ANNEX III.

ECONOMIC VALUE OF URANIUM RECOVERED FROM LWR SPENT FUEL AS FUEL FOR HWRs

III-1. INTRODUCTION

In this study it is shown that, assuming an efficient market, reprocessed uranium from LWRs could be sold to HWRs at more than double the current price of natural uranium. If reprocessed uranium is a by-product of MOX reprocessing, this would represent pure profit to the preprocessor. The existence of such a market would severely impact another potential use for reprocessed uranium which is discussed in a different annex of this report – Annex XXVIII – mixing it with ^{241}Am to produce a natural uranium equivalent for use in HWRs.

If light water reactor (LWR) fuel is reprocessed to extract plutonium to make fuel for MOX-burning reactors, by-products will include fission products, minor actinides (MA), and uranium with an isotopic composition different from natural uranium (NU). This recovered (or reprocessed) uranium (REPU) may have a higher ^{235}U content than NU and could in principle be used to generate economic revenue from power production, and thereby reduce the net cost of reprocessing. In order to evaluate the potential revenue from REPU, it has been assumed that an efficient REPU market exists where its price would be comparable to its economic value[1] as an energy source. No such situation currently exists, because nuclear fuels must be very well characterized for their end use, with the result that suppliers and users of REPU have to be closely matched, making an efficient market impossible.

There are a number of scenarios for using REPU. Some of these include:

- Re-enriching the REPU for use in LWR fuel;
- Manufacturing a Natural Uranium Equivalent (NUE) fuel for use in heavy water reactors (HWRs);
- Direct re-use of REPU in HWRs.

An economic analysis of scenario (1) was developed in [III-1] and demonstrated for some specific REPU in another ANNEX of this report. The result for the REPU having 0.924 weight % (wt.%) ^{235}U/U, corresponding to spent fuel with 33 MWday/kg burnup, shows that REPU should have a value that is 10% to 25% higher than the price of NU for high market prices of the latter ($300 or more) and very similar to that of NU for low prices ($50 or less). The analysis in this ANNEX will attempt to quantify the economic value of REPU to an HWR in scenarios (2) and (3).

The potential for re-use of REPU in HWRs has been extensively summarized in an earlier IAEA Technical Document [III-2]. The analysis reported on here differs from others by attempting to:

- Create a metric 'economic value' to attempt to quantify and compare this approach to the use of REPU with other scenarios;

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[1] The 'value' of REPU is defined in this document as the maximum price that a buyer would be willing to pay and assumes no scarcity or oversupply. It is assumed that the potential buyer has an alternative fuel (natural uranium) at a well-known price and that the value of REPU is based on the ability of the buyer to switch easily to using this other fuel if the REPU is not obtainable at a low enough price.

- Calculate using a specific (high quality) REPU composition, corresponding to a nominal 33 MWday/kg LWR spent fuel (allowing direct comparison to other calculations for REPU value [III-1],[III-3].
- Analyze using a current advanced fuel cycle bundle design which incorporates a non-fuel central element for reduction of coolant void reactivity (CVR) in an HWR.
- Perform sensitivity studies on the price of NU and HWR bundle manufacturing costs, and the effects of varying the ^{235}U and ^{236}U (in the REPU) and dysprosium (Dy) concentrations (in the central absorber).

III-2. METHOD OF CALCULATION

III-2.1. WIMS-AECL

The reactor physics code used to calculate the exit burnup of used fuel was WIMS-AECL v.3.1.2.1 [III-4], a lattice physics code that solves a multi-group integral neutron transport equation in combination with burnup, using an 89-group nuclear data library based on ENDF/B-VII.0 [III-5]. The code was used to model a unit lattice cell consisting of an HWR fuel bundle, pressure tube, calandria tube and square outer boundary (see Table III-1 and Fig. III-1). Boundary neutron current conditions corresponding to the average leakage of neutrons from a CANDU-sized reactor were imposed. In other words, a critical spectrum was used for burnup calculations.

TABLE III-1. HWR FUEL COMPOSITION

Quantity	Value, Units
Lattice pitch (square)	28.575 cm
Moderator D_2O purity	99.8 wt.% D_2O
Pressure tube (PT)	Zr-2.5Nb
Calandria tube (CT)	Zr-2
Average D_2O coolant	99 at%D_2O , 561 K
Fuel	NU or REPU as oxide
Average fuel temp.	860 K
Density of fuel	10.55 g/cm^3
Cladding material	Zr-4
Central element	$Dy_2O_3ZrO_2$,7.1 g/cm^3
Length of bundle	49.5 cm
Inner element radius	0.633 cm
Outer element radius	0.572 cm
Heavy element mass	18.9 kg

III-2.2. Fuel bundle concept

In an HWR, the coolant provides a relatively small fraction of the total moderation, so the negative reactivity effect of the loss of moderation in a loss-of-coolant accident (LOCA) can be outweighed by positive contributions related to flux spectrum and shape. An absorbing central pin, such as is shown in Fig. III-1, takes advantage of central flux peaking after a LOCA, mitigates the coolant void reactivity (CVR), and creates a type of low void reactivity fuel (LVRF).

