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Research Article

Comprehensive analysis of proliferation protection of uranium due to the presence of ^{232}U and its decay products*

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Abstract

For a comprehensive assessment of the protection of uranium against proliferation due to the presence of uranium-232 in it, the authors of the article propose and substantiate an integral protection criterion for this material. The criterion is based on the physical barriers against the proliferation of uranium created by uranium-232, namely: (1) the radiolysis of uranium hexafluoride, which hinders attempts to re-enrich uranium and, as a result, a significant critical mass; (2) hard γ-radiation, which leads to incapacity and death of those who try to handle this material without radiation protection; (3) increased heat release, which disables the components of a nuclear explosive device; and (4) a significant source of neutrons that causes predetonation and thereby reduces the energy yield of a nuclear explosive device. These barriers appear at various stages of uranium handling not only in the indicated order but also act simultaneously, mutually reinforcing one another.

Keywords

Uranium protection, integral protection criterion for uranium, radiolysis of uranium hexafluoride, critical mass, hard γ-radiation, heat release, neutron source

Introduction

For various scenarios of the proliferation and theft of nuclear materials that can be used to create a nuclear explosive device (NED), it is desirable to have some criterion that would make it possible to estimate the attractiveness of these materials for such purposes. It is extremely difficult to propose such a criterion, since barriers of different physical nature can stand in the way of the unauthorized use of nuclear materials. When various physical barriers are combined into a single criterion, a difficult task arises to assess the contribution of each barrier to the protection of nuclear materials. Thus, the criterion, although based on physical processes, however, does not represent a specific physical quantity but is essentially an expert assessment of a specialist. Of course, such an assessment can be only approximate. Moreover, depending on the parameters included in the criterion, the contribution of each barrier to it, as well as the attractiveness of different materials, may turn out to be different. In this case, the question may well arise why such an indefinite criterion is needed. Unfortunately, in multidisciplinary and multi-physical problems,

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when it is necessary to take into account and compare various phenomena, nothing better than an expert assessment has been proposed so far. In other words, if it is necessary to choose a solution, then it is better to be guided by at least an assessment than by nothing. In addition, the assessment is offered by experts in this field of knowledge, and it allows the main patterns to be identified, on the basis of which decisions can be made.

In the United States, two national laboratories – at Los Alamos and Livermore – are engaged in the development of nuclear weapons. In Russia, such centers are VNIIEF (Sarov) and VNIITF (Snezhinsk). The laboratories were established in 1942 and 1952 to develop the world's first nuclear weapon and to accelerate work on the creation of a thermonuclear bomb, respectively. The criterion for the attractiveness of nuclear materials was developed by Dr. Charles Bathke of Los Alamos National Laboratory (Bathke et al. 2012), the staff members of which are well versed in this problem.

It is supposed to protect the uranium produced in the thorium blanket of a thermonuclear neutron source, i.e., uranium-233. However, nothing prevents us from considering the more general problem of protecting not only uranium-233 but also uranium-235, which we will do below.

Physical barriers to the use of uranium with uranium-232 in a nuclear explosive device

The barriers that may prevent the use of uranium containing uranium-232 are listed below. Firstly, if an attempt is made to enrich uranium-233 (or uranium-235) in centrifuges, an intense source of α-particles of the radioactive decay of uranium-232 ($T_{1/2}$ = 69 years) and daughter nuclides of its decay chain can cause radiolysis of uranium hexafluoride, which can significantly complicate or even prevent the enrichment process. Secondly, if enrichment is not carried out or significant enrichment cannot be achieved, then a second barrier arises – this is the value of the critical mass of the material, which can turn out to be significant, leading to a large weight and size of the NED, i.e., making it difficult to use this material. Thirdly, when trying to make the NED using this nuclear material, the direct executors of this work will encounter hard χ-radiation present in the decay chain of uranium-232 (Tl-208, E_γ = 2.615 MeV with a yield of 100%), which can lead to exposure of the executors and even to a lethal dose with an instant state of coma. Fourthly, after the NED is assembled, due to the heat release associated with the α-activity of uranium-232 and its daughter nuclides, both the nuclear material itself and its surrounding components (for example, chemical explosives) can overheat and fail. And, fifthly, if the NED is intended to be detonated, then, due to a powerful source of neutrons from spontaneous fission of uranium-232, as well as neutrons arising from (α, n)-reactions on unremovable microimpurities (carbon, nitrogen, oxygen, etc.), the explosion power may be significantly less than the nominal power (up to a value of less than 1% of it). This is a case of so-called "predetonation".

