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An Updated Perspective on the US Nuclear Fuel Cycle

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ABSTRACT

There has been a resurgence of interest in the possibility of processing the US spent nuclear fuel, instead of burying it in a geologic repository. Accordingly, key topical findings from three relevant EPRI evaluations made in the 1990-1995 timeframe are recapped and updated to accommodate a few developments over the subsequent ten years. Views recently expressed by other US entities are discussed.

Processing aspects thereby addressed include effects on waste disposal and on geologic repository capacity, impacts on the economics of the nuclear fuel cycle and of the overall nuclear power scenario, alternative dispositions of the plutonium separated by the processing, impacts on the structure of the perceived weapons proliferation risk, and challenges for the immediate future and for the current half-century.

The main conclusions are:

- Near-term US adoption of spent fuel processing would incur a substantial cost penalty. In addition, to reap the major benefit possible to uranium conservation and/or the major reduction possible to required repository capacity, processing would have to be accompanied by deployment of fast reactor plants. But demonstration fast reactor plants to-date has mostly proved expensive and unreliable, which aggravates processing's economic handicap.
- However, decisions on a possible second repository will not really be necessary until at least mid-century, so there are decades available to see whether an escalating uranium ore price will create an incentive to adopt processing and/or whether engineering development can reduce the costs of the processing scenario. All the existing spent fuel will still, of course, be accessible for processing should that be the decision.
- The nation needs a broad consensus on which processing/fast-reactor technology combination is the best choice to take through as far as a demonstration. Developing and demonstrating an acceptable, affordable and reliable fast reactor appears likely to control the overall schedule and should receive appropriate development program emphasis.
- Whether the US adopts processing or not, if an expansion of US nuclear power is to be part of a global expansion, substantially improved international agreements and safeguards provisions will be necessary.

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INTRODUCTION

1.1 Scope

This brief update:

- Recaps topical findings from three EPRI evaluations made in the 1990-1995 timeframe
- Incorporates a few updatings resulting from subsequent inputs
- Discusses relevant views recently expressed by other US entities

1.2 Background

Circa 1990, a new justification, i.e., a waste disposal benefit, was promulgated for the US development program that addressed potential chemical processing of spent light water reactor fuel plus deployment of fast reactors to consume plutonium and minor actinides extracted by the chemical process. The original justification for this development program had been increased nuclear fuel resources, but this justification had become less persuasive as nuclear plant deployment dried up and more uranium ore was found. The waste disposal benefit was claimed by some to include elimination of the need for a geologic repository. EPRI therefore evaluated the waste disposal benefit (Rodwell et al., 1991).

After staff review, the US Department of Energy expressed acceptance of EPRI's findings and requested a small supplemental effort applying the accrued data to identifying R&D that might validate a way of substantially delaying the need date for a second repository (Rodwell et al., 1992).

Five years later, EPRI made a more detailed and broader-scope evaluation (addressing MOX-LWRs as well as fast reactors) of just the cost impacts (Burch et al., 1996).

Salient 2003-2005 fuel cycle documents have recently been reviewed in order to note 1) reasons for updating the findings from the 1990-1995 EPRI evaluations, and 2) views appropriate to discuss in this 2006 perspective. Documents found to have such contents are, of course, identified, and all the documents reviewed are listed in Appendix A.

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KEY FINDINGS, RECENT RELEVANT INPUTS, AND DISCUSSION

2.1 Waste Disposal Findings

Removal of the actinides from spent light water reactor (LWR) fuel would not qualify the residue for near-surface instead of geologic disposal (first EPRI evaluation). Even if further development of partitioning technology achieves a tenfold improvement in transuranic separation efficiencies, none of the waste packages would be downgraded from geologic to near-surface disposal. Enclosed residual transuranics, extremely long-life fission products, extremely long-life activation species and medium-life, high-activity fission products would still be too high. This finding applied both to aqueous processing and to pyrochemical processing.

The following small extract from the first EPRI evaluation serves as an example. It derived from quantification of the long-established aqueous process known as PUREX. The largest residual waste, after removal of the voluminous uranium (plus the fellow-traveling plutonium and 90% of the neptunium) is the fission products raffinate. The fission products raffinate is also by far the residual waste form that releases the most heat over the first several decades. This raffinate is concentrated and vitrified, and packages of the resulting glass blocks are each enclosed by an inner and an outer stainless steel container. The raffinate contents exceed near-surface disposal criteria with respect to 1) the medium-life, high-activity fission products cesium/barium and strontium/yttrium, 2) the extremely long-life fission product technetium, 3) a residue of the plutonium isotope 241, and 4) a collection of alpha emitters. If the PUREX process is supplemented by a similar process known as TRUEX (recently developed at the time of the first EPRI evaluation) to remove the americium and curium plus residual plutonium, uranium and neptunium, the raffinate's plutonium-241 is reduced some ten-fold and the alpha emitters more than a thousand-fold. However, not even the plutonium-241 and the alpha emitters then no longer exceed near-surface disposal criteria. The technetium could be separated to its own raffinate package, but not thereby achieve near-surface disposal criteria compliance for either the technetium or the main raffinate package.

The salient 2003-2005 fuel-cycle documents reviewed for this update do not express any expectation that the waste packages from processing would achieve near-surface disposal criteria compliance, such that a geologic repository would not be needed after all, so there is no cause to revisit this first EPRI finding. The 2003-2005 documents do report that the US is developing a modification to the PUREX process, known as UREX, in which the voluminous uranium is removed first, unaccompanied by the plutonium. This is then removed with fellow-traveling minor actinides. (This process re-arrangement offers a small contribution to weapons proliferation resistance.) The 2003-2005 documents do not suggest that the re-arrangement produces waste packages that achieve near-surface disposal criteria compliance.

On the repository's retention of the unprocessed spent fuel's isotopes, contemporaneous analyses were showing that dissolution rates plus travel times, as understood at that time, would provide large margins over very conservative regulated isotope leak rates (first EPRI evaluation). Each isotope of concern was reviewed separately before drawing this general conclusion, addressing each isotope's particular quantity, half-life, dissolution rate and travel time. Furthermore, the projected residual health impact was so low that the cost increase justified per 10 CFR 50 criteria for eliminating this residual health risk was vanishingly small. The salient 2003-2005 fuel-cycle documents reviewed for this update do not express any challenge to these conclusions, so again there is no cause to revisit this EPRI finding.

