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About the Enrichment Limit for Research Reactor Conversion : Why 20% ?

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Abstract

This paper reviews the rationale of selecting an enrichment of just less than 20% (low-enriched uranium) as the preferred enrichment level for research reactor fuel in order to minimize overall proliferation risks. The net strategic value of the nuclear material associated with reactor operation is evaluated for a variety of enrichment levels, ranging from slightly enriched to weapon-grade fuel. To quantify the proliferation potential, both the demand of fresh uranium fuel as well as the plutonium buildup in the irradiated fuel are estimated via cell burnup calculations. The analysis confirms the usefulness of the current enrichment limit and challenges a recent trend to reconsider fuel enrichment levels between 20% and 50% for new research reactor projects.

Introduction

The enrichment, i.e. the weight fraction of U-235, determines the main characteristics of any uranium composition both with respect to its performance as a reactor fuel or fissile material in a nuclear weapon. Below a certain enrichment limit, weapon designers attest that the construction of a nuclear weapon or explosive device becomes impractical. For this reason, low-enriched uranium (LEU) and highly enriched uranium (HEU) have been introduced.

The concept of low-enriched uranium was first used by the U.S. Atomic Energy Commission in or prior to 1955.[1] The same convention was later also adopted by the International Atomic Energy Agency (IAEA), which defines low-enriched uranium as "enriched uranium containing less than 20% of the isotope ^{235}U."[2] Likewise, the IAEA classifies LEU as a so-called *indirect use material,* which in turn is defined as a nuclear material that cannot be used for "the manufacture of nuclear explosive devices without transmutation or further enrichment."[3]

Using HEU to fuel research reactors directly leads to a set of inevitable and obvious proliferation risks that are associated with diversion or theft of the material.[4] The lower the enrichment level of any uranium-based nuclear fuel, however, the higher the plutonium buildup via neutron capture in uranium-238. In fact, plutonium production becomes the leading proliferation concern for reactors fueled with natural or slightly enriched uranium, while the uranium itself becomes rather unattractive. It is therefore intuitively clear that it should be possible to identify an optimum uranium composition that suppresses plutonium buildup as far as possible while maintaining the initial uranium fuel unattractive for use in a nuclear weapon or explosive device. Historically, this limit has been set at an enrichment of just less than 20%, but the adequacy of this

[1] At the first Atoms for Peace conference held in Geneva in 1955, Alvin Weinberg reported that he had "just received information from my country that sample UO_2-aluminum 20 per cent enriched fuel elements of the type which will be available to foreign countries have now been tested both in the LITR and in the MTR" (Session 9A, Vol. II, August 12, 1955, p. 430). Although, Weinberg does not use the term LEU in his paper nor in the discussion explicitly, his statements suggest that a policy was already in place distinguishing LEU and HEU. All domestic U.S. research reactors were HEU-fueled at that time. The export of HEU was authorized by the U.S. only in 1958.

[2] International Atomic Energy Agency. *Safeguards Glossary. 2001 Edition.* International Nuclear Verification Series, No. 3. Vienna, 2002, cf. §4.12.

[3] IAEA, op. cit., §4.25 and §4.26.

[4] IAEA safeguards are designed to address some of these proliferation risks, i.e. to timely detect and deter diversion of nuclear material. Safeguards, however, cannot prevent theft or diversion and are ineffective in a breakout-scenario. For almost three decades, experts have therefore emphasized the importance of increasing the inherent proliferation-resistance of the nuclear fuel cycle, a measure that has also been acknowledged by the member states of the IAEA during the International Nuclear Fuel Cycle Evaluation (INFCE, 1978–80).

conversion goal for research reactors is by no means obvious. Detailed, albeit still idealized, scenarios for the operation of a generic MTR-type research reactor are therefore defined and evaluated below.