Note that hard γ-radiation will, of course, irradiate the direct executors at the stage of preparing uranium for enrichment. However, this is not considered as an independent barrier, since in this case uranium-232 will be mixed not only in fissile nuclides (uranium-233 and/or uranium-235) but also in raw materials (uranium-238 and (or) thorium-232), which are contained in the fuel several times more.

Radiolysis of uranium hexafluoride

The first barrier associated with the radiolysis of uranium hexafluoride actually determines the value of the critical mass of nuclear material, which in turn determines all the other barriers. Therefore, the first barrier cannot be taken into account in the criterion along with the others and it has to be considered separately. Apparently, the authors of (Bathke et al. 2012) came to the same conclusion, since they acted in a similar way. Note that enrichment of the fissile isotope of uranium (233 or 235) is enrichment of all the light isotopes of uranium, starting from this isotope (233 or 235, respectively). Thus, enrichment leads to a greater increase in the content of lighter uranium-232 in uranium than uranium-233 or, even more so, uranium-235. This strengthens all the other defense barriers associated with uranium-232. For example, it was shown in (Bathke et al. 2012) that, if 0.03% uranium-232 is added to natural uranium, then uranium-235 enriched to 3% (an increase of 4.2 times compared to natural 0.71%) will already contain 0.18% of uranium-232 (six times), and its further enrichment to 90% in uranium-235 (127 times) will lead to an increase in its uranium-232 content to 6.24% (208 times). At the same time, the content of uranium-234 also grows faster than that of uranium-235 but more slowly than that of uranium-232, from 0.005% in natural uranium to 0.028 and 0.93%, respectively.

Let us estimate the fraction of uranium hexafluoride molecules subjected to radiolysis. In this case, we take into account that the energy of one uranium-232 α-particle is E_α = 5.414 MeV, and for the radiolysis of one uranium hexafluoride molecule, it needs to transfer the energy $E_{rad} \approx 111$ eV. This means that one α-particle is capable of destroying about 48,700 molecules of uranium hexafluoride, if all the energy of the α-particle is used for this. The contribution of other uranium isotopes to the radiolysis is negligibly small. The number of uranium-232 nuclei in time t is described by the equation of its radioactive decay:

$$N(\text{U-232}, t) = N(\text{U-232}, 0)\cdot 2^{(-t/T)},$$

where N(U-232, 0) is the number of uranium-232 nuclei at the initial moment of time; T is the period of its half-life (68.9 years). The number of α-particles emitted by uranium-232 per second coincides with its activity:

$$A(t) = |\, dN(\text{U-232}, t)/dt \,| = N(\text{U-232}, 0)\cdot 2^{(-t/T)}\ln(2)/T = N(\text{U-232}, t)\cdot\ln(2)/T.$$