The removal (and destruction) of large fractions of the transuranics (plutonium plus the minor transuranics) from the spent fuel would reduce the repository-bound waste's heat output and thereby increase the GW-years of power generation that a repository could support (first EPRI evaluation). For example, if the bulk of the transuranics are removed from 25-year old spent fuel, the heat release at that point in the spent fuel's aging is reduced by about 25%. (The 25-year old age was picked for this example because the spent fuel will de facto have an average age of at least a quarter of a century by the time it is deposited in the repository.)

An alternative or additional way to reduce the heat output and thereby increase a repository's capacity is to delay further the uncooled emplacement of either the spent fuel or the processing waste packages that contain the cesium and strontium (second EPRI evaluation). Extending the above example, if the spent fuel or the waste packages are stored external to the repository until fifty years instead of twenty-five years have elapsed, the heat release rate is about 65% (for the spent fuel) or 40% (for the waste packages) of that of the 25-year old spent fuel. Continuing delay accrues further heat release reduction for the waste packages, but beyond sixty years accrues minimal additional benefit for the spent fuel, because the transuranics then keep the heat release up.

Expressing these percentages as repository capacity increments involves introducing heat accumulation as opposed to simply heat rate, and impacts from the assumed disposition of the transuranics removed in the processing option, and addressing differing locations within the repository (all of which considerations regrettably work in the direction of somewhat reducing the value of delaying the uncooled emplacement). These effects are reflected in later portions of this perspective, where appropriate.

2.2 Recent Waste Disposal Inputs and Discussion

The above potential benefit, from delaying uncooled emplacement of the spent fuel, has since been de-facto accrued, not by deliberate further delay to emplacement of the spent fuel in the repository, but by incorporating into it a tunnel cooling system, which will operate beyond this 50-year spent fuel age. At the time of the 1990-1995 evaluations, the repository's technical capacity (having no tunnel cooling) was expected to be around 100,000 metric tons. Today, a higher capacity is referred to in recent literature. Thus in a recent testimony from Matthew Bunn (Bunn, 2005a):

> "... it is possible that even if all existing reactors receive license extensions allowing them to operate for 60 years, Yucca Mountain will be able to hold all the spent fuel they will generate in their lifetimes, without reprocessing."

And from Phillip Fink (Fink, 2005):

> "The ultimate technical capacity of Yucca Mountain is expected to be around 120,000 metric tons, using the current understanding of the Yucca Mountain site geologic and hydrologic characteristics. This limit will be reached by including the spent fuel from current reactors operating over their lifetime."

If Yucca Mountain accommodates the current plants' lifetime spent fuel output, the need date for a second repository is deferred until that determined by a potential new nuclear plant deployment program. If that program's spent fuel is not deposited until it is fifty years old or so (the above alternative way to accrue the heat reduction benefit), then its repository will not need to open till circa 2070 (and probably later), and major decisions on that repository will not be necessary till mid-century. This alternative requires more interim storage capacity, but no tunnel cooling system. These dates apply even if the second repository needs to accommodate the tail end of the existing program's spent fuel.

This lack of a real urgency regarding a second repository is reflected in the literature. Thus from Roger Hagengruber (Hagengruber et al., 2005a):

> "There is no urgent need for the US to initiate reprocessing or to develop additional national repositories."

In addition, separate analyses recently completed for EPRI (Apted, 2006; Kessler, 2006) suggest that much higher Yucca Mountain capacity could be achieved via changes to the repository configuration, using only geology data that have already been characterized and not deviating from existing design parameters. If this approach is adopted, a single expanded-capacity repository at Yucca Mountain will meet US needs for the foreseeable future.

2.3 Economics Findings

Turning to the above option that could (in some scenarios but not all) accrue a large repository capacity increase via removal of the transuranics, the costs of the various fuel cycle elements are currently discouraging for scenarios involving processing (third EPRI evaluation). However, continuing operation of existing nuclear plants and deployment of additional plants will deplete the most accessible, highest-grade uranium ores and cause the ore cost and price to rise. Because processing fuel cycles use less uranium ore, their cost handicaps versus not processing will decrease. But the economic trade-off between not processing and processing is not very sensitive to uranium ore price, so it will take a big increase in ore price to cancel processing's current handicap. Uranium Redbook (OECD, 2001) data indicate that it will take a major deployment of additional LWRs several decades to cause that big an ore cost (and thereby price) increase. In addition, the rise will likely be slowed down measurably by leaving less uranium 235 in the enrichment process tails than is current practice.

Explaining the above parenthetical note that not all processing scenarios would accrue this large repository capacity increase anyway, the primary sources of the spent fuel's problematic heat release are the plutonium 238, 240 and 241 isotopes (the 241 mainly via its daughter Am-241). These can be consumed in fast reactors, but only to much lesser degrees in other reactor types. For example, the reactor type already in extensive use (in France and a few other countries) for consuming separated plutonium is the LWR, with the plutonium mixed with the uranium (Mixed Oxide, or MOX, fuel). The MOX-LWR does consume a substantial fraction of the most abundant plutonium isotope, 239, and thereby keeps the overall inventory of plutonium down (Tinturia et al., 2005), but the MOX-LWR has little net effect on the heat-releasing isotopes, 238, 240 and 241(+Am-241). Thus, there is little net reduction to the repository capacity eventually required, unless and until fast reactors are deployed to consume at least these heat-releasing isotopes. Unfortunately, the demonstration fast reactor plants built to-date have mostly been unreliable, which aggravates the above finding that processing scenarios are economically unattractive.

2.4 Synergism

A modest synergism emerges. If, for repository considerations, a new deployment program's spent fuel is not deposited till it is say fifty years old, and thence major decisions on a second repository are not due till mid-century, several decades are available for seeing where the uranium ore cost and price goes and where processing's cost handicap goes, for determining whether fast reactors can be made reliable, and for updating an assessment on whether and when to adopt a processing scenario. All the existing spent fuel will still, of course, be accessible for processing should that be the decision.

2.5 Political/Public Acceptance

A non-technical aspect that was flagged but not discussed in the '90-'95 EPRI work is political/public acceptance. This has proved to be a big obstacle to the Yucca Mountain repository and understandably drives the recent enthusiasm for a processing scenario that offers a long deferral of the need date for a second repository. However, as noted above, major decisions on a second repository are not necessary till at least mid-century anyway. Also, processing will need political/public acceptance of a perceived health risk near term instead of many thousands of years hence and political/public acceptance of a differently-structured perceived near-term weapons proliferation risk (as returned to below).