Uranium Enrichment Level and Proliferation Potential of Research Reactor Fuel

In order to get representative and reasonably accurate estimates of the spent fuel compositions required for the proliferation assessment below, extensive cell burnup calculations have been performed for a typical MTR-type reactor geometry and various initial uranium enrichments ranging from 93% down to 5%.[5] The concentration of uranium-235 in the fuel is fixed at 0.948 g/cc and held constant for all enrichment levels by increasing the total uranium density in the fuel matrix correspondingly. The effective uranium density is therefore close to 1.0 g/cc for HEU and reaches 4.8 g/cc at an enrichment level of 19.75 wt%. All results presented below are scaled to a 30 MW MTR-type reactor operated at an average core power density of 125 kW/l.

The main difficulty in assessing the proliferation potential or the 'strategic value' of the fissile inventory associated with reactor operation is to relate and compare the corresponding uranium and plutonium inventories in the fuel. Uranium may be separated from the fresh fuel and possibly further enriched. In addition, both plutonium and uranium may be separated from the irradiated fuel. The feasibility of these approaches depends upon the skills of the proliferator and upon the availability of the required nuclear infrastructure.[6] The following analysis is therefore highly simplified in making inevitable *ad-hoc* assumptions.

Several assessment options are suggested. They are based on the fundamental assumption that a one-year's supply of fresh (unirradiated) fuel required to operate the reference reactor *and* a one-year's amount of spent fuel at 40% U-235 burnup are available.

[5] All results were obtained using a computational system, which has been developed specifically for research reactor analysis. The system is primarily based on the existing neutronics codes MCNP 4C and ORIGEN 2.2. For a discussion, see A. Glaser, *Neutronics Calculations Relevant to the Conversion of Research Reactors to Low-Enriched Fuel,* Ph.D. Thesis, Darmstadt University of Technology, 2005; J. F. Briesmeister (ed.), *MCNP — A General Monte Carlo N-Particle Transport Code, Version 4C,* LA-13709-M, Los Alamos National Laboratory, December 2000; A. G. Croff, *A User's Manual for the ORIGEN2 Computer Code,* ORNL/TM7175, Oak Ridge National Laboratory, July 1980; and S. Ludwig, *Revision to ORIGEN2 — Version 2.2,* Transmittal Memo, May 23, 2002.

[6] There are a number of historic precedences that illustrate the practical relevance of these scenarios. The most prominent examples are Israel and India, which have used unsafeguarded facilities (Dimona, Cirus, and Dhruva), all formally classified as research reactors, since the early 1960s to produce plutonium for their respective weapon programs. Israel destroyed the Iraqi HEU-fueled Osirak reactor, which had been supplied by France, in June 1981 suspecting the intention for covert plutonium production or HEU diversion. In 1991, Iraq had planned a "crash program" to divert safeguarded 80%-enriched fuel from a Soviet-supplied research reactor (IRT-5000) for further enrichment.

Different assumptions are made, however, regarding the ultimate usage of the material in a nuclear device depending upon the nuclear capability of the proliferator.

Basic nuclear capability

For the first scenario, it is assumed that an effort is undertaken to build a crude nuclear device based on the gun-type method. Only uranium is usable in such a device and, while the uranium is recovered from the spent fuel, the respective plutonium inventory is discarded from further use. The reference quantity of fissile material used for this assessment is one bare critical mass of uranium M_B, which is about the quantity needed for a gun-type device.[7] The diminished usability of uranium with reduced U-235 content is taken into account by applying a weighting factor η_1 to the critical mass ratio m/M_B. The probability of a spontaneous-fission-free millisecond in the material is used for this purpose.[8] The total strategic value $\mathrm{CM}_{\mathrm{A}}^{\star}$ of the material extracted from the fuel is defined as follows.

$$\mathrm{CM}_{\mathrm{A}}^{\star} = \eta_1(\epsilon_{\mathrm{FF}})\,\frac{m_{\mathrm{FF}}}{M_B(\epsilon_{\mathrm{FF}})} + \eta_1(\epsilon_{\mathrm{SF}})\,\frac{m_{\mathrm{SF}}}{M_B(\epsilon_{\mathrm{SF}})}$$

The indices FF and SF of mass m and enrichment level ϵ refer to the uranium contained in the fresh and the spent fuel, respectively. Based on the results obtained in the burnup calculations, $\mathrm{CM}_{\mathrm{A}}^{\star}$-values are calculated for a target burnup of 40% U-235 and a variety of enrichment levels. Results are shown in Figure 1. Table 1 lists additional numerical data on fissile inventories, critical masses, and weighting factors.

