# A Crazy idea? Isotopic Denaturing of Iran's 5% $UF_6$ Stockpile with Reprocessed Uranium.

Dalnoki-Veress, PhD
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## ABSTRACT

The most challenging problem in the negotiations between Iran and the P5+1 is dealing with the scope of the enrichment program envisaged by Iran. Iran has stated that it requires enough enrichment capacity to be able to provide fuel for the Bushehr reactor requiring at least 100,000 SWU/year, which is an order of magnitude more capacity than Iran currently has installed. However, the P5+1 are likely to insist on an annual production limit a factor of 20 times less. Another challenge is the quantity of low enriched $UF_6$ that currently exists in Iran's stockpile or may be produced in the future, which could be re-enriched to weapons grade in a breakout scenario. We propose the possibility of denaturing low enriched $UF_6$ (such as the near 5% material) with foreign (Russian) reprocessed uranium (RepU) in order to decrease the risk of the current and future stockpiles of enriched $UF_6$. In a first step, 7952.9 kg of near-5% $UF_6$ is blended down to 3% using 6950 kg natural uranium. In a second step the material is blended with 17% $RepUF_6$ (with >4.9 ppm U-232) to bring the material back up to 5% U-235 enriched material. This material is significantly less attractive for use in a nuclear weapon if further enriched to weapons grade. [1] The reason for this is that U-232 present in reprocessed uranium is enriched along with the U-235 increasing the number of neutrons both through spontaneous fission but also due to the $(\alpha,n)$ reaction on light element contaminants in the material. The advantage to Iran is obtaining at least twice the amount of 5% enriched material which can be used for the Iranian nuclear program, but the disadvantage is that the enhanced radioactivity of the material needs to be considered in the use of the material at low enrichment in the civilian nuclear program.

Isotopic denaturing is the process of artificially changing the natural isotopic composition of a chemical element in order to give it new, desirable properties. Weapons grade U-235 is easily denatured by adding enough U-238 (blending down to 20% enrichment) to the material to increase the neutron count rate so that a ms free of neutrons becomes unlikely. However, this material is not truly denatured because it can be re-enriched to weapons grade. We suggest an alternate approach where reprocessed uranium is blended with $UF_6$ making it highly impractical to enrich it further to weapons grade to construct a nuclear explosive device while still allowing the LEU $UF_6$ fabrication into fuel and for reactor use. In fact, if U-232 is added the neutron emission rate increases when enriched to weapons grade rather than decreasing. In this note, we consider the possibility of:

[1] See IranFactFile.org "By the Nubers Page" for the current status of the Iranian program and the concept map at: http://www.iranfactfile.org/2015/02/22/concept-map-iranian-fuel-cycle-latest-safeguards-report/.

- **Denaturing 5% $UF_6$ Stocks**: First, Iran's stockpile of near-5% is blended down to 3% enriched material using natural uranium, then the 3% material is blended back up to 5% enrichment using 17% enriched reprocessed $UF_6$ in order to prevent it from further enrichment to weapons grade and eventual use in a nuclear explosive device. The advantage of this is that the material now includes U-232 which is difficult to remove.

Denaturing uranium with reprocessed uranium was suggested before in different contexts and we draw upon these publications as an option for consideration for Iran. [2] In order to do this calculation we follow the following steps:

- Derive expression for the masses and U-232 concentrations of the 2-step blended material based on the initial feed mass of 7952.9 kg near-5% U-235 mass.
- Calculate neutron production as a function of the concentration of U-232 due to alpha particle activity from U-232 daughters interacting through the (α,n) reaction on assumed impurities present if the $UF_6$ is converted to metal form (assumed composition of metal as on the Novosibirsk Chemical Concentrate Plant website). We use SRIM 2008 to calculate the α-particle energy loss, TENDL-2013 for the cross-sections of the impurities, and ORNL's Scale 6 to calculate the quantity of U-232 daughters after an assumed 1 year of decay.
- Calculate fraction of U-232 in 5% blended $UF_6$ if it is further enriched to weapons grade U-235. The ratio of the fraction of U-232 in 90% enriched material and the 5% enriched material we call γ.
- Knowing γ and the number of neutrons produced as a function of U-232 concentration, we can derive the required concentration to produce a neutron-free ms making construction of a bomb more difficult. [3]
- We calculate the dose from a 5 kg sphere of 90% U-235 enriched uranium including the added U-232. We calculate a dose of 178 mrem/hr. It is not *self-protecting* at this level but it would complicate the manufacturing process into a bomb. We also find that the dose from the near-5% blend is a factor of 22 less. This is more manageable as long as precautions are in place to protect the workers and environment. [4]

The Iranian Government may be hard to convince that a reprocessed uranium blend is acceptable since the material may be perceived as "inferior" to enriched natural uranium, and this may be judged to be discriminatory. However, we inject this into the current discussion on Iran's nuclear program since this approach may be part of the formula for Iran to "save face" and alleviate tension between Iran and P5+1. Especially because the government desires high quantities of enriched $UF_6$ for their civilian nuclear program. Material that has been denatured in the way we discuss does not eliminate the threat from the

[2] P. N. Aleseev et al, T*he Concept of the Use of Recycled Uranium for Increasing the Degree of Security of Export Deliveries of Fuel for Light-Water Reactors*, Physics of Atomic Nuclei, v 73, no 14, pg 2264-2270, 2010. E. F. Kryuchkov et al, *Evaluation of Self-Protection of 20% Uranium Denatured with 232U Against Unautorized Reenrichment*, Nuclear Science and Engineering, 162, p. 208-213, 2009. See also Chapter 14 by Kryuchkov et al. in *Nuclear Power – Deployment, Operation and Sustainability*, edited by P. Tsvetkov, 2011.