2.6 Recent Economics Inputs and Discussion

The essence of the above overall finding on processing fuel cycles (modest waste disposal benefit at substantial but slowly declining cost) has been echoed to varying extents in recent reports from other entities. Thus MIT (Beckjord et al, 2003):

> a “We do not believe that a convincing case can be made on the basis of waste management considerations alone that the benefits of partitioning and transmutation will outweigh the attendant ... economic costs. ... For our fundamental conclusion to change, ... not only would the expected long term risks from geologic repositories have to be significantly higher than those indicated in current assessments, but the incremental costs [of partitioning and transmutation] ... would have to be greatly reduced relative to current expectations and experience.”
>
> b “We believe that the world-wide supply of uranium ore is sufficient to fuel the deployment of 1000 reactors [1 GW, once-through] over the next half century and to maintain this level of deployment over a 40 year lifetime of this fleet.”

The global deployment scenario postulated in this quote would consume less ore than that estimated by the Uranium Redbook to be accessible at less than ~\$40/lbU_3O_8, backed up by a similar amount estimated or speculated to be accessible at less than twice that cost. The next few years should reveal whether the recent price rise to around \$40/lb U_3O_8 indicates that this Redbook estimate is inaccurate or whether the recent rise reflects that forecast, a decade or two ago, to occur when the market has eliminated the over-capacity/production of the mines established circa 1970 when global nuclear plant deployment was very aggressive.

c "We considered reprocessing and one-pass fuel recycle with current technology, and found the fuel cost, including waste storage and disposal charges, to be about 4.5 times the fuel cost of the once-through cycle."

This is a surprisingly high ratio. Its derivation is outlined in the report's appendix, which reveals that the ratio applies just to the fuel that is plutonium enriched, e.g., to MOX fuel assemblies within a core of otherwise UOX assemblies, or to all-MOX reactors within a fleet of otherwise UOX reactors. In the model that the appendix analyses, the MOX fuel is only ~16% of the total, so the cost ratio for the overall MOX/UOX complex is ~1.5, not 4.5. This is still substantial (an increment of 2.8 mills/KWh), but not as devastating.

A caution; this observation needs to be kept in context. For the scenario in which the spent fuel from the existing fleet of US plants is processed and enough all-MOX plants to use the separated plutonium are deployed (say 18 GW), such plants would carry the initial (larger) interpretation of the fuel cycle cost penalty.

Then the Belfer Center (Bunn et al., 2005b):

a "At a reprocessing price of \$1,000 per kilogram of heavy metal ... reprocessing and recycling plutonium in existing light-water reactors (LWRs) will be more expensive than direct disposal of spent fuel until the uranium price reaches over \$360 per kilogram of uranium ..."

This assumed processing price of \$1,000 per kilogram is a little higher than that indicated by Appendix B below (~\$800/Kg), which derives a nominal break-even uranium price of \$300/KgU, reasonably close to the Belfer Center conclusion.

The assumed price of processing dominates such trade-offs, and therein lays much uncertainty. The three biggest contributors to the uncertainty are 1) how much will European experience and continuing R&D reduce costs below those incurred at the existing European processing plants, 2) how much will processing facility replication and/or capacity increase reduce costs, and 3) what discount rate will apply to these high capital cost facilities. In any case, the break-even uranium price will be well above the level that the Uranium Redbook indicates should (but not necessarily will) cover more than enough uranium to fuel the 1,000-GW deployment scenario postulated in the MIT report (see above).

Related, from the separate testimony of Matthew Bunn (Bunn et al., 2005a), is the statement:

"World resources of uranium likely to be economically recoverable in future decades at prices far below the price at which reprocessing would be economic are sufficient to fuel a growing global nuclear enterprise for many decades, relying on direct disposal without recycling."

b "At a uranium price of $40/kgU ... recycling at a reprocessing price of $1,000/kgHM would increase the cost of nuclear electricity by 1.3 mills/kWh."

This compares with the 2.8 mills/KWh derived by the MIT report (see above), with the same assumption for the big-ticket item (processing price). Appendix B below indicates somewhat less than 1 mill/KWh, thus the lowest of the three estimates.

In case a reminder is needed, this cost increment applies, as the quote says, to the cost of nuclear electricity, i.e., to the overall MOX/UOX complex, not just to the MOX portion. Thus, for the most obvious scenario, in which the spent fuel from the existing fleet of US plants is processed and enough all-MOX plants to use the separated plutonium are deployed, the cost incurred to the nation would essentially equate to increasing the lifetime cost of the whole fleet (100 GW of UOX + 18 GW of MOX) from day-1 by 1 mill/KWh (per EPRI), or by 1.3 mills/KWh (per the Belfer Center), or by 2.3 mills/KWh (per MIT). (This is not instead of the 1 mill/kWh waste fee; it is in addition to it.)

c "Even if the capital cost of new FRs [fast reactors] could be reduced to equal that of new LWRs, recycling in FRs would not be economic until the uranium price reached some $140/kgU."

For equal FR and LWR plant capital costs, Appendix B below indicates break-even at a nominal $165/KgU, i.e., similar to the Belfer Center estimate, a bottom-line agreement that masks differences in other input assumptions.

Nothing should be drawn from this result that the break-even uranium price for the FR is likely to be lower than that for the MOX-LWR. This indication results from the major assumption that the FR will have the same capital cost as the LWR, Because of the dominance of capital cost in nuclear power economics, a credible excess in the capital cost for the FR would close (perhaps reverse) this difference in break-even uranium prices. Both the Belfer Center report and the EPRI evaluation suggest that the FR costing more than the LWR is more likely than the reverse.

On the other hand, a break-even uranium price for the MOX-LWR as low as that for the FR would have little meaning, because if the uranium price rises this much it will presumably be on a roll. Adoption of MOX-LWR would dampen it a little but not stop it, because MOX-LWRs would not reduce the long-term consumption of uranium ore much; whereas FRs would not contribute to a continuing uranium ore price rise, because they would not require any more ore to be mined.

