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HALEU: Some Safeguards and Non-Proliferation Implications

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1. Introduction

HALEU (high-assay low enriched uranium) is an informal term applying to uranium enriched to greater than five percent and less than 20 percent in the isotope uranium-235. HALEU fuel is attracting considerable interest because, relative to current low enriched uranium (LEU) fuel, it will enable higher fuel utilisation and longer operating periods between refuelling. HALEU is being considered for a number of SMR (small modular reactor) and other advanced reactor designs.

Although the term HALEU is relatively new, fuel enriched in the HALEU range is already in widespread use as research reactor fuel. Compared with research reactors, if HALEU is adopted for power reactor programmes, both the total quantities of material and numbers of fuel movements (transportation) will be far greater.

For safeguards purposes, enriched uranium is categorised by enrichment level in two categories: LEU – less than 20 percent U-235; and highly enriched uranium (HEU) – 20 percent U-235 and above. Currently, typical LEU power reactor fuel is enriched up to 5 percent U-235. This is not a formal limit but is the result of practical and economic factors.

HALEU's higher enrichment level, compared with typical LEU, has a number of safeguards and non-proliferation implications.[1] Addressing these issues is not urgent, as the introduction of HALEU-fuelled power reactors is some years away and the likely numbers and locations of these reactors is not known. Also, technical characteristics of HALEU fuel and the costs involved are uncertain at this stage. Nonetheless, it is advisable to consider potential problems now so appropriate safeguards and institutional arrangements can be established in good time.

2. Safeguards and non-proliferation issues

The potential challenges with HALEU related to safeguards and non-proliferation can be briefly outlined as follows:

(1) Higher attractiveness for diversion. This relates primarily to the possible diversion of HALEU as feedstock for high enrichment. However, a recent paper has also raised the possibility that HALEU could be used directly for a nuclear explosive device.[2] Whatever the practicability of this, the issue certainly highlights a major difference with HALEU compared with current LEU fuels.

If HALEU is diverted for further enrichment to weapon-grade HEU (90 percent U-235 and higher), the enrichment effort required would be significantly less than using typical LEU. For example, to produce HEU at 90 percent enrichment using as feedstock HALEU at 19.75 percent enrichment would require little over 40 percent of the enrichment effort compared with using LEU at 5 percent enrichment (see section 3 following).

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1. A good overview is Warren Stern et al, *Implications for IAEA Safeguards of Widespread HALEU Use*, Brookhaven National Laboratory, 2021, presentation to National Academies, https://www.nationalacademies.org/documents/embed/link/LF2255DA3DD1C41C0A42D3BEF0989ACAECE3053A6A9B/file/D510EFD2C81FFF967900DB1152D2AB4D70DEBEFED05F?noSaveAs=1.
2. R. Scott Kemp et al, *The weapons potential of high-assay low-enriched uranium*, Science, 6 June 2024, https://www.science.org/doi/10.1126/science.ado8693.

(2) Economic incentive to reprocess. The higher residual enrichment of spent HALEU, compared with spent LEU, could change the economics of reprocessing. As shown in the Annex to this paper, preliminary analysis suggests reprocessing HALEU could be economically attractive. Whether this is in fact the case will depend on the cost of reprocessing, which in turn will depend on practical aspects, especially burnup levels (affecting the proportion of fission products in spent fuel) and whether the higher fissile content of spent HALEU fuel causes significant complications in reprocessing HALEU.

If reprocessing HALEU is viable, this would raise the following considerations:

(a) nuclear latency issues, if new reprocessing plants are established in states that do not currently reprocess (currently the only non-nuclear-weapon State with a commercial reprocessing facility is Japan);

(b) diversion risk for HALEU recovered for re-enrichment and for separated plutonium (assuming plutonium separation from HALEU is undertaken – see section 4 below).

Major factors affecting questions of risk include the type of fuel and the type of fuel cycle involved. For example, currently there is no practical technology for reprocessing TRISO fuel.[3] Currently, therefore, TRISO fuel is seen as presenting low proliferation risk.

If in-line recycling is used, the diversion risks are different to those for current reprocessing operations and output. Acquisition path analysis would have to be based on the specific design of the reactor and associated processes.

3. Enrichment

The following is an approximate comparison of the enrichment effort needed to produce one safeguards *significant quantity* (SQ) of weapon-grade HEU using feedstock of natural uranium, LEU and HALEU.

