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Possibilities for Nuclear Isotopes Production in WWER-1000 type of Reactors for Military Purposes

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Abstract. Weapons-grade substance is a material with level of enrichment or with characteristic suitable for nuclear bombs production. The most commonly used weapon-grade isotopes in different experiments are uranium-235 and plutonium-239. It is known that isotopes like uranium-233, neptunium-237 and some isotopes of americium have also been used for the purposes of experimental researches, but by now there is no information they have been used for a real nuclear weàpons production. The goal of the present analysis is to be examined if the spent nuclear fuel of the most common nuclear reactors for electricity production, viz. pressurized water reactors, can be classified as practically unusable or not for nuclear explosive made-up. The possibilities for nuclear materials producement are analyzed and the concentration levels of the main isotopes (plutonium-239, neptunium-237, americium-241, americium-242m and americium-243) are examined and estimated. The significant quantities necessary for nuclear bombs production according to International Atomic Energy Agency are also estimated by comparing them with the obtained results. The results of this analysis may be useful in specifying the technical and organization actions which can increase the proliferation resistance of the fissile materials.

Keywords: explosive device, nuclear bomb, significant quantity, weapons-grade material

1 Weapons-Grade Materials

Weapon-grade substance is a material with level of enrichment or with characteristic suitable for nuclear bombs production. Most commonly used materials for nuclear weapons production are uranium and plutonium. The classification of these materials is based mostly on their chemical purity.

Only fissile isotopes of definite elements have the potential to be used for nuclear weapons production. These isotopes are uranium-235 and plutonium-239. But one of the requirements for such usage is high available concentration of fissile isotopes. The uranium, extracted from natural sources, is enriched through isotope separation, and plutonium is artificially produced in the nuclear reactors.

The most commonly used weapon-grade isotopes in different experiments are uranium-235 and plutonium-239. It is known that isotopes like uranium-233, neptunium-237 and some isotopes of americium (americium-241, americium-242m, americium-243), have also been used for the purposes of experimental studies, but by now there is no information they have been used for a real nuclear weàpons production.

Weapons-grade Uranium

The share of uranium-235, most suitable for military purposes, in natural uranium is 0.711% and the rest is consisting almost of uranium-238. The uranium-235 separation from natural uranium is executed through method utilized the differences in their masses. Enriched uranium is quantity of uranium in which the percentage share of uranium-235 is increased with isotopic enrichment process. Therefore weapons-grade uranium represents uranium with percentage share of uranium-235 above 90%.

Uranim-233 is artificially produced after neutron absorption on thorium-232 (Eq. (1)). The obtained uranium-233 in thus way does not require enrichment and can be easily separated from the residual thorium-232.

$$n + {}^{232}\mathrm{Th} \rightarrow {}^{233}\mathrm{Th} \xrightarrow[22\ \mathrm{min}]{\beta^-} {}^{233}\mathrm{Pa} \xrightarrow[27.4\ \mathrm{days}]{\beta^-} {}^{233}\mathrm{U}^{(160\,000\ \mathrm{years})} \quad (1)$$

For this reason uranium-233 is controlled as “special nuclear material” only by his total presence quantity. That is why he is deliberately blended with uranium-238 in order for increasing the proliferation resistance [1,2].

Weapons-grade Plutonium

Plutonium-239 is also artificially produced in the nuclear reactors in result of neutron absorption on uranium-238, as it is shown in Eq. (2).

$$n + {}^{238}U \rightarrow {}^{239}\mathrm{U} \xrightarrow[24\ \mathrm{min}]{\beta^-} {}^{239}\mathrm{Np} \xrightarrow[2.4\ \mathrm{days}]{\beta^-} {}^{239}\mathrm{Pu}^{(24\,000\ \mathrm{years})} \quad (2)$$

Weapons-grade plutonium is defined by the concentration of plutonium-240, which is $\leq 7\%$. Plutonium-240 is produced after the neutron absorption on plutonium-239. The most intrinsic characteristic of plutonium-240 is the high rate of spontaneous fission events, making it an undesirable contaminant. Exactly the plutonium-240 con-

centration is the reason for the impossibility for producing gun-type plutonium bombs.