At that time, a mix of MOX-LWRs and FRs may prove appropriate, at least for a while. If and when FRs are deployed to cap a rising ore price, they will need only a fraction of the plutonium that will have been generated (third EPRI evaluation). One of several options for the rest of the plutonium is MOX-LWR, which may have been rendered close to economic by the ore price rise that triggers the FR deployment. (To maximize the repository benefit, it would be necessary to recycle the spent MOX-LWR fuel's transuranics to the FRs, to burn the isotopes that the MOX-LWRs cannot burn.)

Finally, both the Belfer Center report and the third EPRI evaluation point out that an enormous uranium resource in sea water may be tappable at less than these break-even uranium prices, so it is within the range of possible outcomes that MOX-LWR and/or FR deployment may never be free of a residual cost penalty. Although it is a great challenge to achieve the enormous concentrations necessary to realize uranium densities useful for nuclear fuel, this potential sea water option merits further long-term R&D.

2.7 General Fast Reactors Findings

Driving home a point made immediately above, if and when fast reactor deployment does become appropriate, extant LWRs at that time are likely to be producing plutonium at a rate that will support the fast reactor deployment. Plutonium created prior to that time will not be needed. Rather than fast reactors needing this plutonium, it is the plutonium that needs fast reactors, if the current desire to minimize the number of repositories is sustained and is to be satisfied.

Long-term fast reactor and processing development is encouraged, primarily to protect future nuclear power from an eventual diminishing supply of U-235 and resulting large uranium ore price increase (all three EPRI evaluations). Development tasks towards defining the most cost-effective and reliable of the acceptable fast reactor and fuel cycle technologies remain important. It was and remains implicit that we do not yet know which processing/fast-reactor technology combination is the best choice to take through as far as a demonstration. A separate observation is that development/demonstration program success for the fast reactor plant itself appears more challenging than for the fuel cycle facility, and is therefore likely to control the overall schedule and should receive appropriate program emphasis.

The timing of a start to the resulting fast reactor deployment should reflect two practicalities (third EPRI evaluation). There cannot be a sudden step approach to fast reactor deployments, if and when the uranium ore price suggests that fast reactors are now economic. There needs to be a transition, slow enough to take full benefit of early experiences and therefore starting early enough to optimize the overall system economics. In addition, the economically optimum fast reactor deployment program needs to be sufficiently anticipatory of the uranium ore price trend such that enough affordable uranium ore is left to fuel extant and intended LWRs through their long remaining lifetimes.

2.8 Proliferation

Proliferation considerations could affect to-process or not-to-process decisions. As the scopes of the '90-'95 EPRI work were economics and waste disposal benefits, the proliferation issue was merely flagged and not discussed. Today the issue is more topical so an EPRI view needs to be developed. The following is an initial attempt.

EPRI has not had access to the classified information that would allow EPRI to make its own evaluation from scratch, so it has had to build its evaluation on such weapons-expert opinions that get released. These vary from an opinion that a bomb can in theory (and therefore actually might) be makeable from any plutonium isotopic mix, to an opinion that the 238, 240 and 241 isotope contents make impractical a bomb with plutonium from spent fuel taken to LWR discharge burnups (or indeed much lower burnups). (A good introduction to the issue is Pellaud, 2002.) With this degree of uncertainty, it is understandable that the Spent Fuel Standard, which emerged for disposition of excess weapons plutonium, reflects the additional protection/deterrent provided by the very hazardous radiation level of unprocessed commercial spent fuel.

A topical question is can we visualize a separations technology for commercial spent fuel that, although inevitably giving up a good deal of this radiation deterrent, would retain adequate proliferation resistance? A key concern in addressing this question is a vision that US adoption of any separations technology will encourage global use. Then there will be multiple processing locations, each with the potential either for adjusting the process to produce clean reactor-grade plutonium and/or for diversion of no-longer-Spent-Fuel-Standard-protected reactor-grade plutonium to a small undetectable aqueous clean-up unit.

For example, the bulk of the US processing technology development effort over the preceding quarter-century was on a pyro technology that leaves some of the minor actinides and fission products with the plutonium, thereby retaining some of the radiation deterrent. But it will be very difficult to achieve a consensus that such a mix will not be too hazardous to use in a fuel fabrication plant and then in reactor fuel handling yet be too hazardous to divert to a small aqueous clean-up unit. There will also be the question whether a rogue operator of a pyroprocess unit could adjust it to produce clean plutonium. Thus, although this process has a small proliferation resistance value, claims that pyro technology is much more proliferation resistant than aqueous technology are not persuasive. An EPRI review of recent technical literature has not disclosed any new silver-bullet technology; indeed it is difficult to imagine that there could be one.

The recent Bunn testimony (Bunn, 2005a) testimony reflects this concern:

> "... proposed new approaches are not as proliferation resistant as they should be ..."
>
> "... the plutonium-bearing materials that would be separated in either the UREX+ process or by pyroprocessing would not be radioactive enough to meet international standards for being "self-protecting" against possible theft."
>
> "... if these technologies were deployed widely in the developing world, where most of the future growth in electricity demand will be, this would contribute to potential proliferating states building up expertise, real world experience, and facilities that could be readily turned to support a weapons program."

On the other hand, contemporaneous testimony from Roger Hagengruber (Hagengruber, 2005b) allows the possibility of processing proving acceptable:

> "The ultimate assessment should not be based on whether it is theoretically possible to make a weapon from the waste. A meaningful assessment must evaluate practical factors associated with making a weapon: the level of technical sophistication, the willingness to assume risk, the financial resources available, and the likelihood of success."
>
> It is inferred here that Hagengruber is alluding primarily to the above practical difficulties deriving from the 238, 240 and 241 isotopes.

If something additional to the practical difficulties deriving from the 238, 240 and 241 isotopes is truly needed, there is some possibility that the locations of the less-than-perfect processing scenario facilities could be controlled adequately via international agreement plus adequate safeguards at the permitted locations. However, experience to-date is not very encouraging. If doing a particular thing is in a nation's interests, such carrots and sticks as get proffered are frequently inadequate. Also, implementation of a nominally adequate international agreement can prove to be dangerously slow (witness the disposition of surplus weapons-grade plutonium). Notwithstanding this difficulty, establishment of an unprecedented degree of international cooperation plus safeguards is a pre-requisite to a US processing scenario and its inevitable global implications. The necessary degree of international cooperation plus safeguards would, of course, be very dependent on whether reality lies in the above opinion that a bomb might be makeable from any plutonium isotopic mix or in the above opinion that practicalities due to the 238, 240 and 241 isotopes make it essentially impossible with plutonium from spent fuel taken to LWR discharge burnups. In this latter case, safeguards focus would be needed on such low burnup spent fuel that may still get produced, whether legitimately or clandestinely. Such safeguards focus is already merited.