With decreasing enrichment levels, the estimated strategic value of the fuel decreases for two reasons: both the critical mass ratio m/M_B and the usability factor drop simultaneously to low values compared to the WGU-case. For the reference reactor, the material extracted from the fresh and irradiated fuel reaches a $\mathrm{CM}_{\mathrm{A}}^{\star}$ of 0.86 if the facility is fueled with WGU. The absolute mass of recoverable uranium is thus close to the amount needed for a crude gun-type device. About one third of the total value is associated with the uranium contained in the irradiated fuel. At 45% enrichment, $\mathrm{CM}_{\mathrm{A}}^{\star}$ has dropped to 0.21, while it essentially reaches zero for enrichment levels of 20% and below. As expected, because the plutonium contained in the spent fuel is discarded in this scenario, the lower the enrichment level, the lower the proliferation potential of the fuel.

[7] All critical mass values used here and further below have been determined with MCNP 4C at 300 K and a metallic density of 19 g/cc. See Tables 1 and 2 for specific numerical values.

[8] The total assembly-time of a gun-type device is in the order of 1 ms and one or more spontaneous fission events during this time-period, which occur with probability $(1-p)$, may trigger a premature neutron chain-reaction. Numerical values of $\eta_1 = p/p_{\mathrm{HEU}}$ are listed in Table 1.

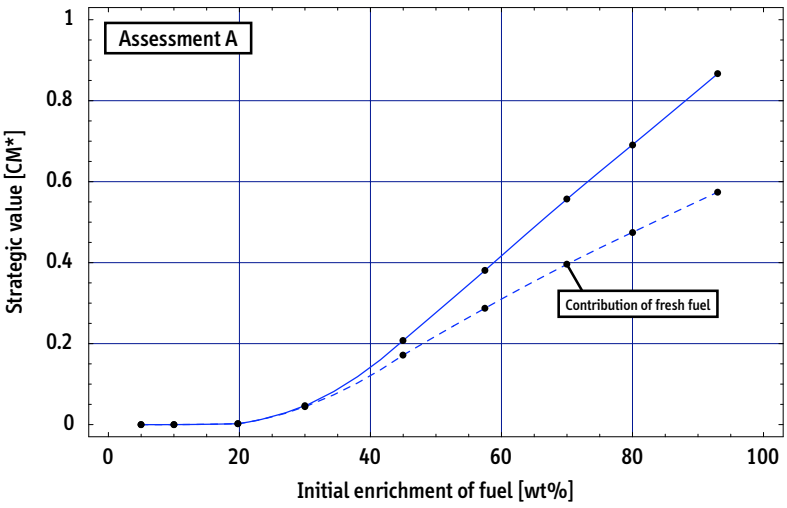

Figure 1: Strategic value of fissile materials associated with research reactor operation assuming that only uranium is extracted from the fresh and irradiated fuel (Assessment A, basic nuclear capability). Assumed objective is the construction of a crude gun-type device. The plutonium inventory in the spent fuel is discarded from further use.

Advanced nuclear capability

The fundamental assumption of the second scenario is that both uranium and plutonium are extracted and used for weapon purposes. This strategy would therefore require the successful implementation of the more sophisticated implosion-type design. As a corollary, however, much less material is needed to build such a device. The reference quantities used in the following are critical masses of uranium and plutonium enclosed by a thick (15 cm) beryllium reflector.

