An Assessment of the Proliferation Resistance of Materials in Advanced Nuclear Fuel Cycles

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Statement of Problem

- Initial Charge: Compare SNM Attractiveness Levels for COEX and UREX+1A reprocessing schemes
- Refinement: Compare SNM Attractiveness Levels for other reprocessing schemes, including:
  - PYROX
  - THOREX
  - DUPIC
  - DIAMEX-SANEX
  - GANEX
  - FLOREX

Comparison will use the following Figure of Merit (FOM).

- The FOM is:

$$FOM = 1 - \log_{10}(x)$$

- Where x is given by:

$$x = M\left[\frac{1}{800} + \frac{h}{4500}\right] + \left[\frac{D}{500}\right]^{\frac{1}{\log_{10} 2}}$$

  - M – bare critical mass (kg)
  - h – heat content (W/kg)
  - D – dose rate of 0.2•m @ 1 m (rem/h)

- This FOM is only applicable to a nation state intending to build a stockpile of nuclear weapons based on fissionable materials in metal form.

Mapping of FOM into Attractiveness Levels† of DOE Nuclear Materials‡

	Attractiveness Level	FOM[a]
WEAPONS Assembled weapons and test devices	A	
PURE PRODUCTS Pits, major components, button ingots, recastable metal, directly convertible materials	B	> 2
HIGH-GRADE MATERIALS Carbides, oxides, nitrates, solutions (≥25 g/L) etc.; fuel elements and assemblies; alloys and mixtures; UF_4 or UF_6 (≥ 50% enriched)	C	1-2
LOW-GRADE MATERIALS Solutions (1 to 25 g/L), process residues requiring extensive reprocessing; moderately irradiated material; Pu-238 (except waste); UF_4 or UF_6 (≥20%<50% enriched)	D	0-1
ALL OTHER MATERIALS Highly irradiated forms, solutions (<1 g/L), uranium containing <20% U-235 or <10% U-233 (any form, any quantity)	E	< 0[b]

† **"Nuclear Material Control and Accountability," U. S. Department of Energy manual DOE M 470.4-6 Chg 1 (August 14, 2006).**

‡ **Depleted, Enriched, and Normal Uranium; ^{233}U; ^{238}Pu; ^{239}Pu; ^{240}Pu; ^{241}Pu; ^{242}Pu; ^{241}Am; ^{243}Am; Bk; ^{252}Cf; Cm; ^{2}H; Enriched Lithium; ^{237}Np; Th; ^{3}H; and Uranium in Cascades.**

a) This column has been added for the purposes of this study, and should not be misconstrued as part of the regulatory process.