In order for plutonium-240 reducement in the total generated plutonium, the nuclear fuel used in the reactors built for military purposes, stays inside the core considerably less (around 3–4 moths) in comparison to conventional nuclear reactors. From this difference originate the fundamental distinction between these two types of reactors – the commercial nuclear reactors for electricity production and the reactors built for both electricity and nuclear materials for military purposes production. In typical conventional nuclear reactor, high burn-up is most desirable. Nuclear reactors as the English Magnox and French Gas Cooled Reactors built for both electricity and weapons-grade plutonium production have been exploited on low power levels with frequent refueling exactly for weapons-grade plutonium production with low plutonium-240 levels. This regimen of working is impossible for light water reactors built mainly for electricity production. In order to produce high-quality plutonium in these types of reactors, they must be shut down and the reactor pressure vessel lid must be removed [2].

Sometimes the commercial nuclear reactors could generate nuclear fuel with low burn-up – when accident happens correlated with fuel damage which will lead to early refueling and removing the damaged fuel. If the "burning" time length of this fuel was sufficiently short, then this spent fuel could be reprocessed in order for weapons-grade plutonium production.

Weapons-grade Neptunium

Neptunium-237 has high fast fission cross section and half-life above 2 million years, therefore it has very low radioactivity. Similar to uranium-235, the gamma ray dose rate is low and therefore it not represents considerable risk for human health. Similar to uranium-233, the spontaneous fission neutron emission rate is also low, therefore it cannot be reason for pre-detonation of the nuclear weapons. Because of these particular reasons neptunium-237 could be used in simple gun-type nuclear bombs production as an alternative variant on the plutonium bombs which require implosion devices for managing the pre-detonation obstacles of plutonium-240. As the heat emission rate of neptunium-237 is also low, it may be used as material for high effective implosion type nuclear weapons also.

Nuclear fuel cycle of light water reactors produces only one isotope of neptunium – neptunium-237. Therefore, in comparison to the uranium and plutonium isotope cases, the chemical separation of neptunium instantly leads to pure neptunium-237 yield without denaturation possibility from other neptunium isotopes. For that reason, the neptunium proliferation resistance improvement is considerably more difficult task, than on all other isotopes, which have the potential for nuclear weapons production. The most significant production branch of neptunium-237 is the transmutation chain of uranium-235 through uranium-237 [3].

$$^{235}\mathrm{U} \xrightarrow{n,\gamma} {}^{236}\mathrm{U} \xrightarrow{n,\gamma} {}^{237}\mathrm{U} \xrightarrow{\beta-} {}^{237}\mathrm{Np} \qquad (3)$$

When neptunium-237 undergoes additional neutron irradiation, it will be put under the following transmutation, Eq. (4):

$$^{237}\mathrm{Np} \xrightarrow{n,\gamma} {}^{238}\mathrm{Np} \xrightarrow{\beta-} {}^{238}\mathrm{Pu} \qquad (4)$$

This transmutation reaction shows us that the neptunium-237 proliferation defense could be improved by multi-staged recycling back in the fuel cycle after it has been reprocessed from the spent nuclear fuel [4]. This process will lead to neptunium-237 destruction which will result in increased heat emission because of the radioactive decay of the plutonium-238. The Proliferation resistance will be increased as a result.