[3] A. Glaser, *On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels*, Science and Global Security, 14, pg 1–24, 2006.

[4] IAEA, *Safety of Uranium and Plutonium Mixed Oxide Fuel Fabrication Facilities*, Specific Safety Guide, No. SSG-7, 2010.

material but would make it more difficult for use in a bomb unless a dedicated re-enrichment program is employed to remove the U-232.

## Advantages of Using RepU

A handful of countries is reprocessing or have reprocessed in the past spent nuclear fuel separating uranium and plutonium from fission products by solvent extraction or by other means. [5] Reprocessed uranium contains a mixture of naturally occurring uranium isotopes such as U-234, U-235 and U-238, but also U-232 and U-236 produced through exposure of uranium fuels in a reactor plus trace levels of other elements and fission products. The U-232 isotope decays through a series (5) of alpha and beta decays (2) until it reaches stable lead. In the process, it emits high energy alpha particles and gamma rays including several high energy gamma rays at the end of the decay chain. Researchers in Russia have calculated that a 5 kg sample of 4% U-235 metallic uranium placed 1 m from a person increased the dose by at least a factor of 3. However, the material is not unsafe to work with and to eventually fabricate into fuel. In fact, the dose is at least several orders of magnitude below what is allowable from fuel assembly manufacture with MOX fuel in the UK. However, the advantage of adding this material is that when it is further enriched to weapons grade in centrifuge cascades the U-232 isotope is enriched along with the U-235, and the radioactivity increases markedly. The increase in dose makes weapon grade Rep$UF_6$ impractical to manufacture into a bomb for several reasons.

First, the presence of high energy alphas will dissociate $UF_6$ molecules making it difficult to enrich the $UF_6$ to high enrichments. We estimate that based on the expected decay of U-232 and the Th-228 decay chain growing in, the presence of U-232 destroys 0.125 moles $UF_6$/g U-232 after 30 days of decay. [6] This increases to 1 mole $UF_6$ /g U-232 after 4.5 months of decay, and 4.12 mole $UF_6$/g U-232 after 1 year of decay. Second, at the end of the decay chain Bi-212 decays 64% of the time into Po-212 and emits a 1.8 MeV gamma ray 1% of the time, and 36% into Tl-208 emitting a 2.6 MeV gamma ray. This increases the gamma dose considerably complicating machining operations with the material if it is enriched further to weapons grade. In addition, the neutron yield increases considerably through (α,n) reactions on light elements in the medium. Kryuchkov *et al*. calculated that for 20% enriched uranium the addition of 0.001%(=10 ppm) U-232 increases the neutron yield by a factor 590 more than the U-238 background making it likely that the bomb will fizzle if it is constructed into a gun-type bomb. [7] Our calculations are consistent with these results as will be discussed. Finally, a significant advantage of the addition of U-232 is that removal of the isotope without a dedicated enrichment program is not possible. The increase

[5] We do not support reprocessing as a means for spent fuel management for a number of reasons but this is not the focus of this article. For insightful discussion on this topic see for example: Makhijani, A., *The Mythology and Messy Reality of Nuclear Fuel Reprocessing*, Institute for Energy and Environmental Research, Takoma Park, Maryland, April 8, 2010. Frank von Hippel, *Managing Spent Fuel in the United States: The Illogic of Reprocessing*, IPFM Research Report #3, January 2007

[6] We follow a similar calculation as done in Kryuchkov. However, we do the calculation for all the alpha emitters after 1 year of irradiation. We assume number of $UF_6$ molecules destroyed per MeV as discussed in H. A. Bernhardt et al, *Radiation Effects of Alpha Particles on Uranium Hexafluoride*, Second United Nations International Conference on the Peaceful Uses of Atomic Energy, 1958.

[7] E. F. Kryuchkov ibid. See Figure 1.

in dose from the material when enriched to weapons grade makes it difficult to construct a nuclear warhead. [8]

## Disadvantages of Using RepU

Reprocessed uranium also contains significant neutron absorbers such as U-234 and U-236 so that over-enrichment is necessary to account for the loss in reactivity. This has required an increase in enrichment of approximately 12% over the un-irradiated enriched fuel (see Table 1). This re-enrichment is costly and can be potentially decreased by blending with LEU up to 17% containing less U-236 advantageous for reactor use but decreasing the barrier for further enrichment to weapons grade. A 2009 IAEA report claimed that for current fuel management strategies the impact on safety of the substitution of fuel with slightly over-enriched RepU fuel was "limited" based on international experience. [9]