As defined by the International Atomic Energy Agency (IAEA) for safeguards purposes, an SQ is a quantity of HEU containing 25 kilograms U-235. For the following calculations, *weapon-grade* is defined as 90 percent U-235 (one SQ of HEU at 90 percent enrichment is approximately 27.8 kilograms of total uranium).

The metric for enrichment effort is the SWU – *separative work unit*. Calculation of enrichment effort depends on the assumptions made, including:

- The ratio between feed material available and planned/acceptable tails assay (depleted output);
- The number of enrichment stages required;
- Enrichment levels – figures used here are 5 percent U-235 for LEU and 19.75 percent U-235 for HALEU.

Based on these figures, to produce one SQ of weapon-grade HEU:

- Starting with natural uranium requires an enrichment effort of 5,370 SWU.[4]
- Starting with LEU enriched at 5 percent U-235 requires 835 SWU, that is, around 16 percent of the effort required if starting with natural uranium.[5]

3. TRISO is TRi-structural ISOtropic particle fuel. A TRISO particle is made up of a uranium, carbon and oxygen fuel kernel.
4. SWU rounded - based on feed of 6.1 tonnes natural U, tails assay 0.3%.
5. SWU rounded - based on feed of 815kg LEU at 5%, tails assay 2.0%.

- Starting with HALEU enriched at 19.75 percent requires 345 SWU, that is, around 42 percent of the effort required if starting with LEU, or just over 6 percent of the effort required if starting with natural U.[6]

The practical effect of a reduced requirement for enrichment effort is less installed capacity required, less time required, or both. It can be argued that the difference between using LEU and HALEU as enrichment feedstock is marginal compared with using natural uranium feed. While this is correct, a difference of almost 60 percent less effort required for enriching HALEU compared with LEU is significant and cannot be ignored.

Current IAEA routine inspection plans for enrichment plants, and for LEU holdings, reflect a context in which LEU is enriched up to around 5 percent U-235. This gives certain calculated quantities for LEU that a state planning clandestine enrichment could seek to divert, and the scale of enrichment operations the state would need for this purpose. For states producing HALEU, or holding stocks of HALEU, the IAEA will need to take into account that the quantities of possible diversion significance are much smaller compared with LEU (or looked at another way, the potential breakout time will be much shorter). An issue for consideration is whether a new material category for HALEU, between LEU and HEU, is warranted.

4. Reprocessing and use of reprocessed uranium

If HALEU enters into widespread use, it could change the currently unfavourable economics of reprocessing. This is because HALEU spent fuel will contain much higher levels of U-235 compared with spent LEU fuel, potentially making the uranium (which, depending on burnup, will comprise some 80 percent or more of the spent fuel) commercially attractive to recover. Unless there is a substantial increase in HALEU enrichment capacity (resulting in lower enrichment costs), reprocessing HALEU could be of interest both because it may be cost effective and because, as discussed below, it could help to meet HALEU demand.

The cost of reprocessing. In considering the economics of reprocessing, the key metric is cost. Reprocessing costs are difficult to ascertain from readily available information, whether for current operations or for possible future reprocessing of HALEU fuels. Costs are affected by factors such as whether a reprocessing plant already exists or is yet to be built, the technology used, the scale (level of throughput) and so on.

Depending on a number of variables, such as residual enrichment and burnup levels, spent HALEU fuel could have a fissile content (comprising residual U-235 plus produced plutonium) in the range of 7-10 percent, compared with typical spent LEU fuel at around two percent (comprising residual U-235 plus produced plutonium). This raises the question of whether criticality could present practical issues for reprocessing HALEU fuel. A higher fissile content could require a specially designed facility – the cost implications are not known. For the purpose of this paper it is assumed reprocessing costs for HALEU per unit of heavy metal will not be substantially different to those for LEU, but this assumption might prove to be optimistic.

Another factor affecting reprocessing costs is the proportion of actinides and fission products in spent fuel. This is affected by the burnup level. In current light water reactor spent fuel the proportion of actinides and fission products is typically around 4 percent. As shown in the Annex to this paper, depending on the burnup level, the proportion of actinides and fission products in HALEU fuel could be as high as 24 percent, or possibly more. This would have a major effect on reprocessing economics.

6. SWU rounded - based on feed of 138kg HALEU at 19.75%, tails assay 2.0%.

In writing a 2016 paper on reprocessing the author found sources suggesting a range of reprocessing costs from $903 to $5,400 per kilogram of heavy metal (kg HM).[7] The author settled on $2,500/kg HM as a reasonable indicative figure for the purpose of analysis. Applying inflation to the $2,500 figure suggests today's equivalent would be around $3,200/kg HM. This is consistent with data in a 2019 French report which, after conversion from euros to US dollars and adjusted for inflation, indicates a similar figure.[8] Accordingly, for the purposes of this paper the figure of $3,200/kg HM is used.