Weapons-grade Americium

The three most important americium isotopes, produced in nuclear fuels, are americium-241, americium-242m and americium-243. When it is removed from the core, the spent nuclear fuel contains mix of these three americium isotopes. Americium-241 is produced via radioactive decay of plutonium-241 (Eq. (5)), which have relatively short half-life of 14.3 years and represents up to 15% from the total plutonium in the spent nuclear fuel [4].

$$^{241}\mathrm{Pu} \xrightarrow[14.325\ \text{years}]{\beta^-} {}^{241}\mathrm{Am} \xrightarrow{n,\gamma} {}^{242}\mathrm{Am} \xrightarrow{\beta^-} {}^{242}\mathrm{Cm} \xrightarrow[163\ \text{days}]{\alpha} {}^{238}\mathrm{Pu} \qquad (5)$$

Pure americium-241 can be generated also in spent fuel after long time storage. The total americium quantity in the spent nuclear fuel is not much (because of high thermal fission cross section of plutonium-241), but significant quantities of americium-241 can be generated after the fission process is stopped [1].

As of the end of 2003, the world inventory of neptunium-237 and americium was estimated to exceed 140 tons, enough for more than 5000 nuclear weapons and the amount is growing at a rate of about 7 tons per year. Almost all neptunium and americium is in irradiated fuel or mixed with high level nuclear waste. Only relatively small quantities of these materials have been separated into forms usable in nuclear weapons. As it was noted above, the neptunium-237 can be separated from irradiated reactor fuel as a single isotope, while the separated americium from the reactor fuel would be composed of americium-241, americium-242m, and americium 243, although older spent power reactor fuel contains mostly americium-241.

Americium is relatively hard for separation with the conventional methods and therefore some states develop alternative strategies for it separation. There is a practice in the MOX fuel fabrication plants for americium separation, although the quantities are insignificant. The reason for the americium partitioning is reducing the dose rates of the staff during the manufacturing processes of the fuel assemblies. MOX fuel fabrication plant with annual capacity of 40 tons could separate about a 90 kg americium-241 annually.

2 Nuclear Materials Requirements for Weapons Production

Uranium-233 requirements

The uranium-233 requirements for weapons production is result only from its high radioactive fission products and especially thallium-208, which has a great influence even if it concentration levels are as low as 0.0005%. Accumulation of uranium-232 during generation of uranium-233 is unavoidable. This is similar to the plutonium isotope contamination problem but occurs to a much smaller extent rate. Nuclear weapons made by using implosion method require concentration levels of uranium-232 below 0.005%. Above this level, uranium-232 is considered a low grade. Nuclear weapons made by using gun-type method require very low concentration levels of uranium-232 also and less than 0.0001% concentration levels of other impurities.

In WWER-1000, uranium-233 is not produced, because of lack of thorium-232 in addition to the startup fuel. Therefore it will not be a subject to the present analysis.

Plutonium-239 requirements

The plutonium-239 requirements for weapons production originate mainly from plutonium-240 content. Pltunonium-240 has very high rates of spontaneous fission, which increases neutrons emission in the nuclear material and can be a reason for pre-detonation of the weapon and consequent blow-up of the implosion fuel before the designed level of compression and reactivity could be attained, thereby greatly reducing the average energy yield of such "fizzle" bombs. In nuclear weapons, a fizzle occurs when the testing of a nuclear bomb grossly fails to meet its expected yield. Therefore these weapons are often referred to as "fizzle" bombs – they do not explode, they pre-detonate (very small explosion/merely fizzle), resulting in blowing-up the nuclear material, which do not allow for a supercritical mass formation [6].

As can be seen from the current generally accepted classification of the proliferation potential of the different plutonium mixtures in Table 1, the presence of more than 7% plutonium-240 reduces the high-yield weapons usability of the plutonium mixture in reactor spent fuel.

Table 1. Nuclear proliferation classification of plutonium grades

Grades	Pu-240 %	Usability
Super-grade	< 3	Best quality
Weapon-grade	3–7	Standard material
Fuel-grade	7–18	Practically usable
Reactor-grade	18–30	Conceivably usable
MOX-grade	> 30	Practically unusable

Neptunium-237 requirements

The neptunium, which is generated in the spent nuclear fuel of light water reactors using uranium and uranium-plutonium fuels, is a single neptunium isotope – neptunium-237. Therefore after its chemical separation, pure neptunium-237 isotope is produced, undenaturated from other neptunium isotopes and completely suitable for nuclear weapons production. This hides the largest hazard for neptunium-237 proliferation. WWER-1000 spent nuclear fuel contains significant quantities of neptunium-237 and therefore it is a subject of interest of the particular analysis.

