation (Tables 3,4), the yield of bremsstrahlung γ-quanta is about 3–3.5% of the initial number of electrons and does not make a significant contribution to the formation of the radiation environment behind the shield. Gamma dose rate measurements did not reveal any differences from the natural background.

Fig. 2. Bremsstrahlung spectrum of electrons from a ^90Sr-^90Y source in tungsten 200 μm thick
Based on the requirements for PPE, the outer layer of the material must be non-hygroscopic and dust and water resistant. The special rubberized PVC fabric material meets similar requirements. The next layer, in our opinion, should be shielding and contain tungsten. To bond the tungsten powder to the fabric layers, some kind of inert elastic adhesive, such as silicone, is needed. And the third layer, facing the body, is desirable from natural fabric. According to the above characteristics, velour looks promising.

Let's evaluate the protective characteristics of a combination of silicone, tungsten and classic fabrics. The table 5 presents experimental data of β-radiation passage through these materials.

Table 5

| № | Material                  | $P$, g/m² | $I$  | Protection efficiency, % | Attenuation ratio $I_0/I$ | $\mu_m$, cm²/g |
|---|--------------------------|----------|------|--------------------------|---------------------------|---------------|
| 1 | Silicone                 | 871      | 891  | 50,5                     | 2,01                      | 7,91          |
| 2 | WC (5g) – 1              | 1768     | 540  | 69,7                     | 3,32                      | 6,8           |
| 3 | WC (10g) – 2             | 3536     | 174  | 90,3                     | 10,31                     | 6,6           |
| 4 | Silicone+WC (1/1)        | 3510     | 98   | 94,5                     | 18,3                      | 8,28          |
| 5 | Silicone+WC (1/2)        | 5278     | 31   | 98,3                     | 57,9                      | 7,69          |
| 6 | Velour+ Silicone+ Special fabric 1 | 2857 | 234 | 86,9 | 7,6 | 7,13 |
| 7 | Velour+ (Silicone+WC 1/1) + Special fabric 1 | 4053 | 103 | 94,3 | 17,4 | 7,02 |
| 8 | Velour+ (Silicone+WC 1/2)+ Special fabric 1 | 5821 | 23  | 98,7 | 79,4 | 7,48 |

Table 5 shows that the introduction of tungsten powder in the amount of 1.768 kg/m² reduces β-radiation flux from $^{90}\text{Sr}^{90}\text{Y}$ source by 3 times. And the use of a mixture of silicone and tungsten in ratio of 1 to 2 between the layers of velour and special fabric with a total density of 5.821 kg/m² provides a protection efficiency of 98.7%.
CONCLUSION

The paper analyzes experimental data and computer simulation data regarding the protective properties from beta-radiation of various materials for workwear. A combination of materials for the production of PPE for work with sources of beta radiation is proposed. This is a three-layer material consisting of an outer layer of special rubberized PVC fabrics, an interlayer of silicone with tungsten carbide powder and natural velour-type fabric. The protection efficiency of such combination of materials at an acceptable surface density reaches 98.7%.

References:
1. Basic Sanitary Rules for Ensuring Radiation Safety of Ukraine. 2005.
2. Radiation safety standards of Ukraine. 1997.
3. Nikolaev S.D., Silchenko E.V. Protecting a person from electromagnetic radiation with the help of tissues // Bulletin of the Kazan Technological University. 2015. vol. 18. № 15. pp. 161-166.
4. Silchenko E.V., Nikolaev S.D. Metallized fabrics for protective suits // News of higher educational institutions. Technology of the textile industry. 2016. № 1 (361). pp. 79-84.
5. Grishchenkova V.A., Vladimirov D.N., Fukina V.A., Khandogina E.N., Shapovalova E.I. Fabric for protection against electromagnetic radiation. Patent for invention № 219.016.c17b. February 20, 2019.
6. Gusev N.G., Klimanov V.A., Mashkovich V.P., Suvorow A.P. Physical basis of radiation protection. M.: «Energoatomizdat». 1989. v. 1.
7. Aksenov I.I., Belous V.A., Goncharov I.G., et al. Laminated material for gamma radiation shielding // Functional Materials. 2009. v. 16. № 3. p. 342-346.
8. Borts B.V., Bratchenko M.I., Dyuldy S.V., Marchenko I.G., Sanzharevsky D.A., Tkachenko V.I. Monte Carlo evaluation of the radiation shielding efficiency of laminated composites under electron and photon irradiation // East Eur. J. Phys. 2014. v. 1. № 3. p. 55-67.
9. Deiev O.S., Mazilov A.A., Mazilov A.V., Maslov N.I., Shulika M.Yu. The research of X-ray and gamma radiation absorption by layered structures // Problems of atomic science and technology (PAST). 2016. № 3 (103). p. 105–110.
10. Deiev O.S., Mazilov A.A., Shulika M.Yu. Absorption of electrons by layered structures // Belgorod State University Scientific Bulletin Series Mathematics & Physics. 2016. № 13 (234). Issue 43. pp. 115-125.
11. Catalog-reference book "Personal protective equipment for enterprises of the nuclear industry
and energy", ed. Rubtsova V.I. Moscow. Rosatom. 2015.

12. Aleksakin V.G., Rodichev S.V., Rubtsov P.M. et al. Handbook "Beta and antineutrino radiation of radioactive nuclei". Moscow. Energoatomizdat. 1989. pp. 359-361.

13. Bochek G.L., Golovash A.S., Kosinov A.V. et al. Double Si detector for detection of beta particles under $\gamma$-radiation conditions // Bulletin of the Russian Academy of Sciences: Physics. 2005. 69(11). 1739-1742.

14. Bochek G.L., Kosinov A.V., Kulibaba V.I. et al. Registration of charged particles under conditions of gamma-radiation background // Poverkhnost Rentgenovskie Sinkhronnye i Nejtronnye Issledovaniya. 2005. № 4. pp. 68-71.