Reprocessing typical LEU fuel. The LEU fuel used today typically has an enrichment level of up to five percent U-235. In spent fuel the residual enrichment is less than one percent U-235 (say, 0.9 percent), which is little more than natural uranium. Applying the figure of $3,200/kg HM to reprocessing typical LEU fuel, the cost per kilogram of recovered product (uranium and plutonium), taking into account the actinide/fission product content (about four percent), is around $3,330 ($3,200 x 1.04). The value of the uranium is only a fraction of the cost of recovery. Each kilogram of this slightly enriched uranium costs $3,330 to recover, but the value in terms of its enrichment level is only around $435/kg.[9] To reprocess 100 kilograms of spent fuel will cost $320,000; the value of the recovered uranium (94 kg x $435) will be about $40,000. Taking into account the value of the recovered uranium, the one kilogram of plutonium recovered from 100 kilograms of spent fuel effectively costs $280,000. These figures illustrate why reprocessing is totally uneconomic today.

Reprocessing HALEU fuel. Compared with the current adverse economics of reprocessing, the major change with HALEU is that the value of the uranium, which will comprise 80 percent or more of the spent fuel, might make the uranium cost-effective to recover. Whether this is the case will depend, inter alia, on the initial enrichment level and the burnup level, which in turn will affect the residual enrichment level and the proportion of actinides and fission products.

A number of scenarios are outlined in the Annex. If the residual enrichment level is around seven percent U-235, the recovered uranium (reprocessed uranium – RepU) could be recycled as standard LEU fuel without requiring re-enrichment, either directly or, if the residual enrichment is high enough, after down-blending to standard LEU levels (see parts 4 and 5 of the Annex). RepU could also be used as feedstock for re-enrichment to HALEU. This could be cost-effective if the residual enrichment level of the RepU is high enough (say over seven percent U-235), even taking into account the costs of compensating for the U-236 content.

The presence of U-236 produced during irradiation is a complication in using RepU. This imposes additional costs in recycling uranium. Uranium-236 is not fissile, so it is undesirable in fuel for thermal reactors, and it cannot be efficiently separated by centrifuge enrichment because the mass difference between U-235 and U-236 is too small. If RepU is re-enriched, U-236 will be split between the enriched and depleted streams, and additional separation effort (SWU) will be needed to reach the required U-235 level. Also, U-236 in enrichment feed will contaminate centrifuges and piping, possibly causing subsequently enriched (non-reprocessed) LEU or HALEU product to be off specification. Consequently, enrichment operators will want to limit enrichment of RepU to dedicated cascades – and are likely to seek an increased SWU price to compensate for this.[10]

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7. John Carlson, *The Case for a Pause in Reprocessing in East Asia: Economic Aspects*, NTI, August 2016, https://www.nti.org/analysis/articles/case-pause-reprocessing-east-asiaeconomic-aspects/.
8. Cour des comptes, *Downstream Nuclear Fuel Cycle*, 2019, https://www.ccomptes.fr/sites/default/files/2023-10/20190704-rapport-aval-cycle-combustible-nucleaire.pdf.
9. The figure of $435/kg is calculated on the basis of enriching natural uranium to 0.9 percent enrichment, taking account of costs for natural uranium feed, conversion and SWU.
10. Note however that if laser enrichment is commercially established, a laser process may be able to separate U-236 from RepU.

Another issue with using RepU, particularly for enrichment, is the presence of U-232, a decay product derived from neptunium-237 (via plutonium-236). Uranium-232 daughter products are strong gamma emitters, so precautions will be required to limit radiation exposure of personnel. This would add to costs.

The greatest challenge associated with reprocessing HALEU appears to be the actinide/fission product content, which is expected to be much higher than with current LEU fuels due to higher burnup. This would have a marked impact on reprocessing cost. If the actinide/fission product content is say 24 percent, then effectively the cost per kilogram for recovered product (uranium and plutonium) will be $3,200 x 1.31, that is, around $4,200/kg. The calculations in the Annex suggest this figure could still be economic in some scenarios, though this is far from certain.