Americium requirements

There are no strict regulation requirements or standards in terms of americium requirements for explosive devices manufacturing as to this moment there is no information if these isotopes have been used for such purpose. Three isotopes of americium are produced in WWER-1000 nuclear reactors, as two of them – americium-241 and americium-243 have the potential for nuclear bomb production, as the solely condition for their usage is their chemical separation from the irradiated nuclear fuel. Americium-241 is most suitable for explosive manufacturing because of its appropriate characteristics (it is cheaper than americium-243 and have less critical mass). Mainly americium-241 and americium-243 are generated in the spent nuclear fuel of WWER-1000 type of reactors, as americium-243 concentration level is higher. Americium-242m concentration level is insignificant, as this isotope possess very high fission cross section which prevents its accumulation in the fuel.

3 Spent Nuclear Fuel Isotopic Composition Examination of WWER-1000 Type of Reactors

The isotopic composition of TVS-A fuel assemblies of WWER-1000 B320 type of reactors is investigated with specialized thermo-mechanical software called TRANSURANUS. The technical characteristics of these fuel assemblies, included in the present model, are represented in Table 2. Fuel rods are divided into ten axial slices with equal high for the purposes of simulation analysis.

Table 2. TVS-A technical specifications, TRANSURANUS

Year of manufacture	1998
Number of fuel assemblies in the core, n	163
Number of fuel rods in one fuel assembly, n	312
Outer fuel diameter, mm	7.57
Inner fuel diameter, mm	1.5–1.4
Fuel assembly high, mm	3530
Fuel cycle length, y	4×320
UO_2 density, kg/m^3	10470
Fuel burn-up, MWd/kgU	55
Outer/Inner cladding diameter, mm	9.1/7.73
Fuel initial enrichment, %	4.39
Grain diameter, μm	10
Burnable absorber	Gd_2O_3
Fuel rod mass/UO_2 mass in one fuel rod, kg	1.60653
Core fuel mass, kg	80603.5
U (HM) mass in fuel assembly, kg	435.864
O_2 mass in fuel assembly, kg	58.636
U (HM) mass in all fuel assemblies/core, kg	71014.9
Surface roughness fuel, μm	≤ 0.2
Surface roughness clad, μm	≤ 1.5

Reliability of the obtained results is validated by comparison with results from simulation model created with specialized sub-module for isotopic depletion calculations, part from the SCALE software. The latter is developed for

comprehensive modeling and simulation suite for nuclear safety analysis and design. Simulation model input parameters are shown in Table 3. The used specialized submodule of SCALE is called ORIGENARP.

Table 3. Simulation model input parameters for spent nuclear fuel isotopic calculation on WWER-1000, SCALE

Type of reactor	WWER-1000
Thermal reactor power, MWt	3000
Initial enrichment, %	4.39
Average thermal power, MW/tU	41.6
Fuel cycle length, days	4×320
Fuel burn-up, MWd/tU	53348
Heavy Metal mass in the core, kgHM	71 015
Refueling time, days	45
Cooling time, years	5–100

Plutonium isotopes concentration levels

Spent fuel isotopic composition information in the end of the fuel cycle is shown in Table 4. Data is obtained from both simulation models – TRANSURANUS and SCALE.