However, the report warned that the validity of the models (loss of coolant and reactivity initiated accident studies, residual heat curve etc.) "must be formally checked." The report warns that if the enrichment needs to be substantially increased to compensate for the lack of reactivity or because of new fuel strategies the safety of the reactor needs to be demonstrated including validation with computer codes. Further discussion on the safety of using RepU as a component of reactor fuel is beyond this memo but should be formally studied if the use of RepU for denaturing Iranian uranium is to be considered an option. In particular, the safety functions outlined by the IAEA for MOX fuel

| Reactor | Enriched Reprocessed Uranium | Enriched Natural Uranium | Ratio (%) |
|---|---|---|---|
| Doel 1 (Belgium) | 4.25 | 3.8 | 14.8 |
| KKG (Switzerland) | 4.85 | 4.3 | 11.8 |
| Borssele (Netherlands) | 4.8 | 4.4 | 12.8 |
| Cruas (France) | 4.1 | 3.7 | 9.1 |
| GKN II (Germany) | 4.59 | 4 | 10.8 |

**Table 1: Reactors that use reprocessed uranium and the increase in enrichment they have needed to keep the same reactivity.**

fabrication facilities apply to RepU fuel fabrication facilities, namely, (1) prevention of criticality, (2) confinement of radioactive material, including removal of decay heat, (3) protection of workers against exposure. Iran could work with nations that currently reprocess uranium for methods to mitigate the risks.

[8] But not impossible. In the Black Sea experiment, it was found that the Soviet Union was constructed their warheads using U-232.

[9] IAEA, *Use of Reprocessed Uranium: Challenges and Options*, No. NF-T-4.4, 2009. See also IAEA-TECDOC-1529, *Management of Reprocessed Uranium: Current Status and Future Prospects*, 2007. To see the range of enrichments and isotopic compositions possible in Russia see V. M. Korotkevich and T. G. Shikerun, *Reprocessed Uranium Handling at Siberian Group of Chemical Enterprises*, in *Use of Reprocessed Uranium,* Proceedings of a Technical Committee Meeting held in Vienna, August 2007, IAEA-TECDOC-CD-1630.

## Reprocessed Uranium for Use in Iran's Nuclear Program

Given the advantages of using RepU to decrease the potential that the material can be used for a nuclear weapon while retaining the use for the material for peaceful purposes, we consider whether the present LEU stockpile could be blended with Russian RepU. This would allow for Iran to enrich it further for making fuel for the IR-40 (if enriched uranium is deemed necessary to decrease the risk of plutonium production), and launch a program for studying whether the fuel can be indigenously produced for the Bushehr reactor or other reactors Iran would like to build.

### Scenario: Denaturing Near-5% $UF_6$ with RepU

In this scenario, we are considering the denaturing of 7952.9 kg of up to 5% enriched $UF_6$, which is first blended down to 3% with natural uranium and then blended up to 17% enriched reprocessed uranium to make the material less proliferation sensitive.

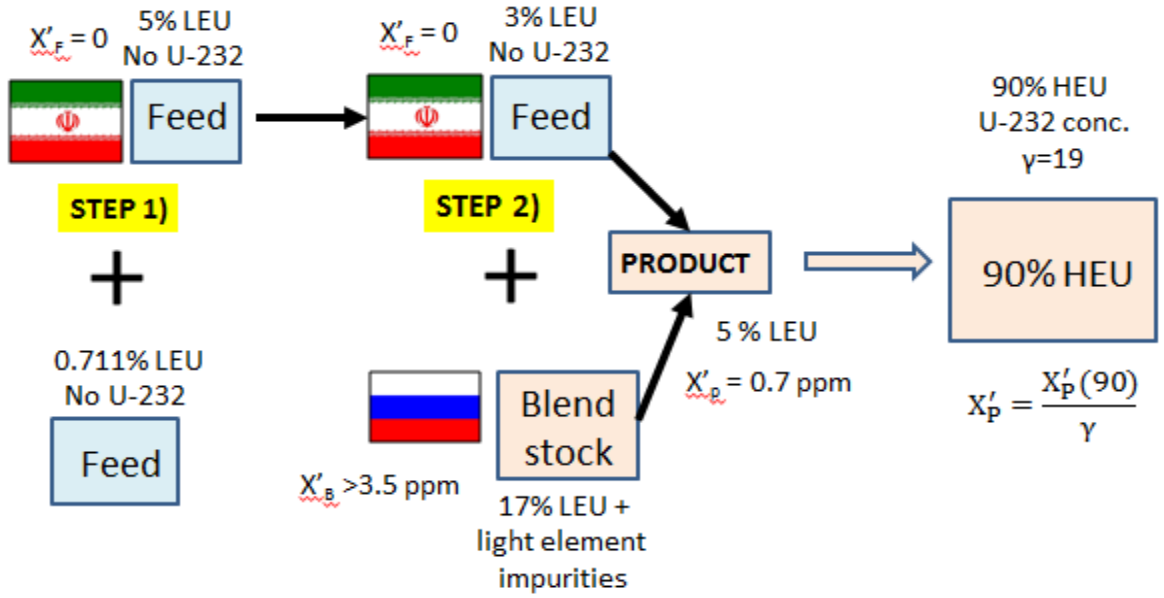


**Figure 1: Denaturing Iranian <5% $UF_6$ with Russian reprocessed uranium. The product blend has an increased neutron rate which when further enriched to weapons grade exceeds the neutron rate at 20% U-235 making it more difficult to construct a nuclear weapon.**