Then the fraction of destroyed uranium hexafluoride molecules during the time Δt is determined by the expression

$$\varepsilon = (E_\alpha/E_{rad})\cdot(A(t)/N(\text{U}, t))\cdot\Delta t,$$

where $N(\text{U}, t)$ is the number of all the uranium nuclei. Given that the ratio $N(\text{U-232}, t)/N(\text{U}, t)$ is the content of uranium-232 in uranium (X), we will obtain the following formula:

$$\varepsilon = \ln(2)\cdot(E_\alpha/E_{rad})\cdot X\cdot(\Delta t/T).$$

The time during which uranium is in the form of uranium hexafluoride in the enrichment cascade (Δt) depends on many characteristics of the cascade (the number of centrifuges and their productivity, i.e., the cascade power or the number of separative works that the cascade can perform per unit time) as well as on the amount of enriched material, the degree of required enrichment and the content of the target nuclide in the waste material. All these parameters can vary over a wide range and strongly depend on the degree of development of the centrifuge enrichment technology. In (Tsoulfanidis 2013), this time is estimated from one day to one month. During these time intervals, the decrease in the activity of uranium-232 can be neglected. Table 1 shows the proportion of uranium hexafluoride molecules destroyed during centrifugal enrichment under various conditions.

Table 1. Fraction of Destroyed Uranium Hexafluoride Molecules in the Process of Centrifugal Enrichment Depending on the Enrichment Time (Δt) and the Content of Uranium-232 in Uranium (X)

Enrichment time, days	U-232 content in U, %		
	0.01	0.1	1.0
1	0.01	0.13	1.3
7	0.09	0.94	9.4
30	0.40	4.04	40.4

It obvious that the enrichment process can be seriously disturbed when the content of uranium-232 in uranium is at the level of 0.1–1% with an enrichment time of the order of a week or more.

Critical mass

According to the IAEA documents (IAEA Safeguards Glossary 2001), uranium with a uranium-235 content of up to 20% is called low-enriched and is considered unsuitable for creating NEDs; therefore, we will take the critical mass of a bare sphere, i.e., without a reflector, from uranium containing 20% uranium-235, equal to approximately 800 kg as a barrier against its use in a NED.

If the critical mass of uranium turns out to be less than 800 kg, then such material will be considered less protected, and if more than 800 kg, then more protected. Approximately the same critical mass is typical for uranium containing 12% uranium-233. The critical mass is determined by the uranium enrichment and the fissile isotope (see Fig. 1). Thus, the critical mass of 90% uranium-235 is about 50 kg and that of uranium-233 is about 15 kg (De Volpi 1982).

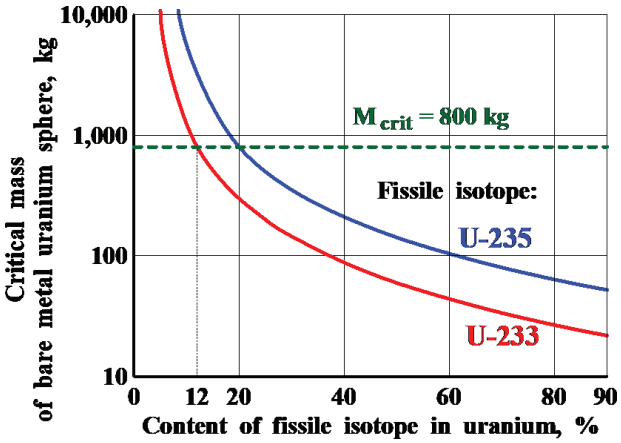

Figure 1. Critical mass of a bare metal uranium sphere depending on the type of fissile isotope and its content.

The calculations of bare uranium spheres with low enrichment were performed using the TIME26 program (Apse and Shmelev 2008) in the 26-group diffusion approximation based on the ABBN-78 library of evaluated nuclear data, which is processed by the ARAMAKO-C1 auxiliary program (Nikolaev et al. 1972), and with high enrichment, using the MCNP code developed at Los Alamos National Laboratory in the USA, using Monte Carlo methods based on the ENDF/B-V library (Kulikov et al. 2018).