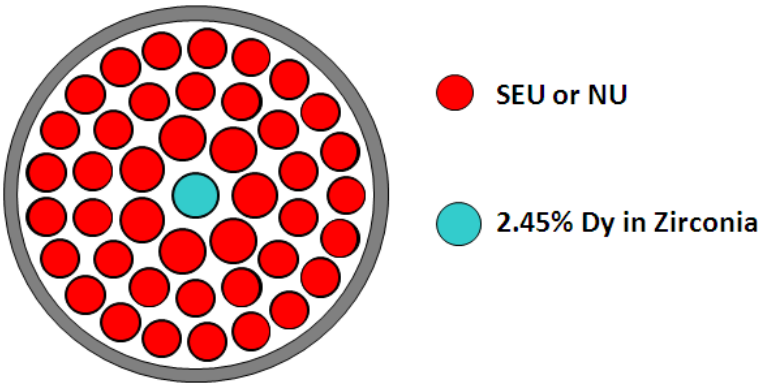

FIG III-1. Advanced fuel cycle bundle with CVR-control central element.

III-2.3. Reprocessed uranium

The reprocessed uranium was assumed to be that from 33 MWday/kg LWR spent fuel (SF) [III-1]. It nominally contains 0.9242 wt.% ^{235}U/U, and 0.4088 wt.% ^{236}U/U. The ^{234}U fraction, which is a much weaker absorber than ^{236}U, was set to zero. Large stockpiles of SF containing uranium of this enrichment exist, although current and future reactors achieve considerably higher burnups (with a corresponding lessening of REPU quality) up to 50 MWday/kg.

III-3. REACTOR AND FUEL CYCLE

A common HWR core design concept is a square array of 380 fuel channels, each holding twelve 49.5 cm long bundles each containing ~19 kg of uranium (in the form of UO_2). Online fuel management consists of eight-bundle shifts. An HWR fuelled with natural uranium uses neutron absorbing reactivity devices (e.g, 'liquid zone controllers', mechanical control absorbers, and adjusters) to help flatten the flux axially, to reduce the power ramping seen by fresh fuel, and to increase the uniformity of bundle power across the core. Core leakage is approximately 30 mk[2] to 40 mk of reactivity and the zone controllers and other reactivity devices are worth another 15 mk to 35 mk. With advanced fuels containing a higher fissile content than NU, core flux shaping can be achieved by using fewer bundles per refuelling shift and shaping the burnup distribution axially. Eliminating the zone controllers increases the core multiplication by 15 mk, but this advantage is reduced by the requirement that more fresh fuel be stationed near the reactor axial edges, increasing leakage from the core. A simple heuristic model was used here having a leakage of 30 mk for a device-free

[2] mk is reactivity unit; mk = 0.001.

core with the same exit burnup as that of a typical modern HWR (i.e. 7500 MWday/t)[3], rising to 40 mk when the exit burnup doubled.

III-3.1. Exit burnup and CVR

A single, axially uniform, fuel channel operating at a steady specific power of 32 W/giHM[4] was modeled in WIMS-AECL and reactor properties were inferred from the burnup-average of the channel properties as the fuel evolved from fresh to its exit burnup. According to the linear reactivity model, an estimate of the reactor fuel infinite-lattice neutron multiplication, k∞, may be made by weighting this quantity over the power history of a single bundle (over N time steps to a total burnup of BU) as:

$$\overline{k_\infty} = \frac{\sum_{i=1}^{N}(k_\infty)_i(\Delta BU)_i}{\sum_{i=1}^{N}(\Delta BU)_i} = \frac{\sum_{i=1}^{N}(k_\infty)_i(\Delta BU)_i}{BU} \qquad \text{(III-1)}$$

For a continuously refueled reactor, the exit burnup is achieved when the weighted sum over the power history makes $\overline{k_\infty}$ equal to 1 + leakage. In this case, as discussed in Section II.4, the sum over the power history must satisfy:

$$1 + leakage = \frac{\sum_{i=1}^{N}(k_\infty)_i(\Delta BU)_i}{BU_{exit}} \qquad \text{(III-2)}$$

This condition is found by extending the power history by hand, step by step, until the weighted sum approaches 1.030 (to within a small tolerance). The true core leakage for this burnup was then estimated assuming that it varies between 30 mk and 40 mk as the exit burnup varies between 7500 MWday/t and 15000 MWday/t. The exit burnup was then re-evaluated with this revised leakage estimate.

The CVR is defined approximately[5] as

$$CVR = (k_{eff})^{no_coolant} - (k_{eff})^{coolant} \qquad \text{(III-3)}$$

If the approximation is made that core axial leakage is approximately the same for both cooled and voided cores[6], we can substitute k∞ and compute the reactor CVR from single channel data as:

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[3] In practice, without zone controllers, too many fuel channel visits would be required per day to shape the flux axially with short bundle shifts if the burnup were not increased (given current refuelling machine limits). Thus this analysis overestimates the value of poor quality REPU fuel.

[4] iHM – initial heavy metals.

[5] The CVR should accurately be a difference between reactivities, and not multiplications, but for k_{eff} near critical the difference is negligible.