This discussion introduces the recognition that if/when, in the long-term, processing does become economic (say because of a major and sustained uranium price increase), processing will likely become global anyway, whether or not we are satisfied at that time with the proliferation risk. This underscores the need for timely, albeit difficult, negotiation of the necessary degree of international cooperation and safeguards in the nuclear power arena.

The plutonium weapons proliferation concerns outlined in the last two paragraphs above exist also for U-235 weapons in the non-processing (once through) scenario. Prevention of mis-use of enrichment facilities too will need greater international cooperation and improved safeguards to support a major global expansion of nuclear power. This requisite has recently been expressed by John Deutch et al. (Deutch, 2005), and has resulted in a proposal by the US for an international nuclear fuel supply and take-back regime that would obviate the need for a large number of national enrichment as well as processing facilities. The weak point for a much expanded global non-processing scenario is potentially more enrichment locations susceptible to rogue operation to produce ideal weapons material. By comparison to clandestine enrichment, the processing scenario offers far from ideal weapons material but has the additional susceptibility to theft, and at multiple locations - the processing plants and the downstream fuel fabrication and nuclear power plants and transport paths between them.

The processing scenario has another weak spot. As noted above, if the motivation for processing does eventually include capping a rising uranium price and greatly expanding the supply of nuclear fuel, the scenario must include fast reactors. But demonstration fast reactors to-date have included blankets, which produce plutonium with little 238, 240 and 241 content. This can be avoided if and while the only motivation for processing is the major increase in repository capacity achievable. For this purpose, fast reactors without blankets will suffice. Needing to be determined is whether fast reactors can also be configured to cap a rising uranium price (i.e., breed plutonium) without producing plutonium low in 238, 240 and 241 content.

Subject to the outcome of the last challenge above, this initial evaluation does not conclude that the processing scenario is worse from proliferation considerations. It may turn out that the proliferation risk difference is not decisive and that the choice between scenarios will hinge on more tangible differences (of which there appear to be two - economics and fast reactor reliability - both encouraging us to stay with non-processing for the near-term).

The Hagengruber testimony (Hagengruber, 2005b) also contains a relevant recommendation, which EPRI endorses:

> "... take the necessary time to carry out more thorough reprocessing research to identify the most proliferation resistant and cost-effective technology."
>
> "If a reprocessing technology is determined to be adequately proliferation resistant and cost-effective, reprocessing can emerge as a consensus decision with industrial, scientific, political, and public support."
>
> A key topical aspect of this recommendation is the sequence; the consensus needs to come early. Otherwise there is a serious risk that the bulk of the available resources and of the available time will be wasted.

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CONCLUSIONS

Near-term US adoption of spent fuel processing would incur a substantial cost penalty. In addition, to reap the major benefit possible to uranium conservation and/or the major reduction possible to required repository capacity, processing would have to be accompanied by deployment of fast reactor plants. But demonstration fast reactor plants to-date have mostly proved expensive and unreliable, which aggravates processing's economic handicap.

However, decisions on a possible second repository will not really be necessary until at least mid-century, so there are decades available to see whether an escalating uranium ore price will create an incentive to adopt processing and/or whether engineering development can reduce the costs of the processing scenario. All the existing spent fuel will still, of course, be accessible for processing should that be the decision.

The nation needs a broad consensus on which processing/fast-reactor technology combination is the best choice to take through as far as a demonstration. Developing and demonstrating an acceptable, affordable and reliable fast reactor appears likely to control the overall schedule and should receive appropriate development program emphasis.

Whether the US adopts processing or not, if an expansion of US nuclear power is to be part of a global expansion, substantially improved international agreements and safeguards provisions will be necessary.

4
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A

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B
ECONOMICS UPDATE

B.1 Introduction

Four specific reasons have emerged during the last ten years for updating a slice of the 1995 EPRI assessment of the economic potential of plutonium in spent nuclear fuel (Reference 1).

These reasons are:

- The author's current view that the targeted rate of return on a financial investment in processing plants will likely be somewhat higher than assumed in the source estimate drawn upon in 1995;
- The inference, from the UK ceasing to re-use uranium released as a by-product from the plutonium separation process, that this uranium has less economic value than had been assumed;
- The implication, of a tunnel cooling system being incorporated in to the repository design, that the '95 assessment of processing benefits to repository capacity is now out-of-date; and
- The implication, of cost reductions now achieved for future LWRs, that it will be more difficult for fast reactors to compete.

None of these reasons has major significance in isolation, but, as they all work in the same direction, collectively they imply a bigger economic disincentive to launch into spent fuel processing.

The above relates to Appendix C, Breakeven Uranium Ore Cost, of the 1995 assessment. Appendix C is therefore the assessment slice that is updated by this current Appendix B. Appendix C had 39 pages. Rather than repeat it in total, with the bulk of it unchanged, this Appendix B update is a condensation, but one intended to stand alone.

This update works in dollars with the dollar value in the 1995 assessment ('93$), then converts the conclusions to a recent dollar value for use in comparing with recent estimates discussed in the main body of this document. The mean between the CPI Index and the GDP Deflator is used for this step.

B.2 Scope and Sequence

This assessment addresses the uranium ore price at which the plutonium in spent fuel becomes economically competitive with uranium 235 as the fissile material in fresh fuel. Two alternative uses of the plutonium are addressed: for thermal-neutron-spectrum reactors represented by the LWR, and for fast-neutron-spectrum reactors represented by the liquid metal reactor (LMR).

The assessment follows the following sequence, first for LWR use of the plutonium and then for LMR use of the plutonium:

1. Summarize the uranium 235 and plutonium scenarios and thereby identify their main differences.
2. Pick out the main cost-bearing elements that would be substantially changed or introduced by adoption of the plutonium scenario.
3. Assign nominal cost impacts for the main cost-bearing elements so identified.
4. Determine the uranium ore price at which these nominal cost impacts balance. (This is the nominal uranium ore price at which the plutonium becomes economically competitive.)