Table 4. Plutonium isotopes content in WWER-1000 spent nuclear fuel in the end of fuel cycle, calculated by TRANSURANUS and SCALE

Simulation model	TRANSURANUS			SCALE
Initial enrichment, %	4.39			4.39
Time in fuel cycle, h	$t = 30720\ (4 \times 320)$			$t = 30720\ (4 \times 320)$
Fuel rod slice	10	4	average	average
Burn-up, MWd/kgHM	20.142	71.176	53.093	54.067
Total Pu, %	0.709	1.245	1.114	1.198
Total Pu, kg			791.11	850.76
Pu-240, %	15.91	23.31	**22.36**	**24.42**
Pu-240, kg			176.90	207.75

Plutonium-240 average concentration for fuel rod in the TRANSURANUS model is 22.33% of total plutonium concentration and 24.42% in SCALE model respectively. Despite this 2 % difference which has no statistician significance in terms of grades, both fuels are categorized as reactor-grade. Plutonium-240 concentration in so called reactor-grade is between 18 and 30% and it is classified as conceivably usable. The fuel in the 10th slice of the fuel rod (the slice with lowest neutron flow) from the TRANSURANUS model, with 15.9% plutonium-240 concentration lands into fuel-grade and it is practically usable for nuclear bombs production.

Table 5. Plutonium isotopes content in WWER-1000 spent nuclear fuel in the beginning of fuel cycle, calculated by TRANSURANUS and SCALE

Simulation model	TRANSURANUS			SCALE
Initial enrichment, %	4,39			4,39
Time in fuel cycle, h	$t = 3336$ (139 day)			$t = 2904$ (121 day)
Fuel rod slice	10	4	average	average
Total Pu, %	0.110	0.342	0.2627	0.2241
Total Pu, kg			186.55	159.14
Pu-240, %	**2.92**	**8.32**	**7.04**	**7.04**
Pu-240, kg			13.13	11.20

Plutonium isotopes content in the WWER-1000 spent fuel in the beginning of the fuel cycle when plutonium-240 concentration reaches up to 7% is represented in Table 5 [7,8]. This means that in case of an accident related to fuel rod damage in the beginning of the fuel cycle and consequent discharge of the fuel (139 days in the TRANSURANUS model and 121 days in the SCALE model), the plutonium produced up to this time will be weapon-grade or with other words with extremely high quality for weapons production.

Plutonium in the upper part of the fuel rod (upmost 35.3 cm) from the TRANSURANUS model will be with 2.92% plutonium-240 concentration and will land directly in super-grade class. This is the highest possible plutonium quality for nuclear bomb production. Super pure material will be produces if eventual extraction in reprocessing factory happens.

Neptunium-237 concentration levels

Neptunium-237 content in WWER-1000 spent nuclear fuel is represented in Table 6. While the TRANSURANUS code do not give the possibility for neptunium-237 concentration calculation, for validating the results obtained on SLALE model, the data are compared with results obtained on Nuclear Fuel Cycle Simulation System, VISTA, represented in [9].

As it can be seen in Table 6, the results are almost completely identical.

Table 6. Neptunium-237 content in WWER-1000 spent nuclear fuel in the end of the fuel cycle, calculated by SCALE and VISTA

Simulation model	SCALE	VISTA
Initial enrichment, %	4.39	4.39
Time of fuel cycle, h	$t = 30720\ (4 \times 320)$	$t = 30720\ (4 \times 320)$
Np-237, %	0.0787	0.0791
Np-237, kg	55.88	56.17

Neptunium-237 accumulation after spent nuclear discharge from the core up to 100 years is represented in Table 7. As it can be seen from the results, the accumulation tendency is gradual and for a time period of 100 years, the generated neptunium-237 will be 50% more than the initial quantity.

Table 7. Neptunium-237 content in WWER-1000 spent nuclear fuel in different stages after the end of the cycle, calculated by SCALE

Cooling time, years	Np-237, %	Np-237, %
0.1	0.08026	56.99
0.3	0.08030	57.02
1	0.08032	57.04
3	0.08039	57.09
5	0.08051	57.17
10	0.08098	57.51
30	0.08451	60.01
50	0.08929	63.41
70	0.09444	67.06
100	0.10220	72.58

Americium isotopes concentration levels

Weighted and percentage share of americium-241, americium-242m and americium-243 in WWER-1000 irradiated fuel is represented in Table 8.