The flow through the cascade can be represented as $\mathrm{P} = \mathrm{F} + \mathrm{B}$ where F and B are the flow rates of the feedstock to be denatured and the blendstock (RepU) with which it is blended. Furthermore, because of mass balance the fractional concentrations of the isotopic mixture follow: $\mathrm{PX_P} = \mathrm{FX_F} + \mathrm{BX_B}$ where $X_p$, $X_F$, $X_B$ are the U-235 concentrations in the various streams. Similarly, $\mathrm{PX'_P} = \mathrm{FX'_F} + \mathrm{BX'_B}$, where $X'_p$, $X'_F$, $X'_B$ are the U-232 concentrations for the 3 streams. We assume that the feedstock (Iranian uranium) concentration of U-232 is 0 so that $X'_F = 0$ (since, the material is not reprocessed). We find that for the first stage when the near-5% in blended down to 3% enriched material:

$$B_1 = F_1\left[\frac{(X_{P1} - X_{F1})}{(X_{B1} - X_{P1})}\right] \qquad \text{Eqn 1}$$

Where, B1 and F1 are the natural uranium blendstock and the near-5% feed $UF_6$ material and P1 corresponds to the stage 1 blended down product. In stage 2 the product from the first stage (F1 +B1) is blended up back to 5% using 17% reprocessed $UF_6$ blendstock. So that the process from stage 1 is linked to the second in the following way:

$$F_2 = P_1 \quad ; \quad X_{p2} = X_{F1} \quad ; \quad X_{F2} = X_{P1} \qquad \text{Eqn 2}$$

Using a similar expression as Eqn 1 but recognizing that F2=P1 we can derive the mass of the blendstock expressing in terms of Stage 1 variables to be:

$$B_2 = F_1\left[1 + \frac{(X_{P1} - X_{F1})}{(X_{B1} - X_{P1})}\right]\frac{(X_{F1} - X_{P1})}{(X_{B2} - X_{F1})} \qquad \text{Eqn 3}$$

We find that the expression for the U-232 concentration of the blendstock is written:

$$X'_{B2} = \left(\frac{P_1}{H_2}\right)(X'_{P2} - X'_{F2}) + X'_{P2} \qquad \text{Eqn 4}$$

$$X'_{P2} = \frac{X'_P(90)}{\gamma} \qquad \text{Eqn 5}$$

Where, $X_p'(90)$ is the U-232 concentration if the blended material is re-enriched to 90% U-235, and γ is the ratio of the U-232 concentration when the final blend is enriched to 90% U-235 to the concentration of U-232 in the final blend before it was enriched.

**Neutron Production from Product if Reenriched to Weapons Grade**

According to the formalism of Yamamoto and Kanagawa, enrichment from ~5% $UF_6$ to 90% results in a γ factor of about 19. [10] The U-232 spontaneous fission rate is 1.3 n/g.s so that the rate will impact the total rate only when the concentration exceeds 0.1% U-232. The probability of a neutron-free ms assuming Poisson Statistics depends on the decay constant associated with neutron production in the medium. [11] Therefore, for 20% U-235 enriched uranium metal the rate must conservatively exceed 5.4e-3 n/g.s. The formula above allows us to determine the U-232 concentrations that the blendstock must have in order to reach a specific target U-232 concentration when enriched to weapons grade. For example, to make the material less attractive for use in a nuclear weapon, the neutron rate should be

[10] Note the calculation of Yamamoto and Kanagawa is consistent with the WISE multi-component enrichment calculator. Both methods were used in this publication. See: I. Yamamoto and A. Kanagawa, Multicomponent Isotope Separating Cascade Composed of Elements with Large Separation Factors, J. of Nuclear Science and Technology, 15,8, p. 580-584, 1978. I. Yamamoto, A. Kaba, and A. Kanagawa, Simple Formula for Analyzing Matched Abundance Ratio Cascade with Constant Separation Factors for Multi-Component Isotope Separation, 24,11, p. 969-971, 1987. See also: H. Wood, *Effects of Separation Processes on Minor Uranium Isotopes in Enrichment Cascades*, Science and Global Security, 16, pg. 26-36, 2008.

[11] A. Glaser, *On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels*, Science and Global Security, 14, pg 1–24, 2006.

comparable to the spontaneous fission rate of a 20% HEU mixture or 5.4e-3 n/g.s at 90% enriched meaning that the concentration of the final blend should be a factor of γ less.

However, neutrons can come from anywhere, and the formula does not take into account additional neutron production from alpha particles produced from actinide decay interacting with light elements in the medium through the (alpha,n) reaction. [12] The number of neutrons that are produced known as the thick target yield is determined by integrating the (alpha,n) production cross-section over the energy loss. The rate of production of neutrons per alpha particle is: [13]

$$\mathrm{Y_{j,med}(E_{th,j}, E_{\alpha,j}) = n_j \int_{E_{Th,j}}^{E_{\alpha,j}} \frac{\sigma_j(E)}{-\left[\frac{dE}{dx}\right]_{med}} dE} \qquad \text{Eqn 6}$$

Where, $n_j$ is the concentration expressed in atoms/cm$^3$ of the target isotope j, σ(E) is the (α,n) cross section for target isotope j for an alpha of energy E, and $\left[\frac{dE}{dx}\right]_{med}$ is the stopping power of the alpha's through the medium and the negative is to ensure that the final yield, $Y_{j,med}$ $(E_{th,j}, E_{\alpha,j})$remains positive. The alpha energy for the actinides are also averaged according to the probability of occurrence. For example, Ra-224, which is a daughter of U-232, has two alpha's one at 5.684 MeV (94.9%) and one at 5448.5 MeV (5.1%) which is averaged to $\overline{E_\alpha} = 5.672$ MeV. The (α,n) cross sections for the light elements are obtained from OECD's TALYS Evaluated Nuclear Data Library (TENDL 2013), which calculates the cross-section for various nuclear reactions including (α,n) reactions. The energy loss is calculated using the SRIM code for uranium metal and assumes a density of 19.043 g/cm3. [14] The product of the inverse of the energy loss and the cross-section as a function of energy is numerically integrated and fit to polynomial functions. With these simplifications the yield (number of neutrons produced per alpha particle) is written as.

