

**F MODULES**  
**SPENT FUEL REPROCESSING**



**Module F1**

**Spent Nuclear Fuel Aqueous Reprocessing Facility**



# Module F1

## Spent Nuclear Fuel Aqueous Reprocessing Facility

### F1-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Complete re-visit of detailed estimating bases for 2009, 2012, and 2015 AFC-CBRs. New unit cost (\$/MTHM) values were obtained for UREX+1a by analyzing the breakdown of bottom-up Westinghouse Savannah River Company (WSRC) pre-conceptual design estimates for hypothetical aqueous reprocessing plants based on UREX technology. These analyses were discussed in the 2016 AFC-CBR update and further discussed in this 2017 version. By reducing lifecycle costs via better project management and reduction of indirect costs, a 24% reduction in UREX+1a unit cost is possible. Since not all technologies have been analyzed in detail, it was decided to not yet change the WIT values for this 2017 version from the 2009 EAS basis. This WSRC-based EAS data was, however, escalated from 2009 to 2017 \$ using the factor presented in the “Escalation considerations” chapter of the mail report. (note: the WSRC documents are part of what were called the Engineering Alternative Studies (EAS) conducted under the GNEP (Global Nuclear Energy Partnership))
- **Estimating Methodology for latest (2009 AFC-CBR) technical update from which this 2017 update was revised and escalated:** The WSRC studies mentioned above, and first presented in the 2009 AFC-CBR, were detailed bottom-up estimates. There was enough of a breakdown of direct and indirect costs by building and process function that for the 2016 AFC-CBR Update and this 2017 version, adjustments could be made to the estimates for improved project execution and lower indirect costs for UREX+1a. The result is a possible lowering of future “What-it-Takes” unit cost ranges for all reprocessing technology technologies, not just UREX+1a. The adjustments to be made would be analogous to those made in Module R1 of this version for “well-executed” LWR projects.

### F1-RH. REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module R1. Costs for this version and those up to 2009 were based on a 2003 Washington Group & Bechtel-BWXT (WGI 2004) study for a UREX-1a reprocessing plant called the Spent Fuel Treatment Facility (SFTF). In the 2009 AFC-CBR the WSRC reports (WSRC 2007, 2008a, 2008b) prepared as part of the EAS became the cost bases for this (2009) and the 2012 and 2015 versions. In 2009 unit costs for UREX 3a and COEX reprocessing technology were also added to the “What-it Takes” (WIT) database. Projected unit costs for the reprocessing of thorium-based oxide fuels based on UREX 1a, UREX 3a, and COEX technologies were also added to the F1 module WIT database in 2009. In the 2016 Update a Chapter entitled “Observations on F1 Module from CBR 2015” was added. Its text and estimated unit cost values have been integrated directly into this 2017 F1 Module. In the 2009 version unit costs for “separations only” and “total reprocessing” plant functions were calculated and presented in the WIT table for all three reprocessing technologies.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2009 (EAS-WSRC data for UREX 1a plant was re-analyzed and adjusted downward for this 2017 version) In the 2016 version this “new adjusted data” for the same facility was first presented. The WIT change for all three aqueous technologies will be reflected in future versions of this document.
- **New technical/cost data which has recently become available and will benefit next revision:**

- No new cost estimates for hypothetical or proposed reprocessing plants have been identified. It is known that India and China are considering the construction of such larger scale facilities
- The EAS data on UREX+3a and COEX needs to be analyzed in more detail to see if reductions unit cost are possible for these technologies.

## F1-1. BASIC INFORMATION

The spent nuclear fuel aqueous reprocessing facility is used for separations of spent nuclear fuel elemental components to support recycling of fissile materials, transmutation, decay management of selected actinides and fission products, and segregated immobilization, storage, and disposal of remaining materials as different classes of wastes. A generic facility typically consists of a spent nuclear fuel receiving area, processing buildings (head-end and chemical separation areas), interim storage facilities for both spent nuclear fuel and separated products, and support buildings for utilities, offices, and laboratories. The plant may also include collocated waste solidification, special nuclear material secured storage, reprocessed uranium conversion facilities, and mixed oxide (MOX) fuel fabrication facilities.

A major feature of the reprocessing facility are the needs for remote handling and massive processing buildings. Multistory, below-grade, heavily shielded operating cells are typical. These building areas may be completely buried or bermed for parts of the process involving separated minor actinides. These large spaces are maintained at negative pressure to manage airborne particulate contamination, generally requiring large banks of high-efficiency particulate air (HEPA) filters.