Issues to consider with reprocessing HALEU include:

(1) Should the plutonium in the spent fuel be separated or left as a uranium-plutonium mix? Plutonium could be separated in reprocessing and used to produce MOX (mixed uranium and plutonium oxides) fuel, as done in current reprocessing programmes. Another possibility would be to leave the plutonium in the product stream, which would then comprise a uranium-plutonium mix.[11] Depending on the enrichment level of the uranium, retention of the plutonium could help to overcome the disadvantage of having a U-236 content.

Depending on burnup, the plutonium content in spent HALEU fuel could be around two percent. This plutonium is likely to comprise around 60 percent fissile isotopes, so retaining the plutonium in the recovered uranium product would effectively be equivalent to an additional one percent enrichment.

(2) What to do about the U-236 content in reprocessed uranium? This could be addressed in two ways:

(a) One approach is to reprocess HALEU that has a sufficiently high residual enrichment level to compensate for the contained U-236. For example, if the residual enrichment is seven percent U-235, and the U-236 content is two percent, the effective enrichment level will be around five percent.[12]

As noted in the Annex (part 4), a potential policy issue raised by compensating for U-236 in the enrichment of RepU is that if an effective enrichment level at the top of the HALEU range (say 19.75 percent) is sought, this would require enriching to slightly above 20 percent U-235. This would cross the threshold of the HEU category. The implications of this require further study.

(b) An alternative approach is blending the RepU with fresh (i.e. non-irradiated) LEU to dilute the U-236 content. The proportions would depend on the enrichment level and U-236 content of the RepU, but something in the order of four-to-one (four parts of fresh LEU to one part of RepU) could reduce the U-236 to an acceptable level. Here too retention of plutonium in the mix would increase the fissile content of the blend.

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11. An example is the Russian REMIX fuel concept, where plutonium remains with the RepU product and the fissile content of the mix is adjusted through blending with unirradiated enriched uranium.

12. Also, as noted above, retention of plutonium with the uranium would have a similar effect to an additional one percent enrichment. So a residual enrichment of six percent, together with the plutonium, would have a combined fissile content of seven percent, allowing for a U-236 content of two percent. This would correspond to an effective enrichment level of 5 percent.

5. Conclusions

An increase in the number of states producing HALEU, holding HALEU stocks and fabricating HALEU fuel, and an increase in movements of HALEU, all have implications for safeguards. This could require adjustments in the frequency and intensity of safeguards inspections, and could also lead to the conclusion that safeguards should be supplemented by additional technical measures[13] and institutional measures (such as control and ownership arrangements) to reduce proliferation risk.

It is possible that reprocessing HALEU could be attractive both on cost grounds and to help meet increasing HALEU demand. The likelihood of this is difficult to assess at this stage. Deployment of SMRs and advanced reactors in significant numbers is still years away – meanwhile enrichment capability may expand, leading to lower enrichment prices, so the incentive to reprocess may diminish.

Currently it is difficult to find the real costs of current reprocessing operations, there are subsidies and hidden costs. There is no common standard for "economic" operations – states are prepared to absorb costs in the interest of research and development. It is notable that some states have proceeded with current reprocessing operations despite the adverse economics. A concern is whether some states may be prepared to overstate the economic case for reprocessing in order to justify establishing a dual-use fuel cycle capability.

Governments and the IAEA need to start considering how best to deal with this situation – the possibility of new reprocessing projects is problematic, even if the plutonium is not recovered as a separate product. Some reactor designs and fuel concepts would enable recycling without current forms of reprocessing, but any spread of capabilities that could assist clandestine separation needs to be dealt with very cautiously.

Accordingly, the safeguards and non-proliferation implications of HALEU should be assessed in the near term so an appropriate control regime, if required, can be established in time to be effective. An important part of future fuel cycle arrangements is likely to be suppliers taking responsibility for dealing with spent HALEU fuel. To address the various concerns touched on here, it may be time to develop a multilateral approach to proliferation-sensitive aspects of the fuel cycle.

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13. Design of facilities, form of fuel, etc.

Annex

Cost and other calculations

As the paper notes, there are many uncertainties about future costs involving HALEU. The figures used here are based on information publicly available in July 2024. These estimates are not intended to be exact but are indicative of potential outcomes to be addressed.

Note these figures do not include fuel fabrication costs.