$$\mathrm{Y_{j,med}\left(E_{th,j}, \overline{E_{\alpha,J}}\right) = n_j D_{j,med}\left(E_{th,j}, \overline{E_{\alpha,J}}\right)} \qquad \text{Eqn 7}$$

$$\text{where,} \qquad \mathrm{D_{j,med}(E_{th,j}, \overline{E_{\alpha,J}}) = \int_{E_{Th,j}}^{E_{\alpha,j}} \frac{\sigma_j(E)}{-\left[\frac{dE}{dx}\right]_{med}} dE}$$

[12] Proposed by Kryuchkov et al.

[13] There are a great deal of useful references: R. Heaton, H. Lee, P. Skensved and B. C. Robertson, Neutron Production from Thick-Target (α,n) Reactions, Nucl. Instr. Methods, A276, p. 529-538, 1989. N. Ensslin, *The Origin of Neutron Radiation*, in Chapter 11 of D. Reilly, N. Ensslin, and Hastings Smith, Jr.*, Passive Nondestructive Assay of Nuclear Materials*, NUREG/CR-5550, LA-UR-90-732, 1981 (PANDA Book). See also: R. Salmon and 0. W. Hermann, *ALPHN: A Computer Program for Calculating (α,n) Neutron Production in Canisters of High-Level Waste*, ORNL/TM-12239, 1992.

[14] http://www.talys.eu/tendl-2013/

Where, $D_{j,med}(E_{th,j}, \overline{E_{\alpha,j}})$ is the integral of the product of the inverse of the energy loss and the (α,n) cross-section from the threshold energy of the cross-section to the average alpha energy for each isotope and has units of volume. [15]

To determine the number of neutrons produced due to the presence of alpha-emitting actinides in the nuclear material, the yield, $Y_{j,med}(E_{th,j}, \overline{E_{\alpha,j}})$ must be multiplied by the alpha activity from the actinide (U-232 and daughters) and summed over all impurities present in the material for all alpha emitters in the decay chain.

We used ORNL's Scale 6 to calculate the build-up of U-232 daughters over 1 year of decay of 1 g of U-232 giving rise to the activity of the actinide daughters shown in Figure 2. The half-lives of the Th-228 daughters are all short lived and is driven by the Th-228 decay rate, with the exception of Bi-212 and Po-212 which have a lower decay rate because they have a 36% and 64% branching probability of decay from Bi-212.

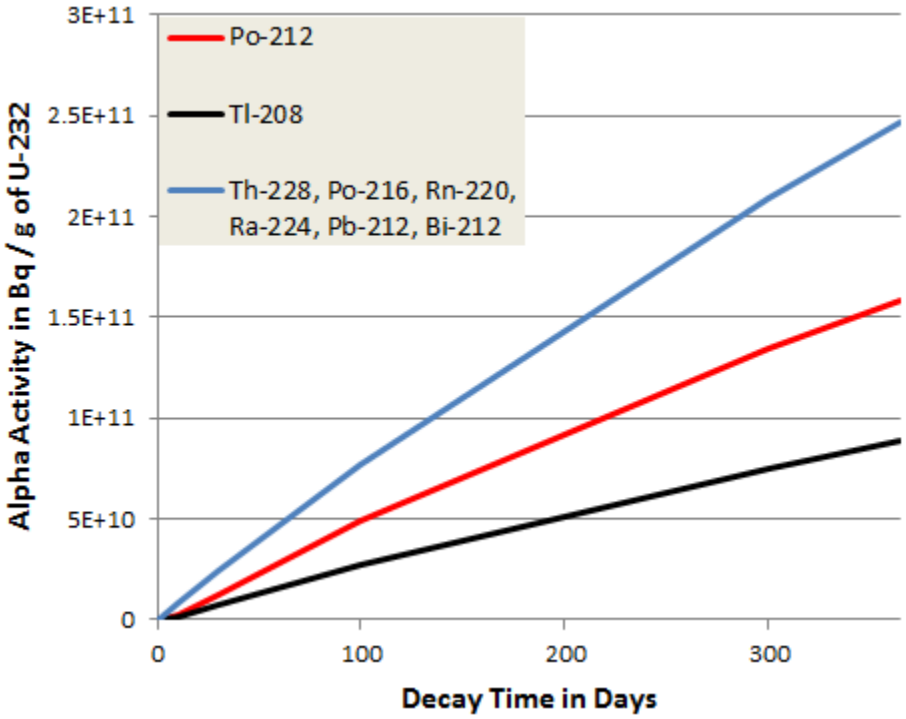


**Figure 2: ORNL's Scale 6 calculation of the build-up of U-232 daughters over 1 year of decay. There are 3 activities driven by the decay of Th-228 and the two branching ratios of Po-212 and Tl-208 at the end of the chain.**

We assume a concentration of light element contaminants in fuels as given in Novosibirsk Chemical Concentrate Plant in Russia (See Table 2). The formula for neutron rate production for 1 g of U-232 with impurities of concentration $[x]_{ppm}$ is written.

$$R_{j=} \, Act_j \, [x]_{ppm} \, Y_{j,med} \qquad \text{Eqn 8}$$

[15] Note that since we did not start the integral from E=0, it is not equivalent to the range of the alpha since it has been tuned to the specific isotope cross-section.