[6] Other studies have shown that the difference in leakage is less than 1 mk, or 10% of the reactivity, for typical cores. Since this analysis is mainly concerned with changes in CVR, rather than its absolute value, the expected error introduced by this approximation will be considerably smaller.

$$\overline{CVR} = \frac{\sum_{i=1}^{N}\left\{(k_\infty)_i^{no_coolant} - (k_\infty)_i^{coolant}\right\}(\Delta BU)_i}{\sum_{i=1}^{N}(\Delta BU)_i} = \frac{\sum_{i=1}^{N}(CVR)_i(\Delta BU)_i}{BU} \quad \text{(III-4)}$$

III-3.2. Economic value

III-3.2.1. High burnup fuel

HWRs overcome the low fissile content of NU by minimizing parasitic absorption throughout the reactor. The result is a higher number of captures in ^{238}U, per fission, than in other reactor designs. The resulting quick buildup of ^{239}Pu compensates for the depletion of ^{235}U in the fuel and leads to a very gradual reactivity loss that allows a very high fuel burnup per initial fissile loading. The slow reactivity decline also means that the exit burnups of HWRs are very sensitive to initial enrichment, with the exit burnup of fuel that is initially only slightly more enriched than NU being much higher than the standard burnup.

Assuming bundle manufacturing costs to be the sum of a uniform assembly cost plus the cost of the fuel, the economic value of REPU in an HWR is defined here as that value which makes replacement REPU bundles (in an all-REPU reactor) equal to the cost of the NU bundles which would otherwise be required to produce the same energy.

The production cost (P) of a fuel bundle containing M kg of heavy metal can be expressed as:

$$P = M \times \{C_F + C_c + C_f\} \quad \text{(III-5)}$$

where CF (F=NU or REPU) is the fuel cost, Cc (Crc) is the cost of conversion of NU (REPU) to UO_2, and Cf (Crf) is the bundle manufacturing cost for NU (REPU) fuel, all per kg of heavy metal. If REPU obtains R times the burnup of NU, then an NU fueled reactor would require R times as many bundles to get the same total energy. Equating the total fuel cost for an NU and REPU fueled reactor gives:

$$RM \times \{C_{NU} + C_c + C_f\} = M \times \{C_{RU} + C_{rc} + C_{rf}\} \quad \text{(III-6)}$$

and the maximum cost that an HWR should be willing to pay, here set as the 'value' of REPU, is:

$$C_{RU} = RC_{NU} + R\{C_f + C_c\} - \{C_{rf} + C_{rc}\} \quad \text{(III-7)}$$

Nominal values of Cf =\$2,000/(19 kg) = \$105.26 /kg and CNU = \$90 /kg have been chosen as the basis for this study. Conversion costs of \$6/kg for NU and \$21/kg for REPU have been taken from [III-1]. In accordance with [III-1], a fabrication cost of \$10/kg more for REPU than for NU has been chosen, so that Crf = \$115.26 /kg.

III-3.2.2. Natural uranium equivalence

REPU could be mixed with DU, then the resulting bundle CVR adjusted with the central poison element so that the initial CVR was re-established. If such a bundle had a burnup of 7500 MWday/t, then it would be equivalent in all respects to the original NU bundle. If the proportion of REPU in the mixture were 'β', it is assumed that the production cost of a bundle, per kg of mixed material, would be the weighted average of the total production cost 'B' of a bundle of each kind (REPU and DU), including material:

$$\frac{P}{M} = \beta B_{RU} + (1-\beta)B_{DU} \quad \text{(III-8)}$$

In order to make economic sense, this production cost must be equal to (or less than) the production costs per unit mass of NU (Eqn. III-5), so

$$B_{NU} = \beta B_{RU} + (1-\beta) B_{DU} \tag{III-9}$$

Eqn. III-9 simplifies to:

$$B_{RU} = \frac{1}{\beta} B_{NU} \frac{(1-\beta)}{\beta} B_{DU} \tag{III-10}$$

In this study we will assume that depleted uranium is available for negligible cost, and that its conversion and fabrication costs are the same as those for natural uranium. Then, expanding the production costs of each bundle in terms of its components yields:

$$C_{RU} = \frac{1}{\beta} C_{NU} + C_c + C_f - C_{rc} - C_{rf}. \tag{III-11}$$

The maximum price, CREPU, that an HWR would be willing to pay (per kg) for REPU will be that value is calculated from Eqn. III-11 for a given β.

III-4. RESULTS

III-4.1. Value of REPU

Figure III-2 shows the calculated burnup of 33 MWday/kg REPU (having 0.9242 wt.% ^{235}U/U, 0.4088 wt.% ^{236}U/U) and a sensitivity study[7] showing how exit burnup changes with different values of ^{235}U wt.% and ^{236}U wt.%.