Two variants of the advanced scenario (B1 and B2) are considered below. As in the low-tech scenario, in scenario B1, no attempt is made to enrich such material to weapon-grade, i.e. to 93% (WGU). Similarly, the usability of uranium is corrected using a weighting factor, but instead of the spontaneus-fission rate, the time constant α is used to characterize the material's weapon-usability.[9] While the reflected critical masses of uranium (M_R) strongly depend upon the enrichment of the material, the critical mass values of plutonium are virtually identical (4.0 kg) for all compositions encountered in

[9]The time constant α is defined via the neutron population n by $n(t) = n_0 \exp[\alpha(t)\, t]$ for a supercritical configuration and determines the time-scale of the divergent fission chain reaction. Initial α-values have been determined with MCNP for a spherical configuration of two bare critical masses at normal (metallic) density. Table 2 lists numerical values of $\eta_2 = \alpha/\alpha_{\mathrm{HEU}}$.

research reactor fuel of the specified burnup (see Table 2). To estimate the total strategic value of the fissile material for Assessment B1, uranium and plutonium contributions are combined.

$$\mathrm{CM}^{\star}_{\mathrm{B1}} = \eta_2(\epsilon_{\mathrm{FF}})\,\frac{m_{\mathrm{FF}}}{M_R(\epsilon_{\mathrm{FF}})} + \eta_2(\epsilon_{\mathrm{SF}})\,\frac{m_{\mathrm{SF}}}{M_R(\epsilon_{\mathrm{SF}})} + \frac{m_{\mathrm{Pu}}}{4.0\ \mathrm{kg}}$$

The results for Assessment B1 are illustrated in Figure 2 and summarized in Table 2. Compared to the low-tech scenario, in which the construction of a gun-type weapon was assumed, the absolute strategic values are now much higher and reach a $\mathrm{CM}^{\star}_{\mathrm{B1}}$ of 3.90 for weapon-grade uranium. The value of $\mathrm{CM}^{\star}_{\mathrm{B1}}$ falls rapidly for sub-weapon-grade uranium, but plutonium production simultaneously becomes more important. As a result, a minimum value of $\mathrm{CM}^{\star}_{\mathrm{B1}}$ is now observed for an enrichment level of 15–20%, below which plutonium starts to dominate the proliferation potential of the fuel. This result, of course, is consistent with the efforts of the RERTR program to convert research reactors to LEU just below 20% enrichment. Compared to WGU, the effective proliferation potential of the fuel is reduced by almost 90% for LEU at 19.75%.

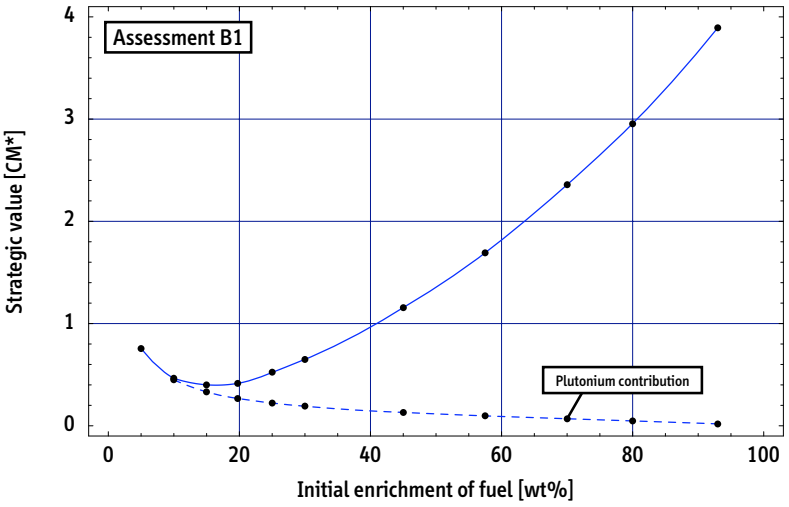

Figure 2: Strategic value of fissile materials associated with research reactor operation assuming that uranium and plutonium are used for an implosion-type weapon (Assessment B1, advanced nuclear capability). Dashed line indicates plutonium contribution to total value.

The second advanced-technology scenario B2 is based on the assumption that a limited amount of separative work, say from a laboratory or pilot-scale enrichment facility, is available to process diverted fuel. The objective would be to produce a maximum

amount of weapon-grade uranium, i.e. HEU at 93%, using the stock of pre-enriched uranium recovered from the fresh fuel and potentially also from the spent fuel. In the analysis below, values between 10 SWU and 640 SWU are considered.[10] If one assumes, for example, that centrifuge technology is available to process the feed material, a set of 60 machines could be used to produce 10 SWU in one month assuming that each centrifuge has an output of about 2 SWU/yr, a typical value for a first generation machine. In the case of centrifuges, it's unreasonable to assume that a cascade with much less than 50–60 machines could be operated in a meaningful way.[11] 10 SWU per month therefore represent a practical lower limit.