Knowing the number of extra neutrons that are produced per gram of U-232 per second and the number of neutrons/g.s. of uranium metal at which a neutron free ms becomes unlikely (ie. the spontaneous fission rate at 20% U-235 or 5.4e-3 n/g.s.), we can calculate the concentration required to make a "fizzle" more likely. We know that 1 g of U-232 corresponds to a rate of 324 n/s, so 1 ppm U-232 added to 1 g corresponds to 3.24e-4 n/s. Therefore, adding 16 ppm U-232 to 1 g uranium metal is equivalent to the neutron emission rate of 20% enriched uranium metal and will significantly decrease interest in use of this material for nuclear explosive purposes.

**Calculating the U-232 Concentration in the Stage 2 Blendstock**

We now use Eqn 5 to calculate the U-232 concentration before enriching it to weapons grade which is a factor of γ less than the concentration at weapons grade or 0.7 ppm. We use Eqn 4 to calculate the blendstock concentration that would be required to add to the <2% feedstock to increase the quantity of U-232 past 0.7 ppm. Assuming an initial RepU $UF_6$ of 17% added to 2% feedstock in order to extract a 5% final blend, we find that the concentration of U-232 to denature the uranium so that if further enriched it is not used for a gun-type weapon the concentration must exceed 4.9 ppm. Using Equation 3 we found that the blendstock mass (B2) was 1/3rd (2483.6 kg 17% enriched $UF_6$) of the initial feed

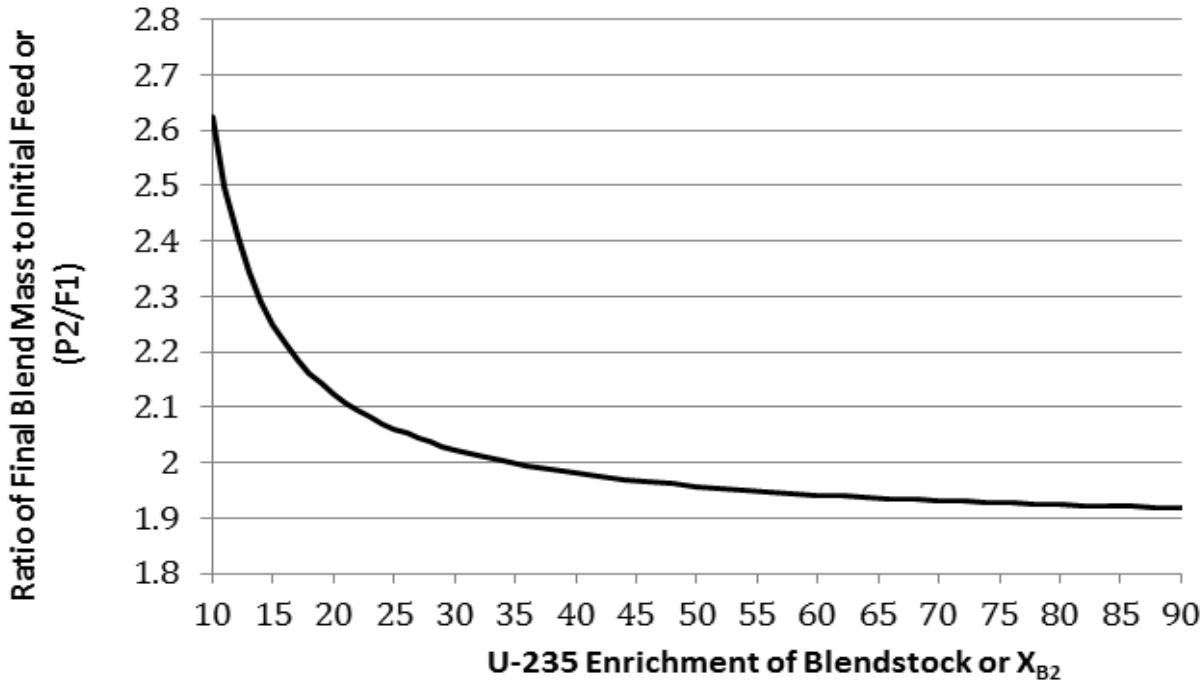


**Figure 3:** Ratio of the final mass of the blend at 5% enrichment (P2) to initial feed (F1). Notice that as the enrichment is increased the ratio approaches 1.9. Therefore, there is no appreciable advantage to using weapon grade material to blend up the feed especially since the quantity will need to be enriched with more U-232 to reach 0.7 ppm in the final blend.