Table 8. Americium isotopes content in WWER-1000 spent nuclear fuel, calculated by TRANSURANUS and SCALE

Simulation model	TRANSURANUS			SCALE
Initial enrichment, %	4.39			4.39
Time of fuel cycle, h	$t=30720\ (4\times320)$			$t=30720$ (4×320)
Fuel rod slice	10	4	average	average
Fuel burn-up, MWd/kgHM	19.59	69.23	51.64	54.07
Am-241, %	2.61E-03	4.10E-03	4.44E-03	5.82E-03
Am-241, kg			3.15	4.13
Am-242m, %	—	—	—	1.25E-04
Am-242m, kg			—	0.088
Am-243, %	8.36E-04	0.0659	0.0362	0.0287
Am-243, kg			25.71	20.38

Americium-241 quantity is insignificant – 3.15 kg in the TRANSURANUS model and 4.13 kg in the SCALE model. Americium-242m is not calculated in TRANSURANUS model, because of its insignificant generated quantity due to its high fission cross section. As can be seen in the SCALE model, the americium-242m concentration in the end of the fuel cycle is only 0.09 kg. The biggest share of americium isotopes, generated during burning process, possess americium-243, which is 25.71 kg in the TRANSURANUS model and 20.38 kg in the SCALE model.

Nevertheless, the major americium quantity is generated through plutonium-241 decay (Eq. (6)) after the end of the fuel cycle. Americium isotopes concentration levels in different stages after end of the campaign are represented in Table 9.

Table 9. WWER-1000 spent nuclear fuel isotopic composition during 100 years of storage, calculated by SCALE

Cooling time,	Isotopes concentration levels, kg			
years	Pu-241	Am-241	Am-242m	Am-243
0.1	127	4.75	0.0886	20.4
0.3	126	5.97	0.0884	20.4
1	122	10.1	0.0881	20.4
3	110	21.3	0.0873	20.4
5	100	31.3	0.0864	20.4
10	78.6	52.5	0.,0843	20.4
30	29.9	98.6	0.0764	20.4
50	11.4	114	0.0693	20.3
70	4.33	117	0.0628	20.3
100	1.02	115	0.0542	20.2

$$^{241}_{94}\mathrm{Pu} \xrightarrow[14.325\ \text{years}]{\beta^-} {}^{241}_{95}\mathrm{Am} \qquad (6)$$

The americium-242m and americium-243 quantity do not change expectantly. Only americium-241 quantity grows up exponentially along with the radioactive decay of plutonium-241. This means that after eventual 100 years dry storage of the spent nuclear fuel, the generated americium-241 will be 36 times higher and the present plutonium-241 will be 125 times less than their initial quantities.

4 Results and Discussion

As a result of the conducted analysis and obtained results the following conclusions for nuclear explosive-related materials, produced in WWER-1000 spent nuclear fuel, can be drawn:

Plutonium

In case of nuclear accident related to fuel rod damage and consequent discharge of the fuel up to 121st day from the beginning of the fuel cycle, the generated plutonium will be weapon-grade i.e. with quality sufficient for 19 high effective nuclear explosive devices manufacturing (19.89 SQ).

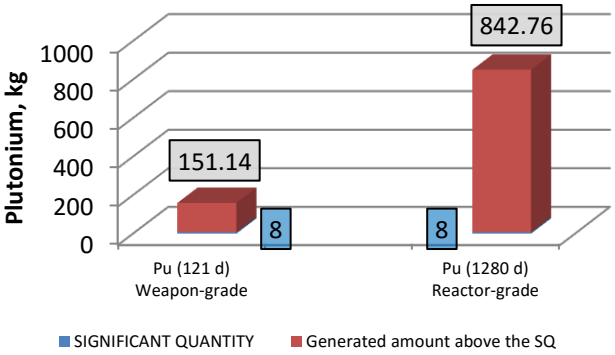

Figure 1. Plutonium generated quantity above the "significant quantity", required for nuclear explosive device manufacturing.