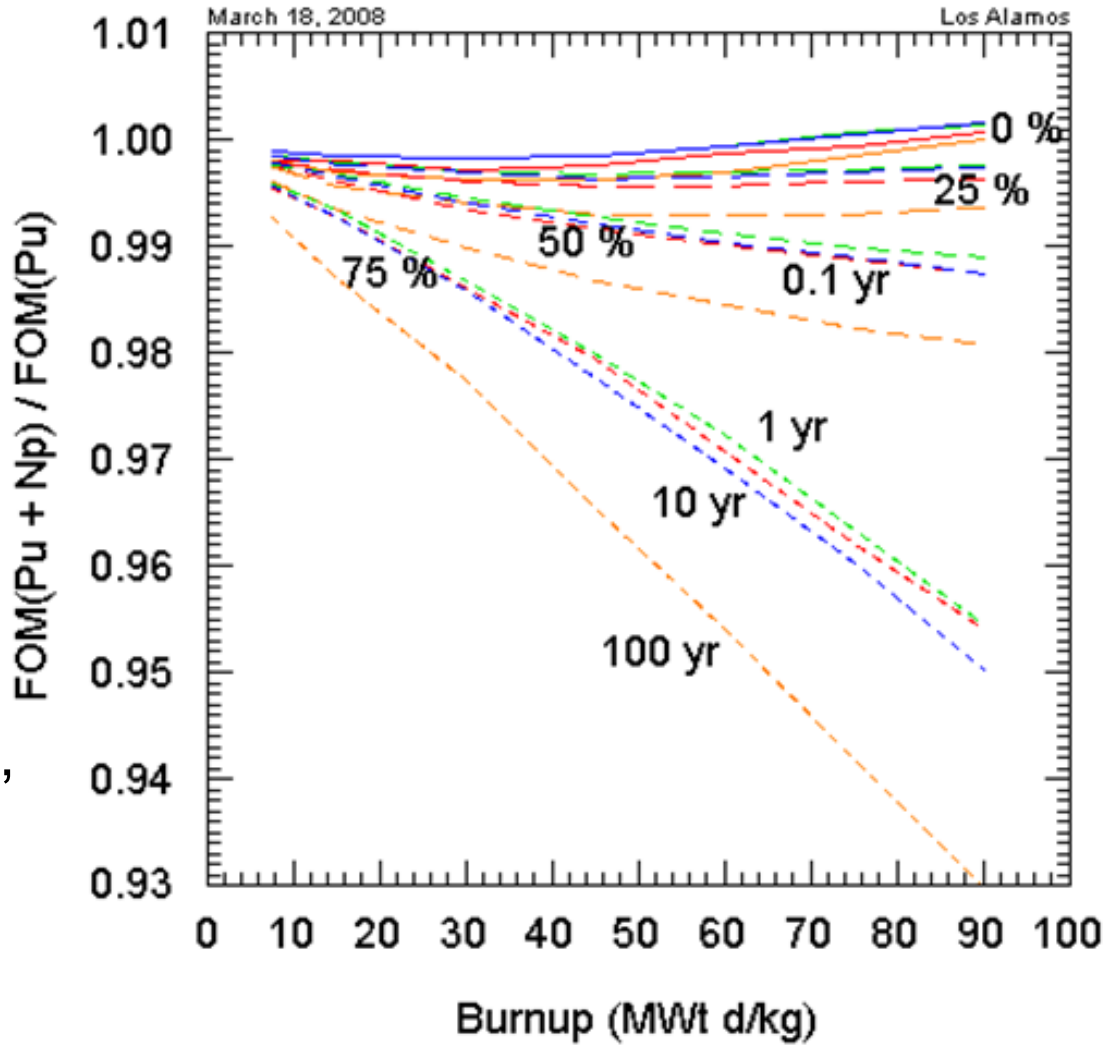
b) This entry is only applicable to materials composed of a single element.

The Attractiveness Levels of Pu and Pu+Np are nearly indistinguishable.

- Age is the time between discharge and reprocessing
- Consider the following ratio:

$$\frac{FOM(\mathrm{Pu}+\mathrm{Np})}{FOM(\mathrm{Pu})}$$

- Range considered:
  - 7.5 ≤ burnup ≤ 90 MW · d/kg
  - 0 ≤ U content ≤ 75 %
  - 0.1 ≤ age ≤ 100 yr
- Over a wide range of burnup, U content, and age, the Attractiveness Level of Pu and Pu + Np metals are identical to within 7 %.