Hard γ-radiation

Hard γ-radiation leads to exposure of personnel handling uranium, who, depending on the time of work with the material, can receive a different dose of radiation. To select the dose value as a barrier against the use of uranium in NEDs, we assume that the personnel are not protected from radiation. Otherwise, this barrier does not work, i.e., it is assumed that the violator of the non-proliferation regime does not have remote technologies available in countries with nuclear weapons for handling highly radioactive materials. Table 2 shows the impact of a single dose of radiation on human health (Kulikov et al. 2018a, Yarmonenko and Vainson 2004).

We are interested in the case when the terrorists will actually not be able to work with the material. This corresponds to a situation where, after receiving a single dose, they almost instantly fall into a coma.

The table shows that this will occur when they receive a radiation dose in the range of 10–50 Sv. Let us choose from this range the radiation dose, say, of 20 Sv as the barrier

Table 2. Human Death Rate Depending on the Received Single Dose of Radiation

Dose of radiation, rem	Human health
100	Death rate in about 10% of cases within a month
300–500	Death rate in about 50% of cases within a week
600–800	Death rate in more than 50% of cases within a few days
1000–5000	Instant coma, death within half an hour
Over 8000	Immediate death

value. Note that in (Lethal Dose of Radiation), 5 Sv was chosen as such. This was apparently done, because this value is considered a lethal dose. However, this does not mean that, when receiving such a dose, the terrorists will be put out of action. Lethal dose means death in about half of the cases and not immediately after receiving the dose.

Heat release of α-decay

In our opinion, the heat release barrier value of 4500 W adopted in (Bathke et al. 2012) is excessive. It is determined by the IAEA requirement (IAEA Safeguards Glossary 2001) for plutonium, which must contain at least 80% plutonium-238 in order to make it difficult to use in NEDs. The heat release of plutonium-238 is 570 W/kg, the heat release of plutonium-239 is low, and the critical mass of bare spheres of both plutonium isotopes is approximately the same, amounting to about 10 kg. Thus, the critical mass of a bare sphere of plutonium, which is 80% plutonium-238, is 570 W/kg · 10 kg · 80% ≈ 4500 W. As the value of the heat release barrier, we will take the previously obtained value of 2900 W, which ensures failure due to the melting of all the NED components within five hours after it has been assembled into a single whole, even with the most carefully pre-planned heat removal from all the NED components.

Neutron source

In (Bathke et al. 2012), the rate of neutron generation by the critical mass of reactor-grade plutonium, which was produced in a thermal reactor and contained 20% plutonium-240 (the main source of spontaneous fission neutrons in plutonium), was chosen as the barrier value for the neutron generation rate.

Since plutonium-238 generates approximately 1·106 n/(s·kg), and the critical mass of reactor-grade plutonium is about 34 kg, the yield of a neutron source from the critical mass of reactor-grade plutonium with 20% plutonium-240 is 34 kg · 20% · 10^6 n/(s·kg) = 6.8·10^6 n/s. It is surprising that the authors of (Bathke et al. 2012) do not take into account the neutrons that arise as a result of (α, n)-reactions on light nuclides of unremovable impurities (carbon, nitrogen, oxygen, etc.) present in uranium. Previously, it was shown that reliable NED predetonation (with a probability of 90%), which reduces the energy yield to less than 1% of the nominal power of a NED containing weapons-grade uranium, requires a neutron source at a level of 8·10^7 n/s. Let us take it as the value of the neutron source barrier.

Integral protection criterion (*IPC*) for uranium

In order to combine various physical quantities in a single criterion, it is obvious that these quantities must be included in this criterion in a dimensionless form. To do this, let us divide the characteristics of uranium nuclear material, such as its critical mass, the dose load it creates, heat release, and the neutron generation rate by the corresponding barrier values adopted earlier, namely, by the critical mass of uranium enriched up to 20% in uranium-235 (M_0 = 800 кг), dose that brings terrorists into a coma state (D_0 = 20 Sv), heat release that disables all the NED components five hours after their assembly (Q_0 = 2900 W), and neutron source that leads to NED predetonation (S_0 = 8·107 n/s). In this case, each characteristic of nuclear material is evaluated by how much it exceeds the accepted safety barrier (when the material is protected) or is below it (when the material is poorly protected).