B.3 LWR Case

B.3.1 Summary of the Alternative (U-235 and Pu) Scenarios

In the U-235 scenario, uranium ore is mined, converted to uranium hexafluoride, and transported to and processed through enrichment facilities. The resulting enriched uranium hexafluorides are transported to uranium oxide fuel assembly fabrication facilities, converted to uranium oxide, and incorporated into uranium oxide fuel assemblies. The fuel assemblies are transported to uranium oxide fueled reactors (assumed to be LWRs for this assessment), used, stored locally, and then transported to their long-term destinations.

In the plutonium scenario, spent fuel is transported from the reactors that created it (assumed to be LWRs for this assessment) and/or from interim storage facilities to spent fuel processing facilities. There the plutonium is separated and is then transported to MOX fuel assembly fabrication facilities, as also is some of the uranium recovered from the spent fuel. MOX fuel assemblies are fabricated and transported to LWRs These LWRs have been designed to accept MOX fuel as well as uranium oxide fuel, a flexibility that mainly impacts the provisions for new fuel handling and reactivity control. The waste from the spent fuel processing facilities is packaged and, after interim storage, transported to high-level and low-level waste repositories. The bulk of the uranium recovered at the spent fuel processing facilities is re-used as feed to enrichment facilities.

B.3.2 Impacted Main Cost-Bearing Elements

This subsection identifies the main cost-bearing scenario elements that are substantially changed or introduced where the plutonium scenario replaces the uranium-235 scenario.

- Some uranium ore is not mined.
- Some uranium hexafluoride is not processed through enrichment facilities.

- Some uranium oxide fuel assembly fabrication is replaced by MOX fuel assembly fabrication.
- Spent fuel processing is introduced.
- Some re-usable uranium is recovered.
- Disposal of the spent fuel that is processed instead of being disposed of unprocessed is replaced by disposal of process waste.

B.3.3 Nominal Cost Impacts for the Main Cost-Bearing Elements

The derivations of the following nominal cost impacts are recorded in subsection B.5 below.

- Uranium Ore not Mined
  Avoided cost determined below
- Uranium Hexafluoride not Processed through Enrichment Facilities
  Avoided cost of $75/SWU
- Uranium Oxide Fuel Assembly Fabrication Replaced by MOX Fuel Assembly Fabrication
  Cost increased by $535/Kg
- Spent Fuel Processing Introduced
  Introduced cost of $620/Kg
- Reusable Uranium Recovered
  Introduced revenue determined below
- Disposal of Spent Fuel Replaced by Disposal of Process Waste
  Cost reduced by $30/Kg

To sum and compare the above cost impacts, it is necessary to convert them to the same units, applicable at the same time. The unit selected is the impact on the fuel cycle cost (in mills/KWh), applied at the time the electricity is generated by the LWRs served by these alternative fissile material sources. The following technical parameters are assumed in making these conversions:

- Average fuel burnup: 50 MWd/Kg
- U-235 enrichment in new fuel: 4.3%
- U-235 content in enrichment process tails: 0.1%
- Net LWR plant efficiency: 33%
- Fissile Pu content in 50 MWd/Kg spent fuel (after 5 years): 0.8%
- Number of fissile Pu atoms needed to replace a U-235 atom in new fuel (for the isotopic spectrum of Pu from the 50 MWd/Kg spent fuel): 1.3

The resulting restatement of the above cost impacts (in mills/KWh) is as follows:

- Uranium Hexafluoride not Processed though Enrichment Facilities
  Avoided cost of 2.3 mills/KWh
- Uranium Oxide Fuel Assembly Fabrication Replaced by MOX Fuel Assembly Fabrication
  Cost increased by 1.6 mills/KWh
- Spent Fuel Processing Introduced
  Introduced cost of 10.2 mills/KWh
- Reusable Uranium Recovered
  Introduced revenue of 4.1 mills/KWh
- Disposal of Spent Fuel Replaced by Disposal of Process Waste
  Cost reduced by 0.3 mills/KWh

These cost impacts to the main cost-bearing elements are supplemented by an avoided cost of 0.1 mills/KWh as the net of a few additional small impacts, including conversion of ore to hexafluoride and various transport steps.

It should be noted that the above cost impacts for the introduction of spent fuel processing and for the reusable uranium are high because obtaining the amount of plutonium needed for one MOX fuel assembly necessitates processing seven spent fuel assemblies.

B.3.4 Nominal Uranium Ore Price at which the Plutonium Becomes Economically Competitive

The above cost impacts balance when the avoided cost from uranium ore no longer being mined equates to 4.9 mills/KWh. This would result from a uranium ore price of \$94/lbU3O8. This is therefore the nominal uranium ore price at which the plutonium becomes economically competitive with uranium-235 as the fissile material in fresh fuel for LWRs.

For use in comparing with recent estimates discussed in the main body of this document, by inflating for the intervening ten years and by expressing the result in different units, the nominal break-even uranium price is \$300/KgU.

B.4 LMR Case

B.4.1 Summary of the Alternative (U-235 and Pu) Scenarios

The uranium-235 scenario is the same as the uranium-235 scenario summarized in subsection B.3.

In the plutonium scenario, spent fuel is transported from the reactors that created it (assumed to be LWRs for this assessment) and/or from interim storage facilities to spent fuel processing facilities. There the plutonium is separated and is then transported to LMR MOX fuel assembly fabrication facilities, as also is some of the uranium recovered from the spent fuel. MOX fuel assemblies are fabricated and transported to LMRs, to constitute their initial charges of new core fuel. The bulk of the uranium recovered at the spent fuel processing facilities is re-used as feed to enrichment facilities. The plutonium in the spent LMR fuel also is separated, to achieve LMR self-sufficiency for replacement fissile material. The waste from both of these spent fuel processes is packaged and, after interim storage, transported to high-level waste and low-level waste repositories.

B.4.2 Impacted Main Cost-Bearing Elements

This subsection identifies the main cost-bearing scenario elements that are substantially changed or introduced where the plutonium scenario replaces the uranium-235 scenario.

- Some uranium ore is not mined.
- Some uranium hexafluoride is not processed through enrichment facilities.
- Some uranium oxide fuel assembly fabrication is replaced by LMR MOX fuel assembly fabrication.
- Some LWRS are replaced by LMRs.
- Spent fuel processing is introduced.
- Some reusable uranium is recovered.
- Disposal of the spent fuel that is processed instead of being disposed of unprocessed is replaced by disposal of process waste.
- Spent LMR fuel processing is introduced.
- Disposal of the spent LWR fuel not created is replaced by disposal of spent LMR fuel process waste.