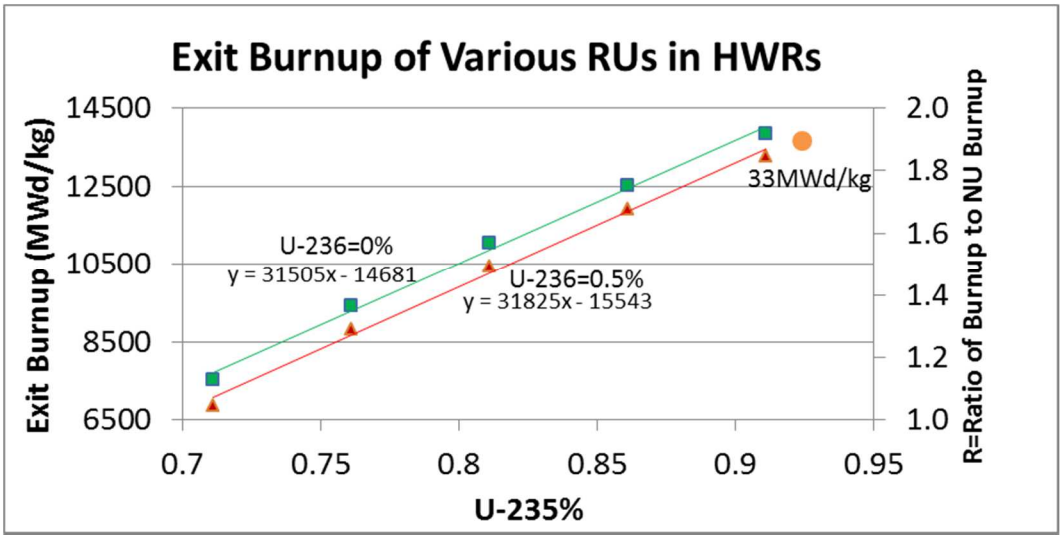

FIG. III-2. Estimated HWR exit burnup using 33 MWday/kg REPU, and the sensitivity of burnup to ^{235}U and ^{236}U.

[7] The lines are fits to experimental data having some scatter. This is why the line for ^{236}U wt.%=0.5 appears to extrapolate higher than the 33 MWday/kg point when it should logically go below.

Figure III-3 and Fig. III-4 show the value of REPU as a function of ^{235}U wt.% and ^{236}U wt.% for NU market costs, bundle fabrication costs, and conversion costs as described in Section III-3.2. The value of the 33 MWday/kg spent fuel is seen to be about $230/kg. For comparison, if REPU were to be re-enriched its value would be dominated by the price of NU. This is because the REPU feed/product ratio declines relatively slowly with increasing enrichment, particularly when the effects of ^{236}U (which forces higher enrichment to create an equivalent fuel) are taken into account. For REPU from 33 MWday/kg spent fuel, fuel fabrication costs of $250/kg ($260/kg) are assumed for NU (REPU) assemblies (more hardware being required for LWR assemblies than for HWR fuel bundles, and the result is a value of approximately $107/kg (as shown in Fig. III-4).

The decline in the value of REPU with increasing ^{236}U fraction (when the REPU is to be used as HWR fuel) is seen to be about $3 for every 0.1% increase in ^{236}U content (Fig. III-4). For the 33 MWday/kg spent fuel, this corresponds to a burnup penalty of ~$12.

Similar calculations of the reduction in value of REPU with ^{236}U when the REPU is to be used for re-enrichment for re-use in an LWR [III-3], result in about a value that is double ($6 for every 0.1% increase in ^{236}U content) that found here for HWRs. This occurs because ^{236}U is a stronger absorber in the epithermal spectrum of an LWR than in the highly thermal spectrum of an HWR. These estimates may be used as a rough guide to when technologies to separate ^{236}U from ^{235}U would become cost-effective in each case.

Using the value of R for the 33 MWday/kg LWR spent fuel of ~1.82, Eqn. III-7 can be inverted to demonstrate the sensitivity to natural uranium market price (Fig. III-5), with fabrication costs held fixed and assumed to be $10 higher for REPU than NU, and conversion costs equal to $21 and $6 for REPU and NU respectively). Alternatively, Eqn. III-7 can be inverted to demonstrate the sensitivity of REPU value to assembly fabrication costs (Fig. III-6, with natural uranium market price and conversion costs held fixed at their previous values). On each line, the LWR value and trends that are plotted for comparison are based on the Bunn [III-1] methodology. It can be seen that the cost advantage of reusing REPU in HWRs (relative to no reuse or reuse in LWRs) increases markedly with both the HWR assembly fabrication cost and with the underlying market price of natural uranium.

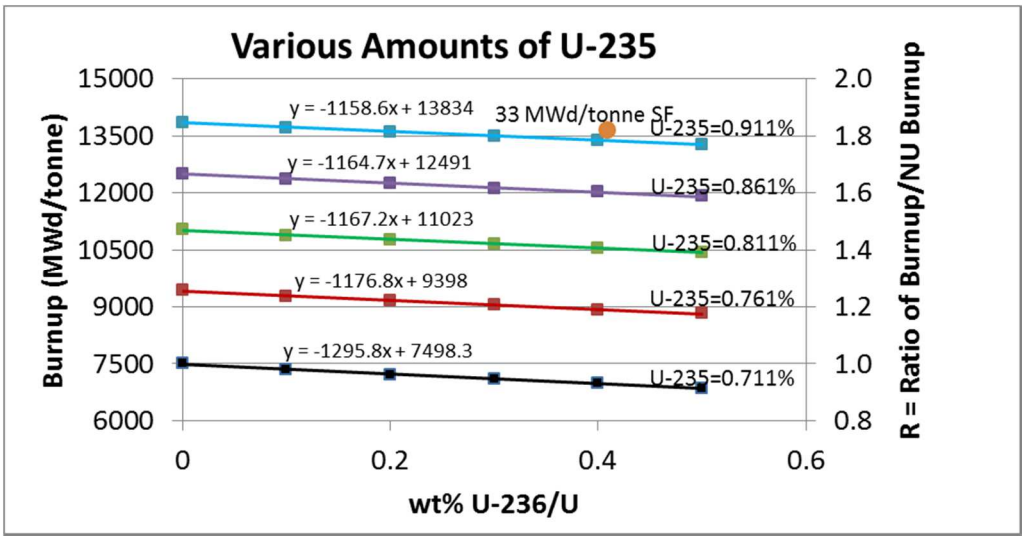

FIG. III-3. Decline in estimated exit burnup of REPU in HWRs with increasing ^{235}U and ^{236}U content.