The amount of weapon-grade uranium that can be produced using the uranium extracted from the fresh and spent fuel as feed-stock is determined with special expressions for multicomponent uranium enrichment, which are required to correctly account for the U-236 content in the irradiated fuel.[12] Once the equivalent amount of the product WGU is known, the final estimate of the total strategic value is assigned via:

$$\mathrm{CM}^{\star}_{\mathrm{B2}} = \frac{m_{\mathrm{WGU,FF}} + m_{\mathrm{WGU,SF}}}{11.7\ \mathrm{kg}} + \frac{m_{\mathrm{Pu}}}{4.0\ \mathrm{kg}}$$

Results for this scenario are illustrated in Figure 3 and listed in Table 3. Similar to Assessment B1, there is a minimum of $\mathrm{CM}^{\star}_{\mathrm{B2}}$ for low enrichment capacities. Specifically, for a separative work of 20 SWU, the position of this weakly pronounced minimum is

[10] These values are extremely small compared to capacities generated by commercial enrichment plants. However, if much more enrichment capacity were available to the proliferator, there would be no need to divert the limited amount of (presumably safeguarded) research reactor fuel. Instead, undeclared feed-stock of natural uranium could be used to produce HEU directly.

[11] In the above-mentioned 1991 crash program, Iraq had planned to divert safeguarded 80%-enriched research reactor fuel for further enrichment with a small cascade of centrifuges (49 machines), a strategy equivalent to the present scenario. For such a low number of separating units however, the operation of the enrichment cascade would inevitably be sub-optimal and significant mixing losses can be expected. These losses would lead to a moderate increase of the time required to enrich the feed-stock to weapon-grade uranium. For a description of the Iraqi crash program, see D. Albright, F. Berkhout, and W. Walker, *Plutonium and Highly Enriched Uranium 1996. World Inventories, Capabilities, and Policies.* Stockholm International Peace Research Institute (SIPRI), Oxford University Press, 1997, pp. 344–349.

[12] A. de la Garza, G. A. Garrett, and J. E. Murphy, *Multicomponent Isotope Separation in Cascades,* Chemical Engineering Science, Vol. 15, 1961, pp. 188–209. To carry out the analysis, several additional assumptions have to be made. In general, the proliferator has the choice to distribute the available enrichment capacity between the fresh and the spent fuel. Even though SWU's are generally more effectively used on the fresh fuel, under specific circumstances, it may be favorable to enrich portions of the spent fuel. Obviously, if the fresh fuel is already weapon-grade, then the entire enrichment capacity could be used to process the irradiated fuel. To keep the analysis as simple as possible, only three basic cases are considered below: the proliferator may either spend the available SWU's on the fresh fuel, spend them on the irradiated fuel, or distribute them equally between both.

close to an initial fuel enrichment level of 20%, but it shifts to lower values with increasing SWU-capacity. As anticipated above, for high SWU-values, virtually the entire amount of U-235 can be extracted from the feed-material.[13] Under these circumstances, the distinction between LEU and HEU obviously is no longer relevant.