Several approaches to aqueous separations exist or are under consideration, ranging from “conventional” Plutonium-Uranium Extraction (PUREX)-based, oxide fuel separation facilities with pure uranium and plutonium oxide products, such as THORP and La Hague, to multistep UREX+ process concepts that separate many actinides and fission products for tailored recycling or disposal. The latter, more complex separations possibly make better use of geologic repository space (Laidler 2003; Vandegrift et al. 2004).

## F1-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

**Front End.** Spent nuclear fuel arrives at the facility by truck or rail (or in Japan by ship). Cranes lift the shipping casks and move them inside to unload the spent nuclear fuel into a temporary storage area (wet or dry storage). Head-end processing begins either with use of a massive shear to cut the fuel assemblies without dismantling or with mechanical separation of the fuel rods from the balance of the fuel assembly hardware followed typically by cropping the fuel rods into short segments. The fuel meat is acid-leached from the chopped fuel rod, and the cladding hulls are washed and prepared for disposal as Greater-Than-Category-C (GTCC), low-level waste (LLW)—depending on their radioactivity level—or for possible recycling and reuse.

**Aqueous Separations.** The dissolved fuel is generally passed through a series of aqueous-organic solvent extraction processes to achieve chemical separations. The number and order of steps is dependent on the number of product streams. These separate liquid streams, typically nitrate solutions, are then subject to further processing to obtain the desired products or prepare them for waste handling. The PUREX process results in two primary product streams: a converted uranium form (uranium nitrate hexahydrate [UNH], salt, a uranium oxide, or UF<sub>6</sub>) and PuO<sub>2</sub>, and a primary high-level waste (HLW) stream that contains the fission products and minor actinides. The UREX+ process has more product or by-product streams, including purified uranium suitable for disposal or recycle. Cesium/strontium and technetium streams can be separated from the other fission product streams, and a suite of minor actinide by-products can be separated and tailored to meet specific fuel cycle by-product objectives (such as Pu/Np/Am/Cm, Pu/Np, Am/Cm, or americium separated from curium).

**Back End.** The back end process includes product storage and shipping facilities, and waste processing, storage, and shipping facilities. The most valuable products are fissile materials or special nuclear materials requiring secured storage and shipping. Collocation of fuel fabrication facilities, such as a MOX facility, can eliminate secured shipping requirements of separated materials as well as provide for synergy of meeting security requirements. Waste processing is necessary to stabilize and solidify liquid waste streams. Streams containing volatile products such as iodine, tritium, and noble gases must also be processed and packaged in appropriate disposal media and containers. The G modules cover many of these steps.

Figure F1-1 shows an example of a proposed UREX+ aqueous reprocessing process flow. The front-end process consists of the dissolver (chop-leach process) with the cladding hulls going to recycling or disposal. The primary aqueous separations are completed in the UREX+ steps, which consist of chemical processes that separate uranium, Cs/Sr, Pu/Np, and Am/Cm. Another alternative is to produce a uranium/group-transuranic oxide product that can be used as actinide burning fuel in fast reactors. This fuel material has the additional qualities of proliferation resistance due to the presence of a much higher radiation field. The back-end processes include denitration, immobilization, storage and decay-storage, uranium LLW disposal or storage, and fission product treatment, packaging, and shipment to the HLW repository.