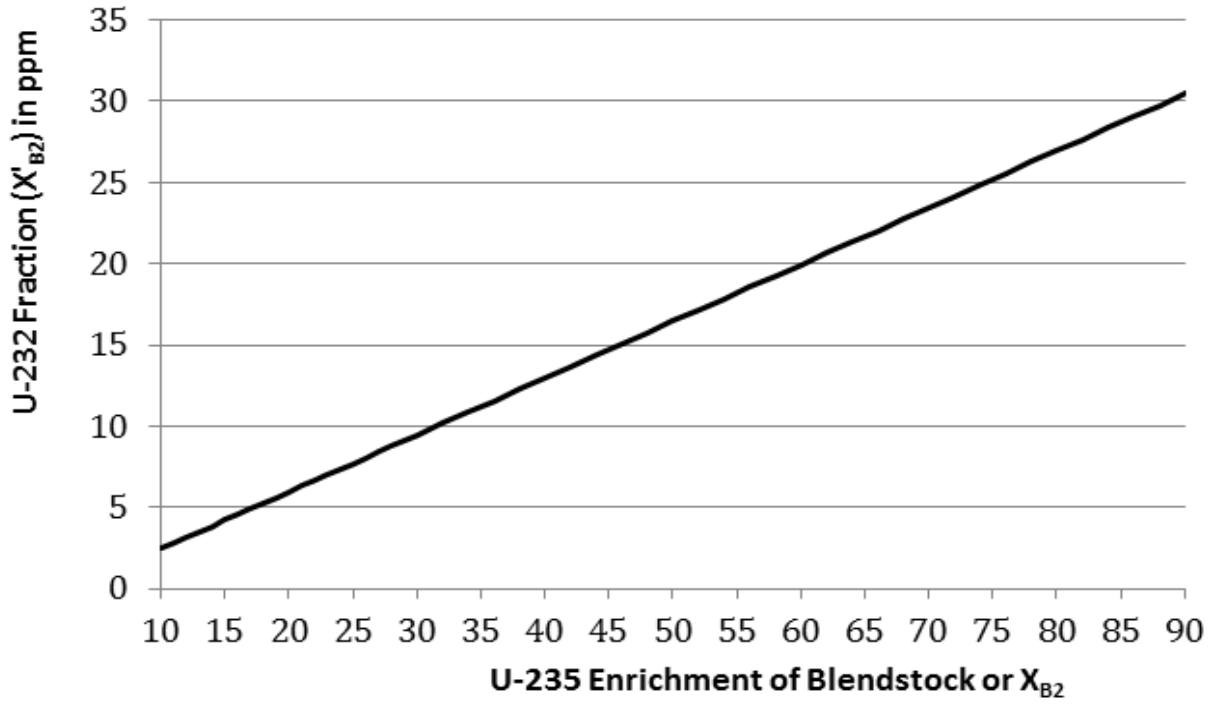


**Figure 4:** U-232 fraction expressed in ppm in the blendstock as a function of the blendstock U-235 enrichment.

( 7952.9 kg near-5% $UF_6$) while the total stockpile is scaled by 2.1. See Figure 3 and Figure 4 for the quantity of the blendstock required as a function of the blendstock U-235 enrichment, and the required U-232 ($X'_{B2}$) enrichment as a function of U-235 enrichment ($X_{B2}$). Crucial for this 2-step process to work is for the blendstock concentration to have several ppm of U-232. The problem is that as the concentration decreases (see Figure 4), the quantity of blendstock required increases almost exponentially (see Figure 3) so it is necessary to have a U-232 concentration in the blendstock of several ppm.

The net gain to Iran in the present scenario is more than twice the quantity of $UF_6$ material, while at the same time greatly minimizing the potential that this material is used in the future for nuclear weapons.

## Dose for 5 kg Weapons Grade Reprocessed U-235

Neutron rate is not the only reason why weapons grade uranium made from reprocessed uranium is difficult to manufacture into a nuclear weapon. The dose emitted from this material through just the gamma-ray rate is also higher when the RepU $UF_6$ is enriched, making machining of the material more difficult. For example, if we assume that in the blending process discussed above the final U-232 composition at 4% U-235 is 0.7 ppm, then when further enriched to weapons grade the concentration increases to 16 ppm. The gamma dose rate approximated as a 4 cm disk at 1-meter distance is:[16]

$$D = \Gamma A \frac{\ln\left[\frac{R^2+h^2}{h^2}\right]}{R^2} \qquad \text{Eqn 9}$$

[16] Joseph John Bevelacqua, Contemporary Health Physics: Problems and Solutions, Wiley, 2009, p.568.

Where Γ is the gamma factor corresponding to the gamma dose at 1 m from the source and for 1 Ci of activity for a particular nuclide. A is the activity expressed in Ci, h (=1m) and R (=4 cm) is the distance from the center of the disk and the radius of the disk respectively. We assume the isotopic composition of the uranium metal for natural uranium and reprocessed uranium as shown in Table 3.