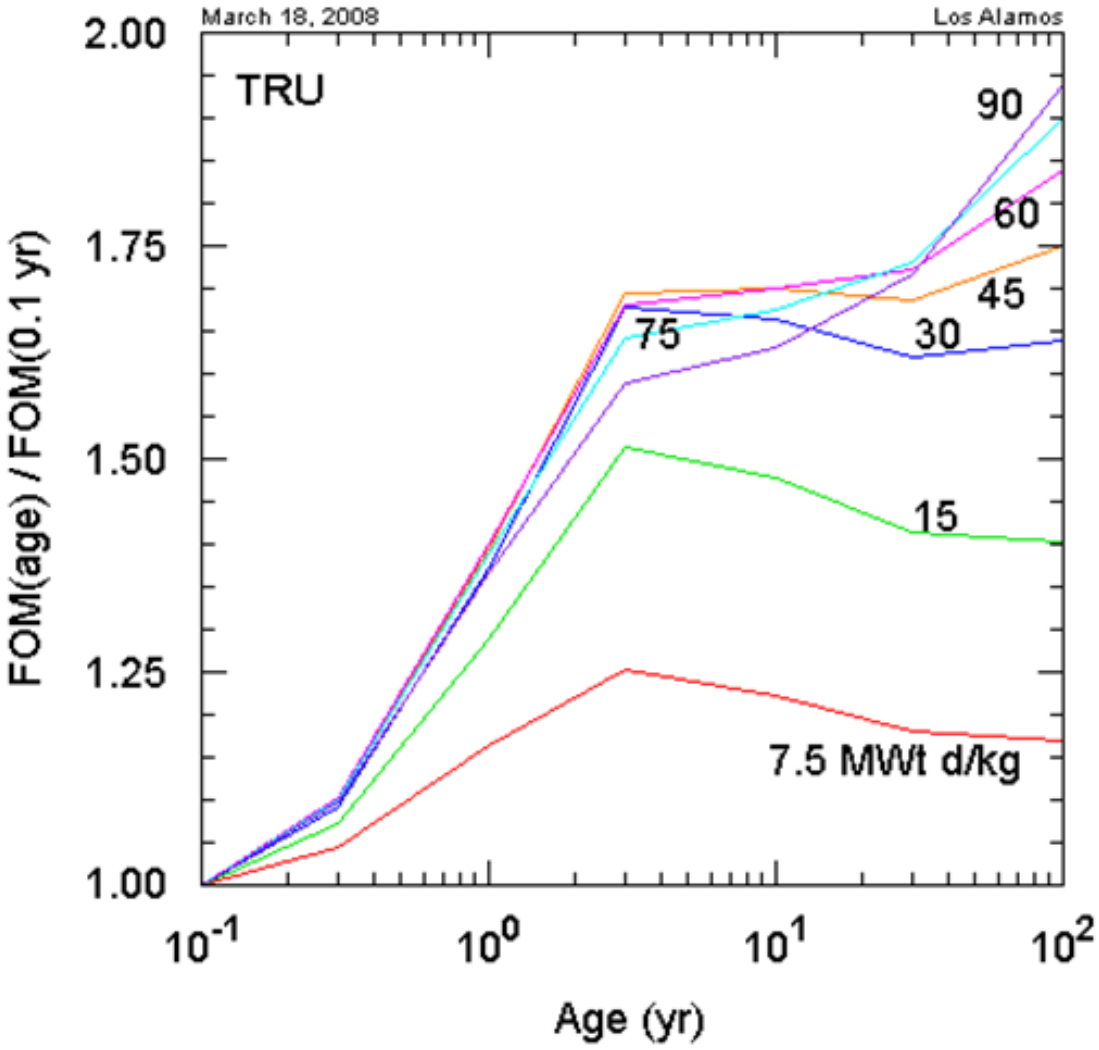


The Attractiveness Level of TRU increases with age.

- Age is the time between discharge and reprocessing.
- Consider the following ratio:

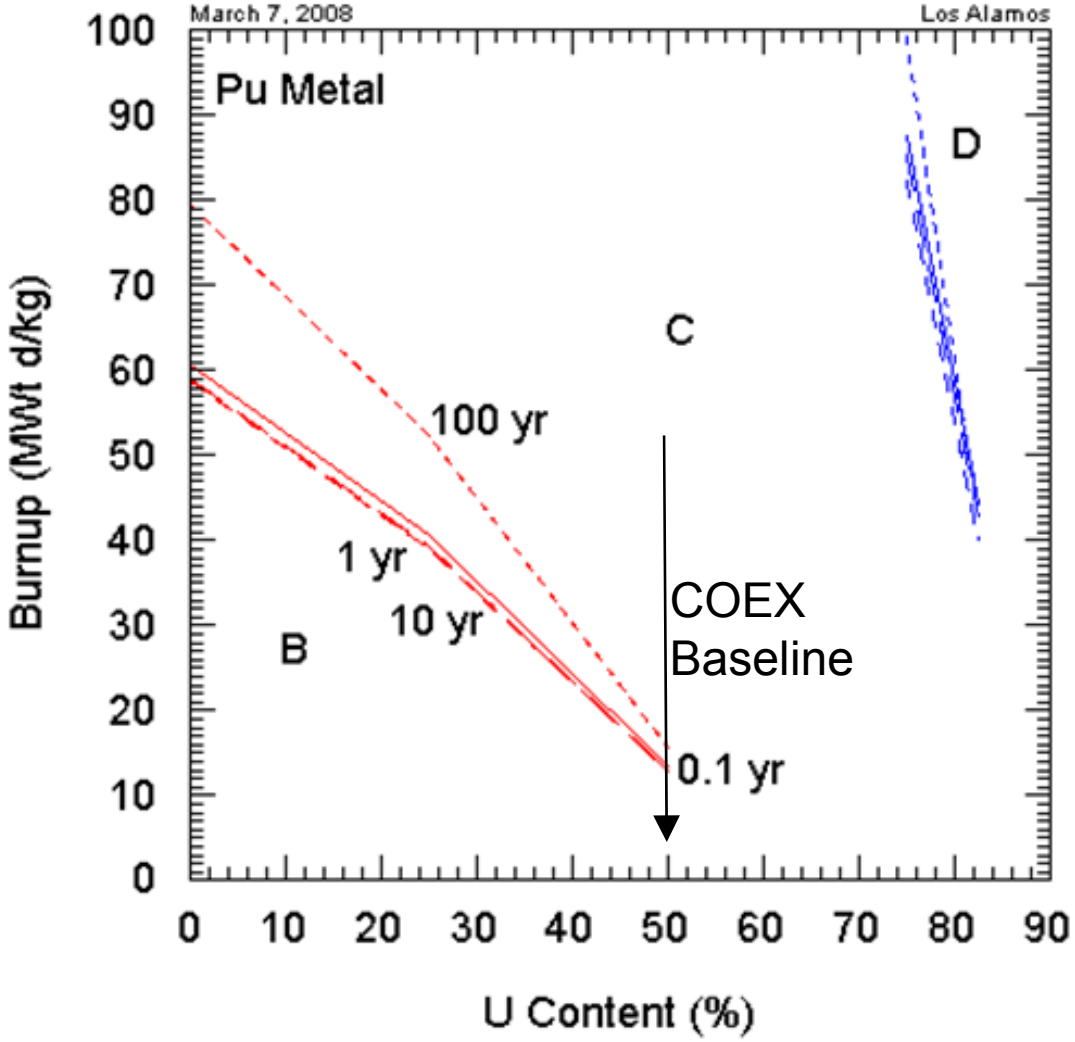
$$\frac{FOM(age)}{FOM(0.1)}$$

- The Attractiveness Level of TRU increases significantly with age:
  - For ≤30 MWt·d/kg, the highest Attractiveness Level occurs at 3 yr.
  - For >30 MWt·d/kg, the highest Attractiveness Level occurs at 100 yr.



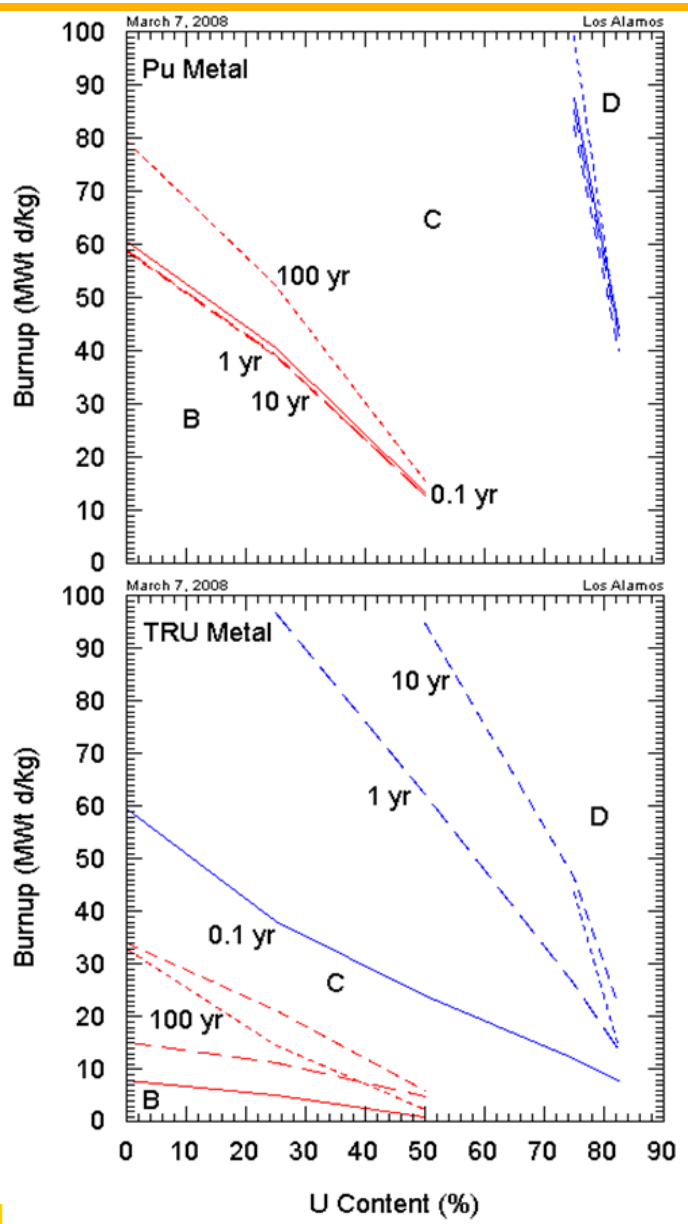
Diluting reprocessed Pu with spent U reduces the Attractiveness Level.