Unfortunately, the barrier associated with the radiolysis of uranium hexafluoride cannot be directly included in the *IPC*. However, its influence on the protection of uranium was considered earlier, and this barrier is indirectly taken into account in the *IPC* through the critical mass of uranium.

It is not advisable to formulate the criterion as the product of the indicated fractions, since, at the initial moment of time, pure uranium-232, without its decay chain, does not emit hard γ-radiation and the dose from the material is zero, which means that the material is not mathematically protected. At the same time, such material may have other barriers. Therefore, it is proposed to form the *IPC* as a sum of individual barriers:

$$IPC = M/M_0 + d(t)\cdot X\cdot M/D_0 + q(t)\cdot X\cdot M/Q_0 + s(t)\cdot X\cdot M/S_0, \quad (1)$$

where M is the critical mass of a bare sphere of nuclear material, kg; $d(t)$ is the radiation dose rate in 30 cm from 1 kg of uranium-232 and its daughter nuclides, rem/(h·kg); $q(t)$ is the heat release rate from 1 kg of uranium-232 and its daughter nuclides, W/kg; $s(t)$ is the neutron source power from 1 kg of uranium-232 and its daughter nuclides, n/(s·kg); X is the content of uranium-232 in uranium. The characteristics $d(t)$, $q(t)$, $s(t)$ depend on the storage time of uranium-232, during which the daughter products of uranium-232 decay are formed and, therefore, change with time.

In (Bathke et al. 2012), the term responsible for the radiation dose is raised to the power 1/lg(2) ≈ 3.3. This leads to

a sharp decrease or increase in the contribution of this barrier to the criterion at a dose, respectively, less or more than the chosen value of the barrier (D_0). This approach was not used, since the barrier value was chosen not as a dose of 5 Sv (as in (Bathke et al. 2012)), which did not instantly affect human performance, but a significantly higher dose of 20 Sv leading to instant coma. In (Bathke et al. 2012), the decimal logarithm is taken from the right side of equation (1), which is subtracted from unity, and the resulting expression is considered as the required criterion. Such a complex construction makes it difficult to analyze both the criterion itself and its components. At the same time, the value of the material protection criterion (1) can be easily interpreted as the degree of protection: if the value of the criterion is less than unity, the material can be considered weakly protected or unprotected; if the value of the criterion is equal to or more than unity, the material is protected; and if the value is several units, the material is multiply protected.

The breeding properties of uranium-232 are somewhat inferior to those of uranium-233 and uranium-235. However, since the low content of uranium-232 in uranium will be considered, it will have little effect on the value of the critical mass of uranium and will be neglected in what follows. For the same reason, we will also neglect the decrease in the critical mass associated with the decay of uranium-232, although time intervals of the order of the half-life of uranium-232 will be considered.

Uranium protection degree analysis

Fig. 2 shows the heat release and neutron source rates from one kilogram of uranium-232 as well as the dose rate of 30 cm from 1 kg of uranium-232, depending on the decay time.

It can be seen that all the characteristics increase sharply in the first years, reaching a maximum by about 10 years, and then gradually decrease. The increase in the characteristics is caused by the accumulation of uranium-232 decay products, the amount of which reaches the equilibrium composition after about 10 years. The subsequent decrease in the characteristics is associated with the decay of uranium-232 itself, which is relatively slower than their growth due to the significant value of the half-life of uranium-232. Note that, at the initial moment of time, the heat release and the neutron source rates, although small, are not equal to zero, since uranium-232 itself generates heat as a result of α-decay and neutrons as a result of spontaneous fission and (α, n)-reactions on light nuclei of unremovable impurities. At the same time, the dose rate at the initial moment of time is equal to zero, since it is determined by the hard γ-radiation of the daughter nuclides of uranium-232, which have not yet been formed from uranium-232.

