Features of light-water reactor fuel made of reprocessed uranium in terms of IAEA safeguards implementation

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Abstract. One of the main priorities of nuclear power development is Non-Proliferation of Nuclear Weapons. So, the possibility of nuclear materials illicit diversion must be ruled out. This study aims to assess the chance of producing significant quantity of Highly enriched uranium (HEU) in case of covert diversion of fresh fuel. Analysis is carried out on the assumption that stolen reactor-grade Low enriched uranium (LEU) fuel was made of reprocessed uranium and got to be enriched to 90% 235U in gas centrifuges. As its isotopic composition contains a set of even-numbered minors 232,234,236U, such operation for producing the main component of nuclear explosive device is harder comparing to one when fuel was made of natural uranium. Despite the higher proliferation resistance of reused fuel, there is a chance that it could be used in undeclared nuclear weapons programs. So, we are highlighting the importance of timely detection of nuclear materials diversion, especially for the LEU, which is the most sensitive to proliferation. Fortunately, due to unique physical properties of reprocessed uranium, such detection is possible with a quick NDA test even in case of a single fuel rod replacement.

1. Introduction
The main security barriers of a nuclear energy system from proliferation are based on its internal characteristics or imposed external measures. Speaking about the first category, in order to increase the resistance of the system to proliferation, steps to increase the intrinsic security of the employed nuclear materials can serve as a universal approach. In the last decades the uranium route to a nuclear weapons become more attractive than plutonium one due to the stealthiness of centrifuge technologies [1]. So, as the greatest risk of nuclear proliferation is connected with low-enriched uranium combined with modern enrichment technologies [2], the measures for increasing its immanent resistance should be imposed. The reasonable ways to do this are linked to 235U, which constitutes an intrinsic barrier against nuclear proliferation. Its presence in the proposed fuel is advantageous as the highly penetrating gamma rays emitted by the daughter element Tl-208, which requires the protection of personnel when working with this material, as well as the protection of the equipment itself. To employ this artificial isotope, the used uranium fuel is supposed to be recycled [3]. For example, in [4] authors proposed fuel half-made of reprocessed
uranium, and [5] come up with the idea of denaturing LEU through blending it down by natural uranium and adding over-enriched reprocessed uranium, containing light element impurities. As for the other even-numbered isotopes, $^{234}$U, being lighter than target fissile $^{235}$U, tends to accumulate in the product flow of the separation cascade (the same is true for $^{232}$U) leading to probable dissociation of working gas UF$_6$ owing to a series of alpha decays hindering the process of enrichment. Another element undesirable by perpetrators is $^{236}$U, which is a strong neutron absorber thus making the material less suitable for diversion due to neutron-physical characteristics. As a bonus, worth mentioning that $^{232}$U and $^{236}$U in LEU uranium serve as individual identifiers of each fuel assembly [2] as the abovementioned TI enhance the detectability of possible diversion, ushering us to the second issue.

Speaking about the second point – exterior control – the compliance with regulations are obligatory under the global Treaty on the Non-Proliferation of Nuclear Weapons [6]. The general measures are prescribed by the IAEA safeguards that aims to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology. These guides address the activities undertaken to effectively facilitate IAEA verification activities such as inspections or surveillance [7]. So, the main aim of exercised routines, as was stated before, is prevention or timely detection of the diversion of significant quantity (SQ) – the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded; it should be done in the interval of ‘Detection time’ – the maximum time that may elapse between diversion of a given amount of nuclear material and detection of that diversion by IAEA safeguards activities [8]. These measures depend on the category of material to be diverted, and in our case as we deal with LEU, principles assume this detection during the year for a quantity of nuclear material, which contains 75 kg of $^{235}$U, hence the purpose of the study should be put as follows:

2. Study object
This work aims to answer the question how the initial composition of LEU fuel connects with its intrinsic resistance to nuclear proliferation. Basically, the statement is as follows: Is it possible to produce enough material for a nuclear explosive device in case of dealing with recycled uranium as a source?

As entry conditions we consider occurrence of an illicit diversion of one significant quantity of uranium from a fresh fuel (made of re-enriched reprocessed uranium) of a VVER-type reactor with an average enrichment of 4.6%, operating in a one-and-a-half-year overload cycle. In the study we estimate the number of separation elements required for producing a significant amount of HEU with an enrichment of 90% over a period from three months to two years with a fixed amount of starting material. Note, that the detection time for stolen LEU should not exceed one year according to IAEA safeguards and has the order of 3-12 months [8].

3. Main part
Speaking about this undeclared activity and its timely detection problem in the framework of our task, the technical objective of the IAEA safeguards is to detect the covert abduction of 691 fuel rods containing 1167.9 kg of uranium dioxide, which corresponds to 1029.4 kg of uranium metal that include 75 kg of $^{235}$U – one significant quantity. For instance, to get the chance of circumventing the standard inspection procedure, the perpetrator could take no more than 10 fuel rods from each of 72 fuel assemblies during their overloading into the reactor.