- Reprocessed Pu is an end product of:
  - PUREX
  - COEX
  - UREX+2,3, and 4.
- The Attractiveness Level of Pu can be reduced with:
  - higher burnup,
  - processing spent fuel sooner rather than later, and
  - dilution with spent (or depleted) U.
- Contour Lines:
  - B-C boundary is red.
  - C-D boundary is blue.



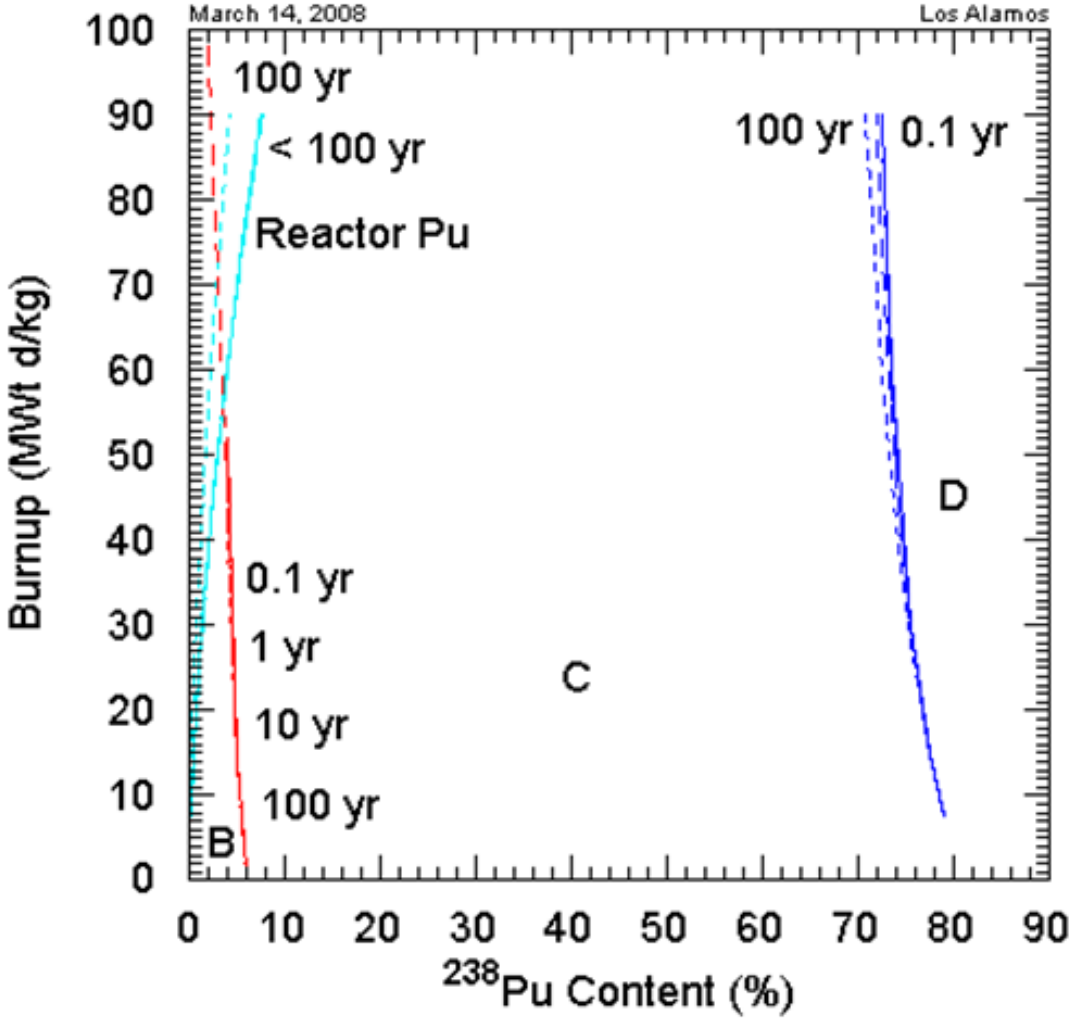
TRU has a lower Attractiveness Level than Pu.