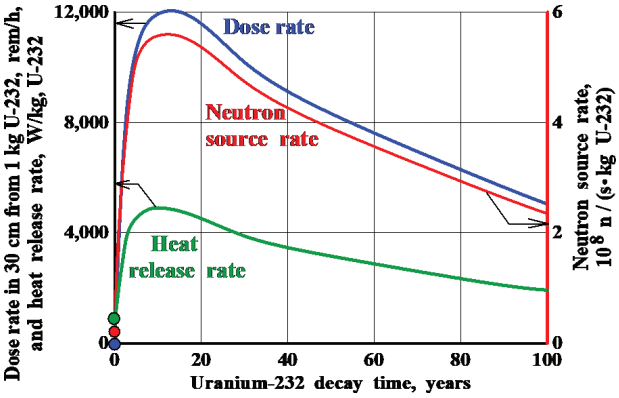

Figure 2. Power characteristics of uranium-232 during its decay (1 rem = 0.01 Sv).

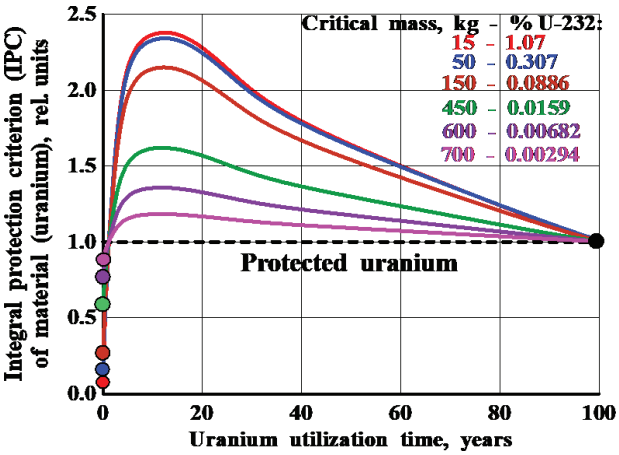

Figure 3. At least one-time protection of uranium with various critical masses by uranium-232 for 100 years.

In the analysis, we will consider various values of the critical mass of a bare uranium sphere: from 15 kg, which corresponds to uranium enriched up to 90% in uranium-233, up to 800 kg, corresponding to uranium enriched up to 20% in uranium-235. As other values, we will consider 50 kg for uranium enriched to 90% in uranium-235 and other intermediate values. Let us consider such additions of uranium-232 to uranium that will provide protection of the material, expressed in the *IPC* at a level of more than unity for a significant time interval (100 years), and after a short initial decay of uranium for several years.

Fig. 3 shows the dependences of the *IPC* for uranium of various critical masses for a period of up to 100 years, and the content of uranium-232 in it is chosen so that at a time of 100 years the *IPC* value will be equal to unity. As can be seen from the dependences, this means that within 100 years the protection of the material will be higher than unity. Moreover, the smaller the critical mass of uranium, the greater the excess of the protection over unity. This is explained by the fact that small critical masses have to be protected by other components of protection: the rate of heat release, neutron background and γ-radiation.

Table 3 shows the contributions of the components to the integral protection criterion of uranium with at least one-time protection for 100 years. It can be seen that as the critical mass becomes larger, the contribution of this component to the protection uranium increases, while the contributions of the other components decrease. At the same time, the content of uranium-232 is reduced to provide the required protection of uranium, which corresponds to the general physical concepts.

Tables 4–6 contain data similar to those presented in Tab. 3 but for cases of higher protection of uranium, namely, at least two-, three- and five-time protection for 100 years. Moreover, the considered critical masses are up to three critical masses of uranium enriched up to 20% in uranium-235, i.e., up to 2400 kg. Of course, in order to enhance the protection of uranium, it is necessary to increase the content of uranium-232 in it.