As the next step to produce HEU the state-of-art technology of gas centrifugation could be applied. In the similar way as the basic cascade of gas centrifuges allows to produce LEU from natural uranium, the HEU could be generated from the LEU-grade hexafluoride after the uranium dioxide conversion. Worth mentioning that enriching LEU to HEU requires less separative work than enrichment natural uranium to LEU [2].
3.1. Calculation model
To summarize the key assumptions for the calculations: 1167.9 kg of \( \text{UO}_2 \) is available from fresh fuel based on re-enriched reprocessed uranium; two types of centrifuges (URENCO supercritical 3-m-long TC-12 machine and Russian-type GC [9]) were considered; concentration of \( ^{235}\text{U} \) in the product flow of the cascade is set at level of \( C_p = 90\% \) – boundary of Weapons-grade enrichment level; the concentration in waste flow was varied in range \( C_w = [0.1\%-4.5\%] \), matched to the task in hand; quasi-ideal cascade [10] that is used in isotope separation theory for multicomponent mixtures was used as computational model; time to produce one significant quantity – 6 months.

3.2. Results and discussion
The possibility of obtaining a significant amount of HEU with 90% enrichment from a given material is shown in figure 1. A significant quantity for uranium with such level of enrichment is the amount of material that contains 25 kg \( ^{235}\text{U} \) (though it is the same for 20% enrichment that is similarly qualified as HEU, but we wanted to demonstrate the capability of recycled fuel to reach the boundary of weapons-grade uranium). As can be seen from this figure, performing the enrichment of one significant quantity (SQ) of low-enriched uranium, at least one significant quantity of highly enriched uranium could be produced, and in the asymptotic limit, with a vanishingly low content of \( ^{235}\text{U} \) in the waste flow, even two SQs, which indicates the importance of detecting source material, i.e. low enriched uranium.

![Figure 1](image)

**Figure 1.** Dependence of the number of "significant quantities (SQ)" of highly enriched uranium (>90%, HEU), derived from a significant amount of LEU, varying the ratio of the \( ^{235}\text{U} \) content in waste flow.

To show the necessary quantity of gaseous centrifuges to perform the operation for producing HEU in 6 months, the figures 2-3 reflect dependence on such cascade parameter as concentration of \( ^{235}\text{U} \) in tails irrespective of initial material.
Figure 2. Dependence of the number of Urenco-type gas centrifuges (required for one significant quantity of HEU) per unit to product on $^{235}$U concentration in waste flow.

Figure 3. Dependence of the number of Russian-type gas centrifuges (required for one significant quantity of HEU) per unit to product on $^{235}$U concentration in waste flow.

Thus, having a large amount of starting material, a significant quantity of HEU can be obtained in just half a year by means of only several gas centrifuges. From figures 2-3 we could also see that considered task could be done in easy-to-hide laboratory-size undeclared facility, providing enough separating elements [11]. Though such machines are strictly accounted, there might be a possibility to acquire some on the black market or getting the secretive help of states who control some nuclear weaponry and collateral technologies [1].

To demonstrate the relation of required separative elements to the time span, let us look into figure 4, where the calculations were made in a similar way but to represent the time scale and $^{235}$U concentration in the waste flow. It should be noted that the higher the concentration in the waste, the more initial material required for an operation.
What is critically important, this figure provides an evidence that one significant quantity of HEU that in our case is essentially the main ready-to-use component of nuclear bomb, could be produced before the expected detection time supposed by IAEA safeguards to lay in interval of 3-12 months. This fact should draw attention that such a material as LEU, which is recognized as an indirect use nuclear material, could be turned into weapons-grade uranium over unexpectedly short time. The situation is even worse for conventional fuel made of natural uranium that has no deterrents such as artificial even-numbered isotopes.

3.3. The method of diverted material detection
Currently, the IAEA uses more than 100 different Non Destructive Assay (NDA) systems to check and monitor nuclear materials [12]. Such verification occurs without changing the physical or chemical properties of controlled materials. NDA instruments range in size and complexity from small portable units used by safeguards inspectors during on-site verification activities to large in situ NDA systems designed for continuous unattended in-plant use.

Most nuclear materials under IAEA safeguards, such as enriched uranium, emit γ rays that makes possible its NDA. Gamma rays have well defined energies that are characteristic of the isotopes emitting them. Determination of the γ ray energies and their relative intensities serves to identify the isotopic composition of the materials. When combined with a measurement of absolute intensities, the γ ray energies can provide quantitative information on the amount of material that is present.

Enriched uranium fuel, for example, has a strong 186 keV γ ray associated with the α decay of 235U, and the 235U enrichment can be verified by measuring this γ ray [13]. But to enhance the safeguards, it is necessary to check the amount of nuclear material in each fuel assembly based on the express analysis of fresh fuel assemblies. This is rather difficult for fuel made of natural uranium, since its indicative gamma lines are affected by the presence of radioactive background and shielding of internal fuel rods by external ones [14].