The plutonium, generated in the end of the fuel cycle, will be reactor-grade plutonium with plutonium-240 concentration levels of 24.42%. Taking into account the effect of isotopic dilution on critical mass (both Pu-239 and Pu-241 are fissile, the others are less so) a bomb fashioned from 8 kg of this material would put out 116 watts (a light bulb of similar size and power is too hot to hold), and 2.8 million neutrons/sec. Using this material in a bomb would be a challenge. The high rate of neutron emission means that pre-detonation is inevitable, even with a very efficient implosion system. With optimal implosion design yields in the range of at least several kilotons are possible. If fusion boosted is used, then the adverse effects properties of reactor-grade plutonium can be completely overcome, allowing its use in efficient high-yield designs although the material would be less convenient to use [11]. Taking this into account and according the definition of "significant quantity" of IAEA, the generated amount of plutonium in the end of the fuel cycle will be sufficient for more than 106 nuclear weapons manufacturing (106.3 SQ).

Neptunium-237

The neptunium-237 (Figure 2), generated in WWER-1000 spent nuclear fuel in the end of the fuel cycle, will be sufficient for more than 2 nuclear explosive devices manufacturing (2.24 SQ).

With increase of the spent fuel time period storage after its removal from the reactor, the amount of generated neptunium also increase. After 100 years storage, the generated neptunium will be in amounts sufficient for almost 3 nuclear explosive devices manufacturing (2.9 SQ).

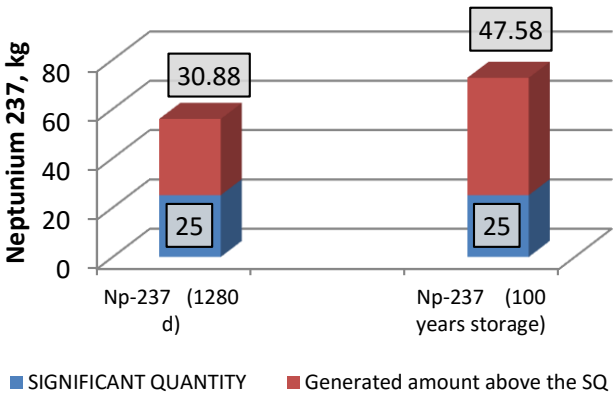

Figure 2. Neptunium-237 generated quantity above the "significant quantity", required for nuclear explosive device manufacturing.

Americium-241

In the end of the fuel cycle, the generated americium amount is not enough for nuclear weapon production, but after a few decades storage (100 years), the accumulated americium-241 will be sufficient for more than 4 nuclear explosive devices manufacturing (4.6 SQ).

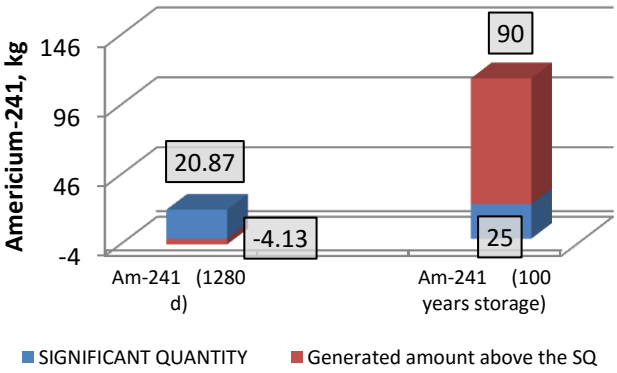

Figure 3. Americium-241 generated quantity above the "significant quantity", required for nuclear explosive device manufacturing.

Significant Quantities

According to the IAEA, significant quantities of neptunium-237 and americium-241 would be similar to the significant quantity for uranium-235 in highly enriched uranium (HEU), namely 25 kilograms (Table 10) [1]. "Significant quantity" is defined as the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded.