For the case of the highest (five-time) protection and the lowest critical mass (15 kg), the content of uranium-232 is significant, reaching approximately 5% (Tab. 6). However, it does not mean that this content of uranium-232 is required in the original uranium. Such a small critical mass suggests that terrorists will obtain approximately 90% of uranium-233 through its isotope enrichment. During the enrichment process, the low initial content of uranium-232 will increase much faster than that of uranium-233, since uranium-232 has an even lower atomic weight than enriched uranium-233 compared to depleted uranium-238. According to (Bathke et al. 2012), if only 0.03% uranium-232 is added to natural uranium, then the content of uranium-232 in uranium-235 enriched to 90% will be 6.24%.

Table 6 shows that it is sufficient to introduce only a few hundredths of a percent of uranium-232 into uranium to provide five-time protection for uranium with large critical masses of 1600–2400 kg. Such critical masses correspond to a uranium-233 concentration below 12%. According to the IAEA standards, nuclear material with an enrichment below this value cannot be directly used to create NEDs. Attempting to reduce these large critical masses through enrichment will result in a disproportionate increase in the uranium-232 concentration.

Table 3. Contributions of Components to the Integral Protection Criterion for Uranium with at Least One-Time Protection for 100 Years

Critical mass of a bare sphere, kg	Uranium-232 content, %	Protection degree at maximum, rel. units	Contributions of components to the integral protection criterion of uranium, % (end-to-end limits)			
			Mass	Heat	Neutrons	Dose
15	1.07	2.37	1–12	9–12	42–48	36–41
50	0.307	2.32	3–33	7–11	32–47	28–40
150	0.0886	2.14	9–63	4–11	18–44	15–37
450	0.0159	1.61	35–91	1–8	5–31	4–27
600	0.00682	1.35	55–96	1–5	2–21	2–18
700	0.00294	1.18	74–98	0–3	1–12	1–10

Table 4. Contributions of Components to the Integral Protection Criterion for Uranium with at Least Two-Time Protection for 100 Years

Critical mass of a bare sphere, kg	Uranium-232 content, %	Protection degree at maximum, rel. units	Contributions of components to the integral protection criterion of uranium, % (end-to-end limits)			
			Mass	Heat	Neutrons	Dose
15	2.16	4.77	0.4–7	10–12	45–48	38–41
50	0.634	4.72	1–19	9–12	39–47	33–41
150	0.198	4.55	4–44	6–12	27–46	23–39
450	0.0522	4.01	14–74	3–10	12–41	11–35
600	0.0341	3.75	20–82	2–9	9–38	8–33
700	0.0263	3.58	24–85	2–9	7–36	6–31
800	0.0204	3.40	29–88	1–8	6–34	5–29

Table 5. Contributions of Components to the Integral Protection Criterion for Uranium with at Least Three-Time Protection for 100 Years

Critical mass of a bare sphere, kg	Uranium-232 content, %	Protection degree at maximum, rel. units	Contributions of components to the integral protection criterion of uranium, % (end-to-end limits)			
			Mass	Heat	Neutrons	Dose
15	3.25	7.17	0.5–4	10–12	46–48	39–41
50	0.961	7.11	1–14	9–12	41–48	36–41
150	0.307	6.95	3–33	7–12	32–47	28–40
450	0.0886	6.14	9–63	4–11	18–44	15–37
600	0.0613	6.15	12–71	3–10	14–42	12–36
700	0.0497	5.98	15–75	3–10	12–41	10–35
800	0.0409	5.80	17–79	2–10	10–39	9–34
1600	0.0102	4.40	46–94	1–6	3–26	3–22

Table 6. Contributions of Components to the Integral Protection Criterion of Uranium with at Least Five-Time Protection for 100 Years