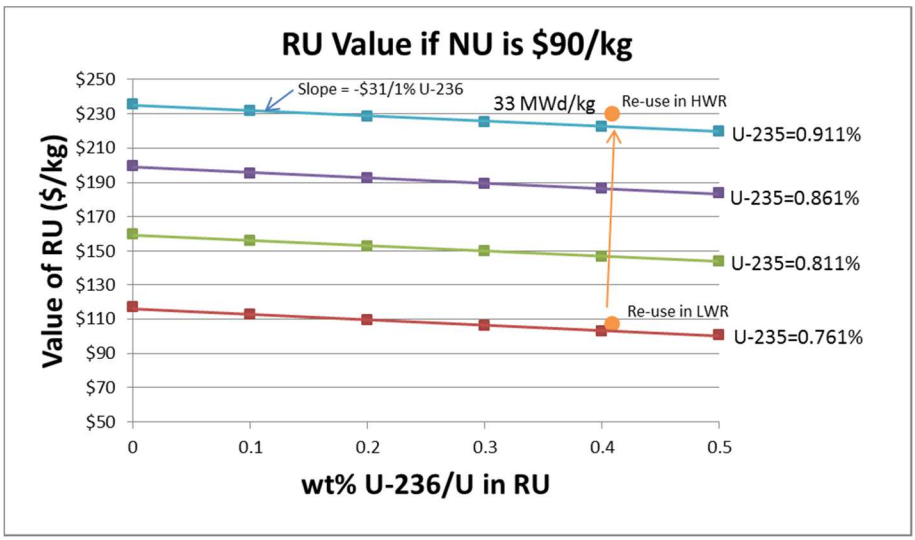

FIG. III-4. Decline in value of REPU in HWRs with increasing ^{236}U content.

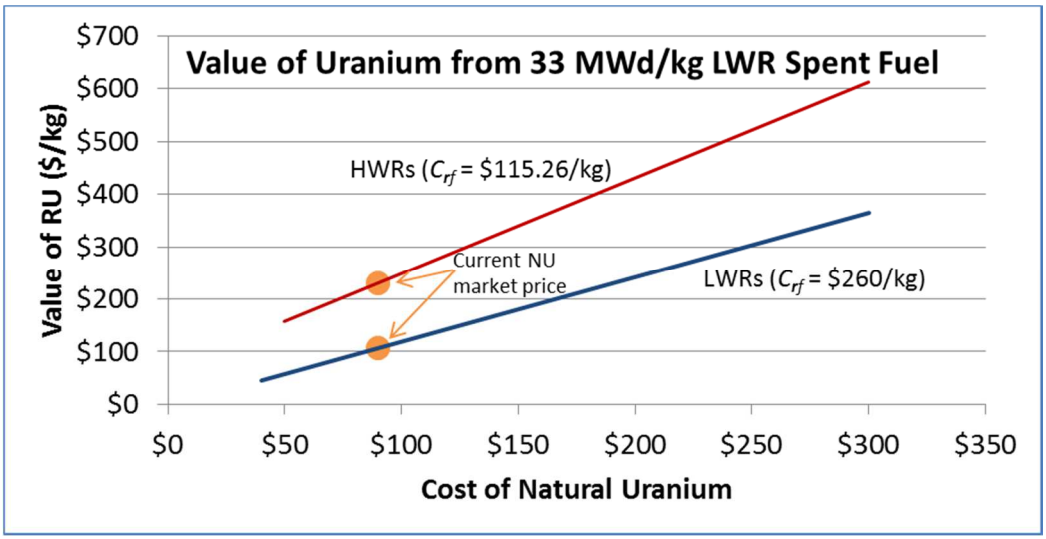

FIG. III-5. The value of reprocessed uranium as a function of the cost of natural uranium, with fabrication costs held fixed.