B.4.3 Nominal Cost Impacts for the Main Cost-Bearing Elements

The derivations of the following nominal cost impacts are recorded in subsection B.5 below.

- Uranium Ore Not Mined
  Avoided cost determined below
- Uranium Hexafluoride Not Processed through Enrichment Facilities
  Avoided cost of $75/SWU
- Uranium Oxide Fuel Assemblies Not Fabricated
  Avoided cost of $225/Kg
- LWRs Replaced by LMRs
  Plant capital cost, O&M costs and plant capacity factor could differ between LWRs and LMRs. This potential is discussed later in this subsection. Initially, this assessment quantifies and sums just fuel cycle cost impacts.
- Spent LWR Fuel Processing Introduced
  Introduced cost of $620/Kg

- Reusable Uranium Recovered
  Introduced revenue determined below

- Disposal of Spent LWR Fuel Replaced by Disposal of Process Waste
  Cost reduced by $240/Kg

- LMR Spent Fuel Processing and Fuel Assembly Fabrication Introduced
  Introduced cost of $2,000/Kg

- Disposal of Spent LWR Fuel Not Created Replaced by Disposal of Spent LMR Fuel Process Waste
  Cost reduced by $240/Kg

These cost impacts are converted to impacts on the fuel cycle cost of the reactors served by these alternative fissile material sources. The following technical parameters are assumed in making the conversion, in addition to those parameters already identified in subsection B.3.

- Average LMR core fuel burnup: 150 MWd/Kg

- Net LMR plant efficiency: 39%

- Fissile plutonium inventory needed to start up an LMR (including one fuel reload): 6 tonnes/GW (This equals the 4.8 tonnes inventory of Superphenix plus 25% for one four-year-interval reload, and is therefore conservative as Superphenix is a 1.2-GW plant.)

- Ratio of blanket fuel to core fuel:
    In the reactor: 1
    In the refueling batches: 0.5
  (These ratios are for LMRs that are just self-sufficient regarding fissile material once started up, i.e., LWRs that generate fissile plutonium just as fast as they consume it. This design is chosen as a convenient reference point, not because the design has been determined to be economically optimum.)

The resulting restatement of the above cost impacts (in mills/KWh) is as follows:

- Uranium Hexafluoride not Processed through Enrichment Facilities
  Avoided cost of 2.3 mills/KWh

- Uranium Oxide Fuel Assemblies Not Fabricated
  Avoided cost of 0.7 mills/KWh

- Spent LWR Fuel Processing Introduced
  Introduced cost of 5.5 mills/KWh

- Reusable Uranium Recovered
  Introduced revenue of 0.8 mills/KWh

- Disposal of Spent LWR Fuel Replaced by Disposal of Process Waste
  Cost reduced by 1.3 mills/KWh

- LMR Spent Fuel Processing and Fuel Assembly Fabrication Introduced
  Introduced cost of 2.6 mills/KWh

- Disposal of Spent LWR Fuel Not Created Replaced by Disposal of Spent LMR Fuel Process Waste
  Cost reduced by 0.2 mills/KWh

These cost impacts to the main cost-bearing elements are supplemented by an avoided cost of 0.1 mills/KWh as the net of a few additional small impacts, including conversion of ore to hexafluoride and various transport steps.

B.4.4 Nominal Uranium Ore Price at which the Plutonium Becomes Economically Competitive Based On Fuel Cycle Considerations Alone

The above cost impacts balance when the avoided cost from uranium ore no longer being mined equates to 2.7 mills/KWh. This would result from a uranium ore price of \$48/lb U_3O_8. This is therefore the nominal uranium ore price at which the plutonium becomes economically competitive based on fuel cycle considerations alone.

B.4.5 Impact of Potential LMR/LWR Plant Capital Cost, O&M Costs and Plant Capacity Factor Differences

The '95 assessment noted a paucity of literature reporting in-depth assessments of likely LMR/LWR plant capital cost, O&M cost and plant capacity factor differences. Reference 5 reported a UK study which indicated that, after first-few-of-a-kind costs for initiating fast reactor deployments have been absorbed, LMRs will incur essentially the same capital cost as future LWRs. Also indicated was that the two O&M costs should also be essentially the same.

The major capital cost differences include extra costs carried by the LMR because of its relatively complex reactor closure structure plus fuel handling equipment and because of the existence of an intermediate heat transport system, all of which are driven by the volatility of sodium. On the other hand, the LMR accrues major cost advantages from an almost total absence of auxiliary systems serving the reactor itself and from across-the-plant sizing reductions due to a much higher steam quality and dependent net plant efficiency.

In the absence of any other literature, the '95 assessment accepted the parity indicated by the UK work, but did throw in a 1% penalty in recognition that the first-few-of-a-kind costs are real and would not vanish altogether even if spread over a large LMR deployment scenario.

This raises the above \$48/lbU_3O_8 nominal uranium ore price at which the plutonium becomes economically competitive to \$51.5/lb U_3O_8. For use in comparing with recent estimates discussed in the main body of this document, by inflating for the intervening ten years and by expressing the result in different units, the nominal break-even uranium price is \$165/KgU.

Although parity was accepted, the '95 assessment expressed a caution, and this update adds another. The earlier caution was to note that solving problems experienced to-date on actual LMR demonstration plants may involve solutions that increase the cost (such as a more robust barrier between the sodium and water in the steam generator). The newly added caution derives from detailed cost estimates generated by EPRI's Advanced Light Water Reactor Program. The indication is that the design switch to passive response systems had achieved substantial cost reduction for future LWRs. As passive response systems were already incorporated in LMR designs reflected in the '95 assessment, this subsequent cost reduction for future LWRs is likely to undermine the parity conclusion from the UK study.

B.5 Derivation of Fuel Cycle Cost Impacts

This subsection explains the fuel cycle cost impacts used in the preceding subsections B.3 and B.4, first addressing those involved in the plutonium-use-in-LWRs case and then the extra ones involved in the LMR case.

B.5.1 Spent LWR Fuel Processing

This impact is addressed first as this assessment has revealed that the cost of spent LWR fuel processing is the biggest single impact in the plutonium-use-in-LWRs case; it is as big as the other impacts put together.