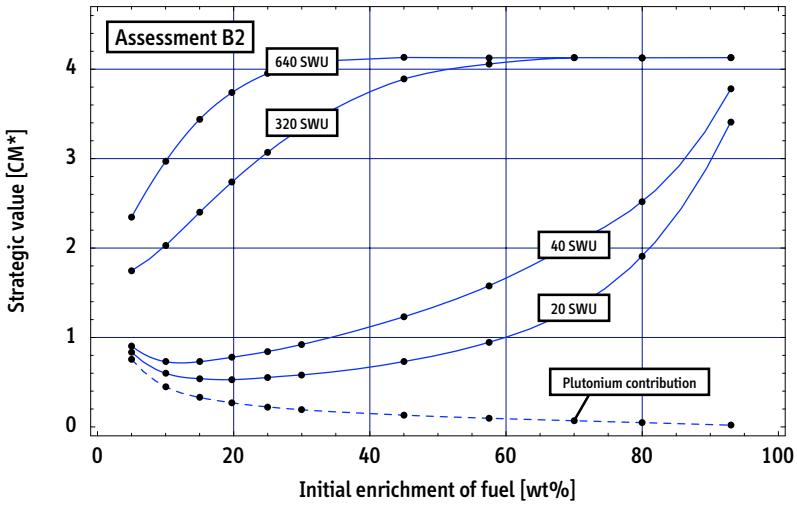

Figure 3: Strategic value assuming that a given amount of separative work is available to produce weapon-grade uranium (Assessment B2, advanced nuclear capability). Dashed line indicates plutonium contribution to total value.

The results of both advanced assessments (B1 and B2) demonstrate that an enrichment level close to 20% does indeed minimize the strategic value of the fissile material involved in operation of a given MTR-type reactor. For enrichment levels of 15% and below, the plutonium component dominates proliferation concerns associated with research reactor fuel. For intermediate enrichments above 20%, the proliferation potential of the nuclear material strongly depends on the assessment type, i.e. on the assumptions made regarding the proliferator's capabilities and available infrastructure. Nevertheless, the absolute values increase in all scenarios above 20% enrichment. As expected, the use of weapon-grade uranium to fuel a research reactor clearly maximizes the overall proliferation potential associated with reactor operation.

[13] As can be inferred from Figure 3, 320 SWU are sufficient to collect more than 90% of the maximum $CM^{\star}_{B2}$ for initial fuel enrichment levels of as low as 40%. At 640 SWU, this fraction is obtained for all enrichment levels beyond 20%.

Conclusion

The preceding discussion demonstrates the usefulness of the distinction between LEU and HEU. Uranium fuel below 20% virtually eliminates the possibility that the material could be directly used for the construction of a nuclear explosive device. Specifically, LEU cannot be used in a simple gun-type device, both because of its large critical mass and the corresponding neutron emission rate. Simultaneously and coincidentally, at an enrichment level between 15–20%, plutonium production is sufficiently suppressed to minimize the total strategic value of the material. For both reasons, the 20%-limit represents a reasonable and even optimum choice as a conversion goal for research reactors.

The analysis challenges the tendency of some recent research reactor projects, in which fuel enrichments beyond the 20%-limit are considered again. Most prominently, the new German research reactor FRM-II, which became operational in 2004 and is currently using 93%-enriched fuel, is required to be converted to an enrichment not exceeding 50% by December 2010.[14] Even though this enrichment reduction is laudable, current plans of the operator do contemplate an enrichment of *exactly* 50% for the converted reactor.[15] Similarly, designers of the French Jules Horowitz Reactor (JHR), which was initially planned for low-enriched fuel, currently consider the use of 35%-enriched uranium as a fall-back option. More recent developments suggest that this option will indeed be exercised.[16] In summary, after a two-decade period of close compliance with the LEU design-goal, there is an emerging attitude among designers, operators, and licensing authorities to interpret the conversion goal for research reactors as a malleable limit. Based on the data and the analysis presented above, this trend cannot be justified with technical arguments as it clearly reduces the proliferation resistance of the nuclear fuel cycle.

[14]Federal Ministry of Education and Research (BMBF), *Vereinbarung über FRM II vorgestellt,* Press release No. 169/2001, October 25, 2001.

[15]More recent analyses have shown that an enrichment level of 28–32% would be feasible with monolithic fuel and with only minor modifications of the core geometry (Glaser, op. cit.).

[16]Nuclear Fuel, *CEA likely to use HEU to start up new test reactor,* Vol. 29, No. 24, November 22, 2004.