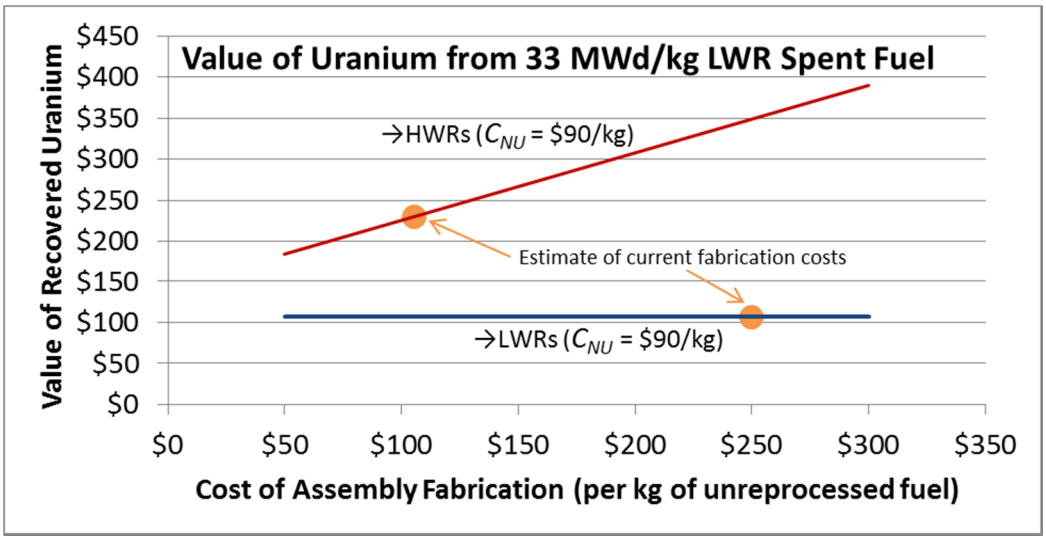

FIG. III-6. The value of reprocessed uranium as a function of cost of fabrication, with NU costs fixed.

III-4.2. Cost of coolant void reactivity mitigation

The LVRF bundles being analyzed have a non-fuel central element with 0.0245 wt.% dysprosium oxide in zirconia which has the effect of reducing the CVR. With this element, the bundle has an exit burnup of 7500 MWday/t (equivalent to current operating practice in HWRs) and the corresponding lifetime burnup-weighted CVR (~13.72 mk) becomes the target CVR to which other fuel types must be reduced. When the core-integrated (i.e., burnup-weighted) CVR is plotted for various kinds of REPU (Fig. III-7), it can be seen that increasing enrichment decreases the CVR, and an increase in ^{236}U increases the CVR. Also, the effect of ^{236}U is much larger (atom for atom) than for ^{235}U above an enrichment of ~0.76%. The sharp rise in CVR for fuels that are less reactive than natural is due to the sensitivity (as discussed in Section III-3.2) of the exit burnup to fuel initial reactivity combined with the higher values of CVR for fresher fuels.

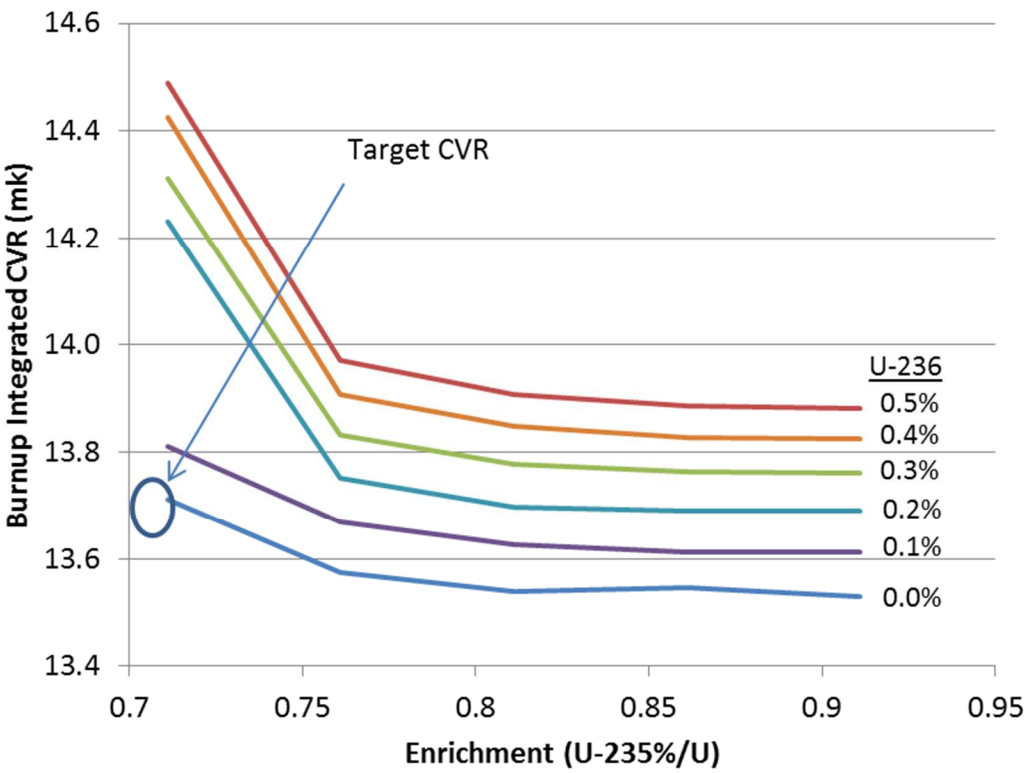

FIG. III-7. Coolant void reactivity for various REPU types.

Above an enrichment of 0.76 wt.% ^{235}U/U the positive contribution of ~0.4% extra ^{236}U to the CVR is significantly larger than the negative one of an extra ~0.15% ^{235}U. If the dysprosium in the central element is increased to compensate, bringing the CVR back to the value for natural uranium (Fig. III-7), then exit burnup will be affected as shown in Fig. III-9.