Critical mass of a bare sphere, kg	Uranium-232 content, %	Protection degree at maximum, rel. units	Contributions of components to the integral protection criterion of uranium, % (end-to-end limits)			
			Mass	Heat	Neutrons	Dose
15	5.43	11.97	0–3	11–12	47–48	40–41
50	1.615	11.91	0–9	10–12	44–48	38–41
150	0.525	11.75	2–23	8–12	37–47	32–40
450	0.161	11.20	5–49	6–11	25–45	21–39
600	0.116	10.97	7–57	5–11	21–45	18–38
700	0.0964	10.78	8–61	4–11	19–44	16–38
800	0.0818	10.60	9–65	4–11	17–43	14–37
1600	0.0307	9.21	22–83	2–9	8–37	7–32
2400	0.0136	7.79	39–92	1–7	4–29	3–25

Fig. 4 shows the required content of uranium-232 in uranium at various critical masses and minimum *IPCs* for the material. It is obvious that an increase in the degree of protection requires an increase in the content of uranium-232. However, for large critical masses, which correspond to the fuel of fast reactors, the content of uranium-232 is on the order of hundredths of a percent.

It should be noted that for materials with large critical masses, a smaller source of neutrons is required as protection against propagation than is included in the integral protection criterion, since it is difficult to accelerate large masses to high velocities or quickly implode them with the creation of significant supercriticality. This leads to an increase in the time during which NED predetonation is possible due to the neutron source, resulting in a decrease in its energy output. Numerical evaluation of this issue requires a separate detailed consideration.

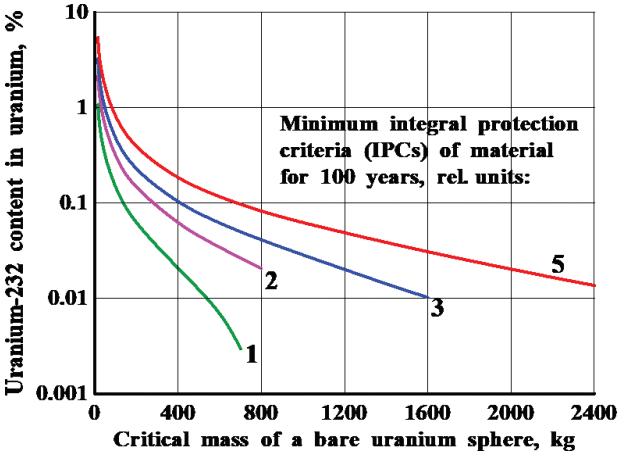

Figure 4. Dependence of the content of uranium-232 in uranium on the value of its critical mass at various *IPCs*.

Conclusion

1. For a comprehensive assessment of the protection of uranium against its unauthorized use due to the presence of uranium-232 in it, the authors of the article propose and justify an integral protection criterion (*IPC*) for uranium. The criterion is based on the physical barriers against the proliferation of uranium created by uranium-232, namely: (1) the radiolysis of uranium hexafluoride, which hinders attempts to re-enrich uranium and, as a result, a significant critical mass; (2) hard γ-radiation, which leads to incapacity and death of those who try to handle this material without radiation protection; (3) increased heat release, which disables the components of a nuclear explosive device; and (4) a significant source of neutrons that causes predetonation and thereby reduces the energy yield of a nuclear explosive device. These barriers appear at various stages of uranium handling not only in the indicated order but also act simultaneously, mutually reinforcing one another.
2. The performed analysis of the contribution of the barriers to the *IPC* shows the significance of all the barriers. This indicates the reliability of the proposed *IPC*. The performed comprehensive analysis of the protection of uranium has revealed that, depending on the required degree of protection of the material and the capabilities of terrorists to enrich it, the required content of uranium-232 in uranium ranges from several thousandths of a percent to several percent, which can be obtained in an irradiated thorium blanket of a thermonuclear reactor, as it was shown earlier. The specific content of uranium-232 must be chosen based on the fact that fuel-producing countries are still able to handle such uranium, but it would be extremely difficult for terrorists to use it to create NEDs on its basis.

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