Fresh Fuel							
Fuel Enrichment	5%	10%	19.75%	30%	45%	70%	93%
Annual U-Demand	463.4 kg	254.6 kg	135.6 kg	91.1 kg	61.6 kg	40.2 kg	30.6 kg
Reference Mass (M_B)	inexistent	1351.0 kg	782.2 kg	367.4 kg	184.7 kg	87.2 kg	53.3 kg
Critical mass ratio	0.00	0.07	0.17	0.25	0.33	0.46	0.57
Usability factor η_1	0.00	0.00	0.013	0.18	0.51	0.86	1.00
$CM^{\star}_{A,FF}$	0.00	0.00	0.002	0.05	0.17	0.40	0.57
Irradiated Fuel at 40% U-235 Burnup							
Initial Fuel Enrichment	5%	10%	19.75%	30%	45%	70%	93%
Residual U-Inventory	451.0 kg	243.4 kg	125.1 kg	80.9 kg	51.6 kg	30.5 kg	21.1 kg
U-235	3.1%	6.3%	12.8%	20.3%	32.2%	55.4%	81.0%
U-236	0.4%	0.7%	1.5%	2.3%	3.7%	6.4%	9.3%
U-238	96.5%	93.0%	85.7%	77.4%	64.1%	38.2%	9.7%
Reference Mass (M_B)	inexistent	very large	1884.6 kg	743.5 kg	324.8 kg	131.1 kg	67.8 kg
Critical mass ratio	0.00	0.07	0.17	0.109	0.16	0.23	0.31
Usability factor η_1	0.00	0.00	0.00	0.019	0.23	0.69	0.94
$CM^{\star}_{A,SF}$	0.00	0.00	0.00	0.002	0.04	0.16	0.29
Combined Strategic Value of Fresh and Irradiated Fuel							
$CM^{\star}_{A,tot}$	0.00	0.00	0.002	0.05	0.21	0.56	0.86

Table 1: Assessment A. Basic nuclear capability. Strategic value of uranium associated with one-year's operation of a 30 MW MTR-type research reactor. Inventories, isotopics, critical masses, and weighting factors for the fresh fuel and the irradiated fuel at a target burnup of 40% U-235.

Fresh Fuel							
Fuel Enrichment	5%	10%	19.75%	30%	45%	70%	93%
Annual U-Demand	463.4 kg	254.6 kg	135.6 kg	91.1 kg	61.6 kg	40.2 kg	30.6 kg
Reference Mass (M_R)	very large	753.0 kg	143.8 kg	68.7 kg	35.6 kg	18.2 kg	11.7 kg
Critical mass ratio	0.00	0.338	0.94	1.33	1.74	2.21	2.62
U sability factor η_2	0.00	0.043	0.16	0.27	0.45	0.73	1.00
$CM^{\star}_{B1,FF}$	0.00	0.015	0.15	0.36	0.78	1.61	2.62
Irradiated Fuel at 40% U-235 Burnup							
Residual U-235 Fraction	3.1%	6.3%	12.8%	20.3%	32.2%	55.4%	81.0%
Residual U-Inventory	451.0 kg	243.4 kg	125.1 kg	80.9 kg	51.6 kg	30.5 kg	21.1 kg
Reference Mass (M_R)	inexistent	very large	379.4 kg	138.2 kg	61.4 kg	25.9 kg	14.4 kg
Critical mass ratio	0.00	0.00	0.330	0.585	0.84	1.18	1.47
Usability factor η_2	0.00	0.00	0.075	0.162	0.30	0.57	0.86
$CM^{\star}_{B1,SF}$	0.00	0.00	0.025	0.095	0.25	0.67	1.26
Plutonium Inventory	3.02 kg	1.80 kg	1.07 kg	0.77 kg	0.52 kg	0.28 kg	0.08 kg
Pu-238	0.32%	0.42%	0.58%	0.77%	1.06%	1.94%	6.87%
Pu-239	79.49%	79.27%	78.97%	78.74%	78.36%	77.59%	73.59%
Pu-240	12.61%	12.57%	12.55%	12.52%	12.55%	12.34%	11.71%
Pu-241	6.88%	7.01%	7.16%	7.23%	7.29%	7.39%	7.12%
Pu-242	0.70%	0.73%	0.74%	0.74%	0.74%	0.74%	0.71%
Reference Mass (RCM)	(4.00 ± 0.04) kg						
$CM^{\star}_{B1,Pu}$	0.76	0.45	0.27	0.19	0.13	0.07	0.02
Combined Strategic Value of Fresh and Irradiated Fuel (Uranium and Plutonium)							
$CM^{\star}_{B1,tot}$	0.76	0.47	0.445	0.65	1.16	2.35	3.90

Table 2: Assessment B1. Advanced nuclear capability. Strategic value of available uranium and plutonium associated with one-year's operation of the reactor. For isotopics of uranium contained in the spent fuel, see Table 1.