1. Enrichment from natural uranium (NU) to LEU @ 5 percent

- 1 kg LEU requires:

– 11 kg NU @ $220/kg	2,420
– conversion @ $60/kg	660
– 7.2 SWU @ $175	1,260
Total cost per kg	$4,340

2. Enrichment from LEU @ 5 percent to HALEU @ 19.75 percent

- 1 kg HALEU requires:

– 4.4 kg LEU @ $4,340	19,000
– 8 SWU @ $1,000[14]	8,000
HALEU @ 19.75% - 1 kg	$27,000

3. Reprocessing

There is little information available on the likely isotopic composition of spent HALEU fuel – this depends on the type of reactor, the enrichment level of the fuel, and the burnup level. The following calculations assume a spent fuel composition per tonne as follows:

– Uranium	738 kg (incl 26 kg U-236)
– Plutonium	21 kg
– Actinides and fission products	241 kg

These figures are based on data for the Russian RITM-200 reactor, with fresh fuel enrichment of 19%, burnup of 64.5 MWd/kgU, and residual enrichment of 5.7%.[15] They might not be representative of future HALEU power reactors, but are used here in the absence of other data for HALEU spent fuel from PWRs.

Based on these figures, to obtain one kg of uranium from spent HALEU would require reprocessing approximately 1.32 kg HM (on the basis that plutonium comprises just over two percent of the spent fuel, and actinides and fission products comprise 24 percent)

– cost of reprocessing assumed as $3,200/kg HM

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14. A substantial premium is expected in SWU costs for HALEU enrichment – see Kirk Sorensen, *HALEU is frightfully expensive (calcs)*, https://energyfromthorium.com/2024/01/09/25k-haleu/.
15. Dmitrii Dziadevich, *Safety and Economy of Floating Power Plants*, Lappeenranta-Lahti University of Technology, 2021, https://lutpub.lut.fi/bitstream/handle/10024/162751/MSc_FPP_Dmitrii_Dziadevich.pdf?sequence=3, and *Solutions for the Shipbuilding Industry*, Atomenergomash, 2020, https://aem-group.ru/static/images/buklety/2020/Booklet_sudostroenie_en.pdf.

- one kg reprocessed U (RepU) will cost ($3,200 x 1.31) = $4,200

4. Re-enrichment of reprocessed U to produce HALEU

As noted above, enrichment requirements here have been increased by eight percent (i.e. multiplied by 1.08) to compensate for the U-236 content in RepU (but see notes below). [16]

Enrichment of RepU to HALEU at 19.75 percent

Residual enrichment	5%	7%	10%
1 kg HALEU requires:			
RepU @ $4,200/kg	4.3 kg - $18,060	3.0 kg - $12,600 (1)	2.1 kg - $8,820
Conversion @ $60/kg	4.3 kg - $258	3.0 kg - $180	2.1 kg - $126
SWU @ $1,000	8.9 SWU - $8,900	5.6 SWU - $5,600 (2)	3.6 SWU - $3,600
Total cost HALEU/kg	$27,218	$18,380 (3)	$12,546 (4)

Notes: (1) Actually the reprocessing cost per kilogram for RepU with 7% residual enrichment is expected to be lower than for 5% RepU, because the burnup will be lower (resulting in a lower proportion of actinides/fission products, therefore a higher proportion of U).

(2) Likewise, due to lower burnup the U-236 content will be lower, so the SWU requirement will be lower.

(3) For the reasons in (1) and (2), for 7% RepU the cost per kilogram of HALEU is expected to be lower than shown here. However, the author has insufficient data to calculate this.

(4) For the reasons set out above, the burnup for spent fuel with 10% residual enrichment will be lower still, so the cost per kilogram of HALEU is expected to be significantly less than shown here.

5. Downblending RepU to typical LEU (5 percent)

Figures adjusted to take account of U-236 content (but see note (5)).

RepU residual enrichment	7%	10%
1 kg LEU requires:		
RepU @ $4,200/kg	0.73 kg - $3,066	0.49 kg - $2,058
NU @ $220/kg	0.27 kg - $59	0.51 kg - $112
Total cost LEU/kg	$3,125	$2,170 (5)

Note (5): As discussed above, RepU with a high residual enrichment will have lower burnup, therefore a lower proportion of actinides/fission products and U-236. Accordingly, for RepU with 10% enrichment the cost per kilogram of LEU is likely to be significantly lower than shown here.

6. Using RepU directly as LEU

16. For 19.75%, calculations based on 21.33%. **Note** this exceeds the enrichment threshold for HEU (20%), raising the policy question, should it be permissible to exceed the HEU threshold if the effective enrichment level, allowing for the presence of U-236, remains below 20%?

If the residual enrichment is similar to LEU (say five percent, taking into account U-236 content), RepU could be used directly as LEU – the reprocessing cost ($4,200/kg U) is less than the cost of newly enriched LEU ($4,340/kg – see part 1 above).