The distinguishing characteristic of fuel made of reprocessed uranium is that this option makes it possible to detect the replacement of even one fuel rod. Since the 209Tl line of 2.6 MeV has good penetrating power (the higher the gamma line energy, the less it is weakened by a shield), the substitution of 1 fuel rod.
leads to decrease in thallium concentration to 311/312. The identification process for such fuel type includes
the following steps:

1. There is an expected value of $^{208}\text{Tl}$ concentration in the fresh fuel assembly depending on the time
exposure that only the manufacturer knows (as special gamma signature of this fuel assembly).
2. The energy of $^{208}\text{Tl}$ in fresh fuel assembly is measured by the corresponding gamma line, then the
concentration of this nuclide is calculated, and the error is assessed.
3. Based on these data, the fact of diversion of nuclear material is concluded.

The efficiency of such identification based on express analysis. Figure 5 shows the minimum time
needed to collect a spectrum for such verification. The time needed to set the spectrum on a germanium
detector (1000 sec) is taken as a unit of time necessary for express test.

![Figure 5. Relative spectrum set-up time for different volumes of diverted nuclear material.](image)

As we could see from this figure, to carry out express identification, we should wait for the thallium
concentration to build up naturally in reprocessed fuel due to the $^{232}\text{U}$ decay. So, in case of 1 fuel rod
diversion, after six months the spectrum acquisition time will be equal to reference option (one express
test), and after a few years it will take even less. Thus such an analysis would be possible in this quick way.
Additionally, it can be seen that there is the possibility of determining the diversion of just a quarter of the
tables from one fuel element, in case of longer time-exposure (although, the time of measurement should
be increased three times comparing to the reference option). The limitation of this method is the requirement
for an identical concentration of thallium in all fuel rods of a given fuel assembly.

4. Conclusion

Turning fresh fuel into weapons-grade uranium is possible with relatively little means, thus timely detection
is necessary. This problem could be eased by using reprocessed fuel as a source material because it contains
a number of artificial isotopes, in particular $^{233}\text{U}$ that makes diversion more difficult and acts as a marker
helpful to disclose the diversion. In this way, it is even possible to detect the replacement of just one fuel rod and make it quickly.

In addition, in spite of some proliferation concerns about nuclear fuel reprocessing [15], we show that greater risks of the most sensitive material diversion could be avoided owing to systems based on used fuel recycling. Though it sounds paradoxical, such a systems managed by nuclear power leaders are more secured and proliferation resistant. Thus, contrary to popular belief, spent fuel reprocessing could bring greater goods even in terms of non-proliferation of nuclear weapons.

Finally, it is necessary to note the need for research in this area in connection with the Rosatom’s prospects of switching to a nuclear fuel leasing export scheme, when the spent fuel will be returned for reprocessing, after which it will be recycled (multiply), providing complete return to the nuclear fuel cycle.

So, transition to closed nuclear fuel cycle is apt to be obstructive to illicit diversion and consequent proliferation.

References
[1] Kemp R S 2012 Nonproliferation Policy Educ. Cent.
[2] Nevinitsa V A, Borisevich V D, Smirnov A Yu, Sulaberidze G A 2010 Phys. At. Nucl. 73 2264–70
[3] IAEA-TECDOC-CD-1630 2007 Use of Reprocessed Uranium
[4] Abbas K, Cojazzi G, Mercurio G, Peerani P, Renda G 2013 Proliferation resistance features of reprocessed uranium in Light Water Reactor fresh fuel Ispra, Italy
[5] Dalnoki-Veress 2015 A Crazy idea? Isotopic Denaturing of Iran’s 5 % UF6 Stockpile with Reprocessed uranium
[6] International Atomic Energy Agency 1970 Treaty on the Non-Proliferation of Nuclear Weapons
[7] IAEA 2014 Safeguards Implementation Practices Guide on Facilitating IAEA Verification Activities
[8] IAEA 2001 IAEA Safeguards Glossary 3 579
[9] Borisevich V, Borshchevskiy M, Zeng S, Jiang D 2014 Chem. Eng. Sci. 116 465–72
[10] Sulaberidze G A, Borisevich V D 2001 Sep. Sci. Technol. 36 1769–17
[11] Wood H, Glaser A, Kemp R 2008 61 40–45
[12] International Atomic Energy Agency 2011 Safeguards Techniques and Equipment 1 34-36
[13] Mujaini M, Chankow N, Yusoff M, Hamid N 2016 AIP Conf. Proc 1704
[14] Relly D, Ensslin N, Smith H, Kreiner S 1991 Passive Nondestructive Assay of Nuclear Materials Los Alamos National Laboratory
[15] IAEA-TECDOC-1587 2008 Nucl. Fuel Cycle Mater. Sect. 151