- Reprocessed TRU is an end product of UREX+1A.
- The Attractiveness Level of TRU can also be reduced with:
  - higher burnup,
  - processing spent fuel sooner rather than later, and
  - dilution with spent (or depleted) U.
- Contour Lines:
  - B-C boundary is red.
  - C-D boundary is blue.



Spiking requires large amounts of ^{238}Pu to affect the Attractiveness Level.

- Reprocessed Pu is an end product of:
  - PUREX
  - COEX
  - UREX+2,3, and 4.
- The Attractiveness Level of Pu can be reduced with:
  - higher burnup,
  - processing spent fuel sooner rather than later, and
  - dilution with ^{238}Pu.
- Contour Lines:
  - B-C boundary is red.
  - C-D boundary is blue.



COEX (and UREX+2,3,4) Conclusions

- Np and Pu have the same Attractiveness Level
  - Adding Np to Pu does not reduce the Attractiveness Level of COEX material. This conclusion applies equally to UREX+2, UREX+3, and UREX+4.
  - Extracting just Pu puts Np into waste stream.
- The U content sets the COEX Attractiveness Level:
  - For U content ≤ 20%, the Attractiveness Level is B.
  - For 20% < U content ≤ 82%, the Attractiveness Level is C.
  - For U content > 82%, the Attractiveness Level is D.
- The Attractiveness Level of Pu is not significantly affected by the post-irradiation decay time.

UREX+1A Conclusions

- The Attractiveness Level of UREX+1A material (TRU) is dependent upon age and burnup:
  - The Attractiveness Level of ≥10-yr and ≤30-MWt·d/kg TRU is B.
  - The Attractiveness Level of <10-yr or >30-MWt·d/kg TRU is C.
- 10-yr, 45-MWt·d/kg UREX+1A material requires a U content > 75% to reduce the Attractiveness Level to D.
- The Attractiveness Level of UREX+1A material is sensitive to the post-irradiation decay time, and should be reprocessed within 10 years of generation.

^{238}Pu-Spiking Conclusions

- The Attractiveness Level of Pu metal spiked with ^{238}Pu is slightly dependent upon burnup:
  - The Attractiveness Level of 30-MWt·d/kg Pu is: B for ^{238}Pu content ≤ 4.5%, C for 4.5% < ^{238}Pu content ≤ 80%, and D for ^{238}Pu content > 80%.
  - The Attractiveness Level of 45-MWt·d/kg Pu is: B for ^{238}Pu content ≤ 4%, C for 4% < ^{238}Pu content ≤ 80%, and D for ^{238}Pu content > 80%.
  - The Attractiveness Level of 60-MWt·d/kg Pu is: B for ^{238}Pu content ≤ 3.5%, C for 3.5% < ^{238}Pu content ≤ 80%, and D for ^{238}Pu content > 80%.
- The attractiveness level of Pu with ^{238}Pu content < 80% is still at least C
- Based on the FOM used in this study, spiking with Pu238 (or fresh fuel spiking w/ Np) will not reduce the attractiveness level to D.