We find that the dose rate at a distance of 1.0 m from a 5 kg sphere with 0.7 ppm of 4% U-235 enriched reprocessed uranium metal amounts to 7.9 mrem/hr whereas when this is enriched to 90% the dose increases by *roughly* a factor of γ to 178 mrem/hr. At this rate a 2 rem (the annual allowable exposure for radiation workers according to the ICRP and IAEA) exposure by a technician would be achieved in <12 hours. In contrast if the material is not enriched the photon dose rate is 7.9 mrem/hr which is more manageable. [17]

## Conclusion

In this article, we consider the possibility of denaturing low enriched natural uranium with reprocessed uranium. The specific scenario we consider is the blending of near-5% Iranian $UF_6$ with Russian 17% reprocessed uranium in two stages. First the quantity of 5% enriched $UF_6$ is blended down to 3%, and then this quantity is blended back up to 5% but using 17% enriched RepU which contains several ppm U-232. This has the disadvantage from the point of view of Iran that the radioactive dose is higher than the same enrichment fresh fuel, and a slightly higher enrichment is necessary to account for the U-236 neutron absorber. However, it also has several significant advantages in terms of decreasing the risk that this material could be used in the future to produce nuclear weapons:

1) The neutron rate due to spontaneous fission of the actinides and neutron production from (α,n) on light elements in the material is comparable to that of 20% U-235 metal when the blend is enriched to weapons grade. We find that 0.7 ppm at 4% is enough to make a neutron free ms unlikely when the material is enriched to weapons grade. This corresponds to 4.9 ppm 17% U-235 enriched blendstock for stage 2 blending up to 5% enriched $UF_6$.
2) High energy alphas due to the alpha decay from the actinides in the reprocessed uranium dissociates the $UF_6$ molecules when enriched to weapons grade. We estimate that based on the expected decay of U-232 and the Th-228 decay chain growing in, the presence of U-232 destroys 4.12 mole $UF_6$/g U-232 after 1 year of decay.
3) The dose rate from a 5 kg sphere of weapons grade uranium metal is estimated to be 177 mrem/hr which would lead to a 2 rem (20 mSv) limit in less than 12 hours. This is not self-protecting but will require additional precautions such as remote manufacturing and complicates construction of a bomb.

[17] http://www.nucleonica.net/wiki/index.php/Radiological_limits

| Target Isotope | Conc. (PPM) | Abundance | Neutron Production Rate due to (α,n) reaction per g U-232 per s. |
|---|---|---|---|
| **C-13** | 200 | 0.0111 | 8.63e-1 |
| **N-14** | 200 | 0.99634 | 3.84 |
| **Cu-63** | 50 | 0.6917 | 6.81e-2 |
| **Cu-65** | 50 | 0.3083 | 3.37 |
| **Ni-60** | 150 | 0.26223 | 7.38e-2 |
| **F-19** | 350 | 1 | 1.92e2 |
| **Cr-50** | 100 | 0.04345 | 5.11 |
| **V-51** | 100 | 0.9975 | 6.01e1 |
| **P-31** | 200 | 1 | 4.55e1 |
| **Mg-25** | 100 | 0.1 | 1.22 |
| **Al-27** | 200 | 1 | 2.12e1 |
| **Cl-35** | 0 | 0.7577 | 0 |
| **Si-29** | 100 | 0.0467 | 8.68e-1 |
| **Si-30** | 100 | 0.031 | 6.34e-1 |
| **O-17** | 0 | 0.00038 | 0 |
| **O-18** | 0 | 0.002 | 0 |
| **Mn-25** | 20 | 1 | 3.13e-1 |
| **K-41** | 0 | 0.067302 | 0 |
| **K-39** | 0 | 0.932581 | 0 |
| | | | |
| **TOTAL** | | | **324 n/s.gU-232** |

**Table 2: Calculation of the number of neutrons emitted per gram U-232 in the material, assuming the energy loss of uranium metal as calculated in SRIM-2008, (α,n) cross-sections as calculated by TENDL-2013, and averaged alpha energy for the daughters of U-232. The build-up of the 8 U-232 daughters was calculated using ORNL's Scale 6. We calculate that the impurities in the uranium metal will increase the neutron rate in the metal by 324 n/s for every gram U-232 added. Low element impurities were as documented for metal on the website of NCCP.** [18]

[18] : www.nccp.ru/en/products/uranium_compounds. See also the composition of fuel on the Ulba website in Kazakhstan at: www.ulba.kz/en/production12.htm.

| Uranium Isotope | Natural Uranium | | Reprocessed Uranium | | Specific Activity in Ci/g | Gamma Constant in rem/hr per Ci at 1 m |
|---|---|---|---|---|---|---|
| | 4% | 90% | 4% | 90% | | |
| **U-234** | 0.0377 | 0.9035 | 0.0429 | 0.9893 | 0.0062 | 0.077589 |
| **U-235** | 4.0000 | 90.0000 | 4.1479 | 90.0000 | 2.1E-06 | 0.338883 |
| **U-238** | 99.2745 | 9.0965 | 95.3464 | 2.3678 | 3.3E-07 | 0.065231 |
| **U-236** | 0 | 0 | 0.4628 | 6.6430 | 0.000063 | 0.073704 |
| **U-232** | 0 | 0 | 7.00E-05 | 1.60E-03 | 21 | 0.088911 |
| | Natural uranium with 0.0055% U-234 enriched to 4% and 90% | | Reprocessed uranium with initial concentration given in Alekseev et al. enriched to 90%. [19] | | See IEM Toolbox: http://www.iem-inc.com/information/tools/ | |

**Table 3: The isotopic composition assumed for a 5 kg metal uranium sphere of various enrichments and for natural and reprocessed uranium. We find that when approximating the sphere as a disk of 4 cm radius and at 1 m distance that the dose from reprocessed uranium is 177 mrem/hour.**

[19] P. N. Aleseev et al, The Concept of the Use of Recycled Uranium for Increasing the Degree of Security of Export Deliveries of Fuel for Light-Water Reactors, Physics of Atomic Nuclei, v 73, no 14, pg 2264-2270, 2010.