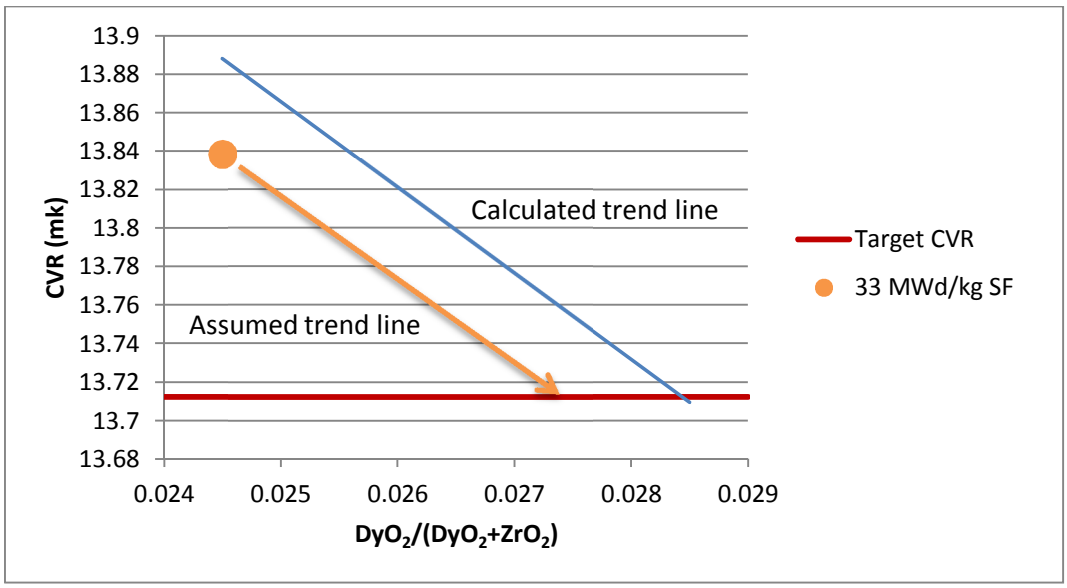

FIG. III-8. Reduction of CVR with increasing neutron poison in the central element.

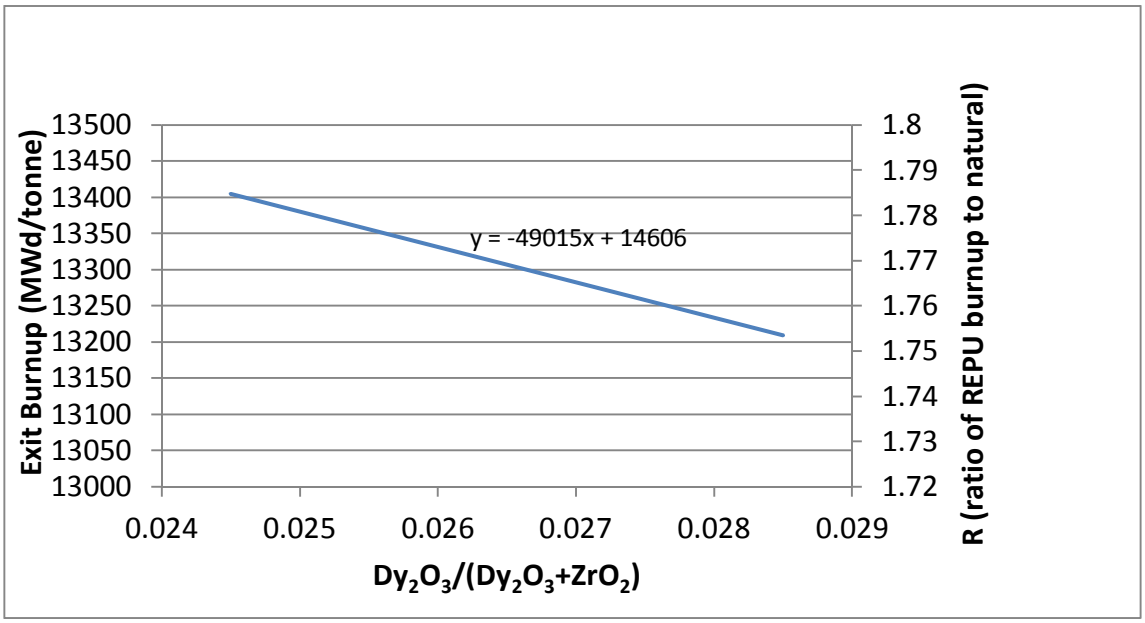

FIG. III-9. Bundle exit burnup as a function of the dysprosium content of the central element.