Table 11. Significant quantities, IAEA

Material	SQ
Direct use nuclear material	
Pu[a]	8 kg Pu
U-233	8 kg U-233
HEU (U-235$\geq$ 20%)	25 kg U-235
Np-237 (2)	25 kg Np-237
Am-241 (2)	25 kg Am-241
Indirect use nuclear material	
U (U-235 $\leq$ 20%)[b]	75 kg U-235 (or 10 t natural U or 20 t depleted U)
Th	20 t Th

[a] For Pu containing less than 80% Pu-238.
[b] Including low enriched, natural and depleted uranium.

From the Cochran and Paine analysis [12] can be concluded that the IAEA "threshold amounts" and "significant quantities" are overly optimistic and not technically valid in the light of the persistent reports of large accounting discrepancies at plutonium production facilities intended for peaceful use.

Proof for their inaccuracy is the design of the first tested nuclear bomb and the second of only two nuclear weapons ever used in warfare, Fat Man, which was made from 6.1 kg weapons-grade plutonium (in comparison with 8 kg defined by IAEA as "significant quantity") and has a blast yield of 21 kt. Considering that, the IAEA significant quantities must be reevaluated in order to adequately reflect the technological/sophisticated techniques available to non-nuclear weapon states.

The necessity of lower "significant quantity" threshold come from the fact, that nuclear material can be diverted from more than one source. The practice of setting higher levels to account for manufacturing losses is also impru-

Table 10. Nuclear Explosive-Related Properties of Actinides, IAEA

Nuclide	Half-life, y	Critical mass, kg	Heat emission rate, watts/kg	Spontaneous Fission Neutron Emission Rate, n/kg/sec	Gamma ray dose rate, mSv/hr/kg at 1 cm
U-235	7.038×10^8	53	negligible	negligible	negligible
Np-237	2.14×10^6	56	negligible	negligible	1.04
Pu-238	87.74	10	567	2 590 000	0.19
Pu-239	24.119	13	1.9	16	0.05
Pu-240 [5]	6560	40	6.8	910 000	—
Pu-241 [5]	14.4	10	4.2	49	—
Pu-242 [5]	376 000	100	0.1	1 700 000	—
Am-241	433.6	60	114	1 375	50
Am-242m	141	9(a)	1.5–380(b)	4.6×10^4–6.5×10^7(b)	6500
Am-243	7370	150(a)	6.4	714	38

(a) Calculated; (b) The lower values of heat and neutron emissions correspond to freshly separated Am-242m. These values increase sharply as the curium radioactive daughter product accumulates and decays.

dent, particularly in view of the fact that a significant fraction of these "losses" are technically recoverable [11]. In order to these facts, the WWER-1000 spent fuel generated nuclear materials can be sufficient for more than two times more nuclear weapons in comparison of the number calculated when the "significant quantities" are used as a basis.

While reactor-grade plutonium would probably be of no interest to a nation with access to better grade material, it could be effectively used by a nation capable of good weapon design, but without access to better fissile material. Even a low technology nation could fashion powerful weapons from low quality nuclear material. Therefore, spent nuclear fuel of light water reactors could be used as a source of nuclear materials used for highly effective weapons production and such option must not be excluded by no means [12]. Therefore there is a necessity of even more severe regulatory control, especially in the plutonium production facilities, and higher proliferation resistance on all nuclear cycle stages, which will guarantee higher security and reliability not just on the nuclear energy but on the nuclear industry at all [12].

5 Conclusions

As a result from the conducted analysis, the conclusion that can be drawn is that the WWER-1000 spent nuclear fuel is by no means proliferation resistant. It could be a source of nuclear materials, as suitable for manufacturing high effective nuclear weapons, as such will low levels of compression (power). The WWER-1000 spent nuclear fuel will carry a prolong proliferation risk even after its removal from the reactor core. However, the diminishing of the radiation emissions from the spent fuel fission products and as well as heat emission rate decrease in combination with neptunium-237 and americium-241 amounts increase (after long storage the americium in the spent fuel must be separated in order for a low radiation dose levels of the staff in MOX manufacturing factory) in the future will lead to lower proliferation resistance/high proliferation rate of the nuclear material.

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