The '95 EPRI assessment reviewed prior cost estimates and decided that the most persuasive was one issued by OECD (Reference 2) shortly before the EPRI assessment. OECD's base cost forecast for spent fuel processing was provided mainly by British Nuclear Fuels, which had considerable experience from its THORP plant. The forecast represented a new plant coming on line about now (2006). The forecast was 720 ('91)ECU/Kg, with the possibility of up to a 25% reduction to reflect non-credited improvements expected from THORP and UP3 (COGEMA's comparable plant) operational experience.

EPRI's assessment was visualizing a plant timing later than the above, so there should be time to take full advantage of the above potential cost reducers. This view was reinforced by awareness of several separate on-going technology improvement projects (summarized in the '95 report). In addition, a large US program would involve processing plant replications and/or a large capacity plant(s), either/both of which would accrue a further cost reduction, which EPRI quantified at 25%. The replication benefit would not accrue overnight, so, instead of a total reduction of 50%, the assessment assumed 40%. With units conversion too, the assumed processing cost became '93$515/Kg.

This update sees no reason to change the choices made above, except that within the OECD forecast was an assumed real discount rate of 5%. On reflection, this probably should be higher, at least for US application. US government guidance (Reference 3) is a rate of 7% for a government-owned facility that provides a service to public entities. An alternative valid assumption is private but regulated ownership, for which 8-9% would be appropriate. This update assumes the 7%, thereby raising the assumed processing cost to '93$620/Kg.

This translates to '03$760/Kg. To avoid giving an impression that this highly uncertain cost is known to better than one significant figure, ~'03$800/Kg is alluded to in the main body of this report.

B.5.2 Reusable Uranium

This turns out to be the next biggest impact in the plutonium-use-in-LWRs case, albeit much less than the above processing impact.

The ‘95 assessment noted that, on the one hand, uranium recovered from spent LWR fuel has an enrichment level a little higher than that of natural uranium, but, on the other hand, also has a small content of the 232 and 236 isotopes. This small advantage and disadvantage were assumed roughly to balance, giving the recovered uranium the same value as fresh natural uranium. The fact that the UK was reusing its recovered uranium allowed an inference that this was on the conservative side.

Subsequent UK termination of the reuse of recovered uranium throws the above in doubt. The obvious, but unverified, correlation is that this change of policy derived from the fall in uranium ore to a sustained level of around only \$10/lbU_3O_8, i.e., break-even was at some level fallen through during the descent to \$10/lb U_3O_8. In the absence of knowing the exact break-even level, this update assumes that the value of recovered uranium equals that of fresh uranium less \$10/lb U_3O_8.

B.5.3 Enrichment

This turns out to be the third biggest impact.

The '95 assessment noted that the then average price for enrichment services was roughly '93$100/SWU from the existing diffusion and centrifugal enrichment plants, and referenced a report that expected advanced centrifuge and/or laser plants to reduce prices substantially, largely due to lower energy consumption. The '95 assessment assumed that such advances would be in place by the time the US adopted spent fuel processing and that the resulting price would be ~'93$75/SWU.

This update does not check whether this expected trend has started during the intervening ten years.

B.5.4 LWR Fuel Assembly fabrication

This is a relatively small, but not insignificant cost impact.

The '95 assessment noted that uranium oxide fuel fabrication was already a mature process and noted that the then-current long-term forecast ranged from '93$190/Kg to '93$290/Kg. A nominal of '93$225/Kg was selected.

The assessment 1) noted that most references indicated a near-term cost under '93$1,000/Kg for MOX fuel assembly fabrication, and 2) discussed potential technology improvements and plant capacity increases, leading to selection of a nominal cost for an eventual large US program of '93$760/Kg. The delta cost of replacing uranium oxide fuel fabrication with MOX fuel assembly fabrication was therefore '93$535/Kg.

This update sees no reason to revisit this selection.

B.5.5 Waste Disposal in LWR Case

To a first approximation, the repository capacity is really an accumulated heat release capacity. Since the '95 assessment, the repository design has incorporated a tunnel cooling system, so the repository's accumulation of released heat doesn't start till the cooling is switched off, herein assumed to be about 100 years after the spent fuel leaves the reactors. By this time, the fission products have ceased to be substantial contributors to the heat release, the main contributors now being actinides, particularly Pu-241 (primarily via its daughter Am-241), Pu-238 and Pu-240.

Although use of the plutonium in LWRs consumes much of the Pu-239, the net effect on these heat-releasing isotopes is minimal, they just get essentially stored in the MOX fuel. In a plutonium-use-in-LWRs-only scenario, these heat releasers still need to be disposed of in the repository. The temperature at the controlling location (midway between tunnels) peaks at around twelve hundred years, by which time the accumulated heat is reduced by around only 10% by the plutonium-use-in-LWRs scenario. At the time of the '95 assessment, the cost of disposing of spent fuel was expected to be around '93$300/Kg, so, to a first approximation, the plutonium-use-in-LWRs scenario saves around only '93$30/Kg.

B.5.6 LMR Spent Fuel processing and Fuel Fabrication

In the plutonium-use-in-LMRs scenario, spent LWR fuel processing still has the biggest impact, but is less dominant. The next biggest impacts are those of enrichment (already addressed above) and LMR combined spent fuel processing and fuel fabrication.

The '95 assessment identified several reasons why LMR spent fuel processing and new fuel fabrication will be much more expensive than their LWR equivalents. The assessment reviewed prior estimates for the processing part of the combined operation and decided that the most persuasive estimate was a UK one issued in 1988 (Reference 4). Other references indicated that the fabrication part of the operation would cost about two-thirds that of the processing part. Together, the indicated cost for a first modestly-sized commercial plant was '93$3,000/Kg. For the large US scenario envisaged, with its attendant scale-up and/or replication, the '95 assessment assumed a cost reduced to ~'93$2,000/Kg.

This update sees no reason to revisit this selection.

B.5.7 Waste Disposal in LMR Case

In contrast to the LWR case, the spent fuel's main heat contributors (Pu-241, Pu-238 and Pu-240) are essentially consumed by the LMR. For the scenario described in subsection B.4 for the LMR case, there will remain in the waste packages that portion of Pu-241 that has already decayed to Am-241 by the time of processing, but the 100- to -1,200-years cumulative heat release should be less than one-tenth that of unprocessed spent fuel. This doesn't translate to a full 90% waste disposal cost reduction, because cumulative heat release is not the exclusive disposal cost consideration. But an 80% reduction (say ~'93$240/Kg) seems a reasonable assumption.

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