The parametric studies of dysprosium content vs. exit burnup (Fig. III-9) and CVR (Fig. III-8) yields the relationships (recall that R is the ratio of the exit burnup to the standard of 7500 MWday/t):

$$R = 1.9475 - 6.5353 \times (Dy_2O_3 \text{ fraction}) \quad \text{(III-12)}$$

$$CVR = 14.982 - 44.661 \times (Dy_2O_3 \text{ fraction}) \quad \text{(III-13)}$$

Combining Eqn. III-12 and Eqn. III-13 to get R in terms of CVR, then dropping the constant term, yields Eqn. III-14 relating a variation in CVR with a change in R:

$$\Delta R = 0.1463 \times \Delta CVR \quad \text{(III-14)}$$

Combining Eqn. III-14 and Eqn. III-7 then yields the variation in the value of REPU:

$$\Delta C_{RU} = 0.1463 \times \Delta CVR \times (C_{NU} + C_f + C_c) \quad \text{(III-15)}$$

For the example of \$105.26/kg fabrication costs, \$90/kg NU and \$6/kg conversion, then ΔC_{REPU} = \$29.45(ΔCVR). For the 33 MWday/kg SF composition, where the CVR change required is only approximately 0.126 mk (see Fig. III-8), this corresponds to \$3.70/kg. This reduces the value of REPU to \$226.30/kg.

III-4.3. Value of REPU as an NUE

III-4.3.1. Maximum value (no ^{236}U present)

The ^{235}U enrichment (ε) of a quantity β of REPU mixed with a quantity (1-β) of DU is given by:

$$\varepsilon_{\mathrm{NUE}} = \beta\varepsilon_{\mathrm{REPU}} + (1-\beta)\varepsilon_{\mathrm{DU}} \quad \text{(III-16)}$$

and the value of β which solves this equation is:

$$\beta = \frac{\varepsilon_{\mathrm{NUE}} - \varepsilon_{\mathrm{DU}}}{\varepsilon_{\mathrm{REPU}} - \varepsilon_{\mathrm{DU}}} \quad \text{(III-17)}$$

If the presence of ^{236}U is neglected, then NUE = 0.711 wt.% ^{235}U/U, DU=0.3 wt.% ^{235}U/U and REPU=0.9242 wt.% ^{235}U/U and we have β = 0.658443. Using C_{NU} = \$90/kg, C_f = \$105.26/kg, Cc = \$6/kg, Crf = \$115.26/kg and Crc = \$21/kg yields (Eqn. III-11) C_{REPU} = \$111.69/kg.

III-4.3.2. Value after correction for ^{236}U present

A rough estimate of the ^{236}U correction to the value of REPU in an NUE calculated in the previous Section can be made by demonstration as follows. A mixture of 69.5% REPU (from the 33 MWday/kg SF) and 30.5% DU has an enrichment of 0.734 wt.% ^{235}U/U (Eqn. III-16) and a 0.284 wt.% ^{236}U/U. The ^{236}U/U fraction yields a burnup penalty of ~368 MWday/t (using the bottom line of Fig. III-3). The approximate increase in CVR penalty is 0.33 (Fig. III-7) corresponding to a burnup penalty of 365 MWday/t (Eqn. III-14 multiplied by 7500 MWday/t). The total lost burnup is therefore 733 MWday/t, which is compensated nearly exactly by the difference between 0.711 wt.% ^{235}U/U and 0.734 wt.% ^{235}U/U (~733 MWday/t, using the slope of the two lines on Fig. III-2), as required. The β for this final enrichment is 0.6955 (Eqn. III-17), and therefore the final value of REPU (Eqn. III-11) is \$104.41/kg.

III-5. DISCUSSION

Both downblending to NUE and re-enrichment produce material of approximately the same economic value (\$104/kg - \$107/kg), and these values are considerably less than direct re-use in an HWR (\$226/kg). The existence of a market for direct re-use of REPU in HWRs would therefore impact the economic cases for other uses of REPU (such as mixing with ^{241}Am [III-5] to form an equivalent-burnup bundle for HWRs) because of the reduced opportunity for profit from the sale of REPU for direct re-use in HWRs.

The reduction of REPU value because of a 0.5 wt.% ^{236}U content is found to be about \$15/kg (\$3 per 0.1%) because of its effect of lowering the exit burnup. For a standard LWR spent fuel (33 MWday/t burnup, 0.4022 wt.% ^{236}U/U) the corresponding reduction in its intrinsic value would be ~\$12/kg. Another effect of ^{236}U is to raise the core CVR slightly, but compensating for this (with dysprosium in the central element) can be done for ~\$3.70/kg for this particular REPU. Thus the total price correction for ^{236}U for this high quality spent fuel would be ~\$15.70/kg and is not of great concern, since it is only ~7% of the final fuel value of \$226/kg.

Mixing of the standard REPU with DU to form an NUE, yields an estimate of its value much less than its direct re-use. Without ^{236}U its value is ~\$111/kg, but compensation for the negative effects of ^{236}U brings this down to approximately \$104/kg (7% less). The ^{236}U from this REPU source thus appears to impose a similar penalty in both cases analyzed. Other REPU sources, with less wt.% ^{235}U and more wt.% ^{236}U, corresponding to higher burnups, would incur higher penalties.

The preceding discussion is based on a market price of NU of \$90/kg. An increase in the price of NU correspondingly increases the value of REPU for direct re-use in HWRs.

III-6. CONCLUSION

The economic metric developed in this report indicates that the recycling REPU from a 33 MWday/kg LWR spent fuel directly into an HWR is a more efficient use of resources than two other potential uses of this REPU: recycling into HWRs after downblending to NUE, and re-enrichment for further use in LWRs. It is likely that a similar conclusion would be drawn from the study of other specific REPU compositions.

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