Fresh Fuel							
Fuel Enrichment	5%	10%	19.75%	30%	45%	70%	93%
Annual U-Demand	463.4 kg	254.6 kg	135.6 kg	91.1 kg	61.6 kg	40.2 kg	30.6 kg
@ 10 SWU	0.47 kg	0.86 kg	1.57 kg	2.34 kg	3.69 kg	8.31 kg	
WGU equiv. @ 20 SWU	0.92 kg	1.70 kg	3.08 kg	4.55 kg	7.04 kg	14.69 kg	30.6 kg
@ 40 SWU	1.81 kg	3.31 kg	5.92 kg	8.57 kg	12.84 kg	23.27 kg	
@ 80 SWU	3.50 kg	6.29 kg	10.87 kg	15.18 kg	21.20 kg	29.68 kg	
@ 10 SWU	0.04	0.07	0.13	0.20	0.32	0.71	2.62
$CM^{\star}_{B2,FF}$ @ 20 SWU	0.08	0.15	0.26	0.39	0.60	1.26	2.62
@ 40 SWU	0.15	0.28	0.51	0.73	1.10	1.99	2.62
@ 80 SWU	0.30	0.54	0.93	1.30	1.81	2.54	2.62
Irradiated Fuel at 40% U-235 Burnup							
Residual U-235 Fraction	3.1%	6.3%	12.8%	20.3%	32.2%	55.4%	81.0%
Residual U-Inventory	451.0 kg	243.4 kg	125.1 kg	80.9 kg	51.6 kg	30.5 kg	21.1 kg
@ 10 SWU	0.28 kg	0.53 kg	0.93 kg	1.32 kg	1.87 kg	2.99 kg	5.37 kg
WGU equiv. @ 20 SWU	0.56 kg	1.04 kg	1.81 kg	2.57 kg	3.59 kg	5.56 kg	9.04 kg
@ 40 SWU	1.11 kg	2.03 kg	3.47 kg	4.84 kg	6.60 kg	9.61 kg	13.30 kg
@ 80 SWU	2.14 kg	3.84 kg	6.34 kg	8.57 kg	11.10 kg	14.33 kg	16.21 kg
@ 10 SWU	0.02	0.05	0.08	0.11	0.16	0.26	0.46
$CM^{\star}_{B2,SF}$ @ 20 SWU	0.05	0.09	0.15	0.22	0.31	0.48	0.77
@ 40 SWU	0.09	0.17	0.30	0.41	0.56	0.82	1.14
@ 80 SWU	0.18	0.33	0.54	0.73	0.95	1.22	1.39
Plutonium Inventory	3.02 kg	1.80 kg	1.07 kg	0.77 kg	0.52 kg	0.28 kg	0.08 kg
Critical Mass Ratio	0.76	0.45	0.27	0.19	0.13	0.07	0.02
Combined Strategic Value of Fresh and Irradiated Fuel (Uranium and Plutonium)							
@ 10 SWU	0.80	0.52	0.40	0.39	0.45	0.78	3.10
$CM^{\star}_{B2,tot}$ @ 20 SWU	0.84	0.60	0.53	0.58	0.73	1.33	3.41
@ 40 SWU	0.91	0.73	0.78	0.92	1.23	2.06	3.78
@ 80 SWU	1.06	0.99	1.20	1.49	1.94	2.88	4.03

Table 3: Assessment B2. Advanced nuclear capability. Strategic value of available uranium and plutonium associated with one-year's operation of the reactor assuming that a small enrichment capacity is available to process the fuel. For isotopics of uranium and plutonium in the spent fuel, see Tables 1 and 2.