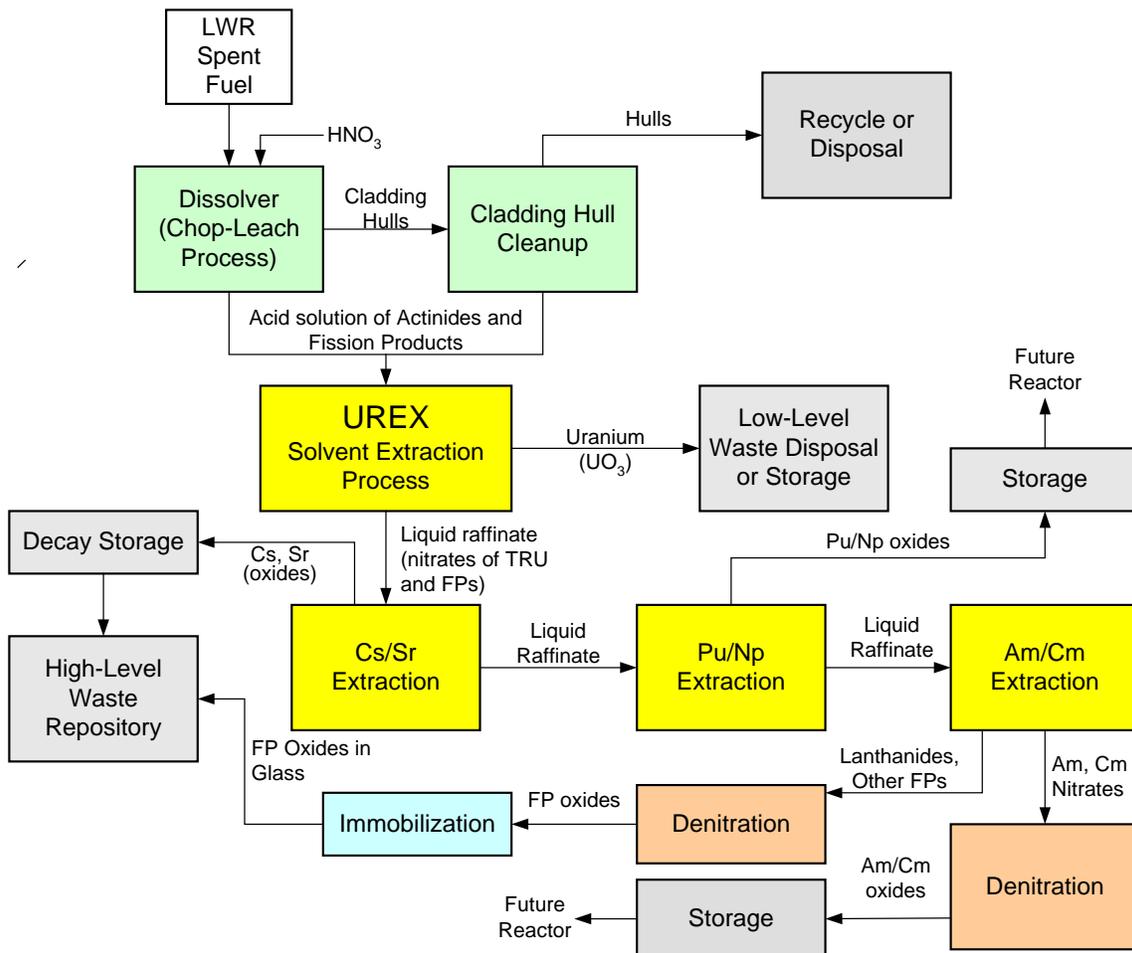


Figure F1-1. Example of UREX+ aqueous reprocessing process flow (Laidler 2003).

### F1-3. PICTURES AND DIAGRAMS

The following pictures, Figures F1-2–F1-4, show reprocessing sites with currently operating PUREX facilities in France and recently shut-down sites in the U.K., and another site in Japan with a PUREX plant now in the commissioning phase. Some of the buildings shown are not directly part of the reprocessing capability, but support other collocated functions.



Figure F1-2. La Hague site, France, with reprocessing plants, UP2-800 and UP-3 (AREVA).



Figure F1-3. Sellafield site, U.K., with THORP and B205 reprocessing plants (BNFL, plc).



Figure F1-4. Rokkasho-Mura site, Japan, with Rokkasho Reprocessing Plant (JNFL).

## F1-4. MODULE INTERFACES

This module interfaces with upstream reactor (Modules R1 and R2) and spent nuclear fuel storage modules (E1 and E2) that supply the spent nuclear fuel, downstream recycled product storage (Module E3 for higher actinides and Module K2 for separated uranium), fuel fabrication (Module F2/D2 for MOX), HLW conditioning/storage/packaging (Module G), waste storage (Module I), and disposal modules (L and M). As noted previously, it is advantageous to collocate the separations and recycled fuel fabrication facilities to share the costs of security and storage as well as minimizing the need for dedicated secure transport for the separated fuel fabrication feed materials.

## F1-5. SCALING CONSIDERATIONS

There are many aspects that impact the scaling of reprocessing plants. A schematic of drivers relating to UREX+ conceptual design is provided in Figure F1-5 as an example. One important factor is appropriate equipment selection in conjunction with the engineering approach used to achieve operational functions of availability and maintainability. Others are flow-sheet adopted; maximum line size for particular separations equipment that can be made criticality safe; the need for fuel receipt, head-end (and fuel fabrication if included) equipment to meet full-scale reactor fuel assembly size regardless of how low the fuel throughput may be; the criticality safety approach adopted (extremes are administrative control versus inherently safe [e.g., geometric control]); margins to accommodate extreme burn-up (low and high) fuels; fuel decay time; overall decontamination factors; recovery factors; and close coupling or de-coupling of process steps, waste management, reagent recycle, etc.

M. Jonathan Haire assessed several plant designs developed in the 1970s and early 1980s and noted that availability improves with designs that include redundancy, although this redundancy comes at a cost of duplicate equipment, additional facility size, and increased operational complexity (Haire 2003). As facilities scale up, parallel process trains may provide increased operational availability, though at reduced throughput, without further equipment duplication. Since the capital cost of small to medium capacity PUREX plants is insensitive to scale (see below), construction of two “small” plants to ensure near constant reprocessing availability has an economic disadvantage.

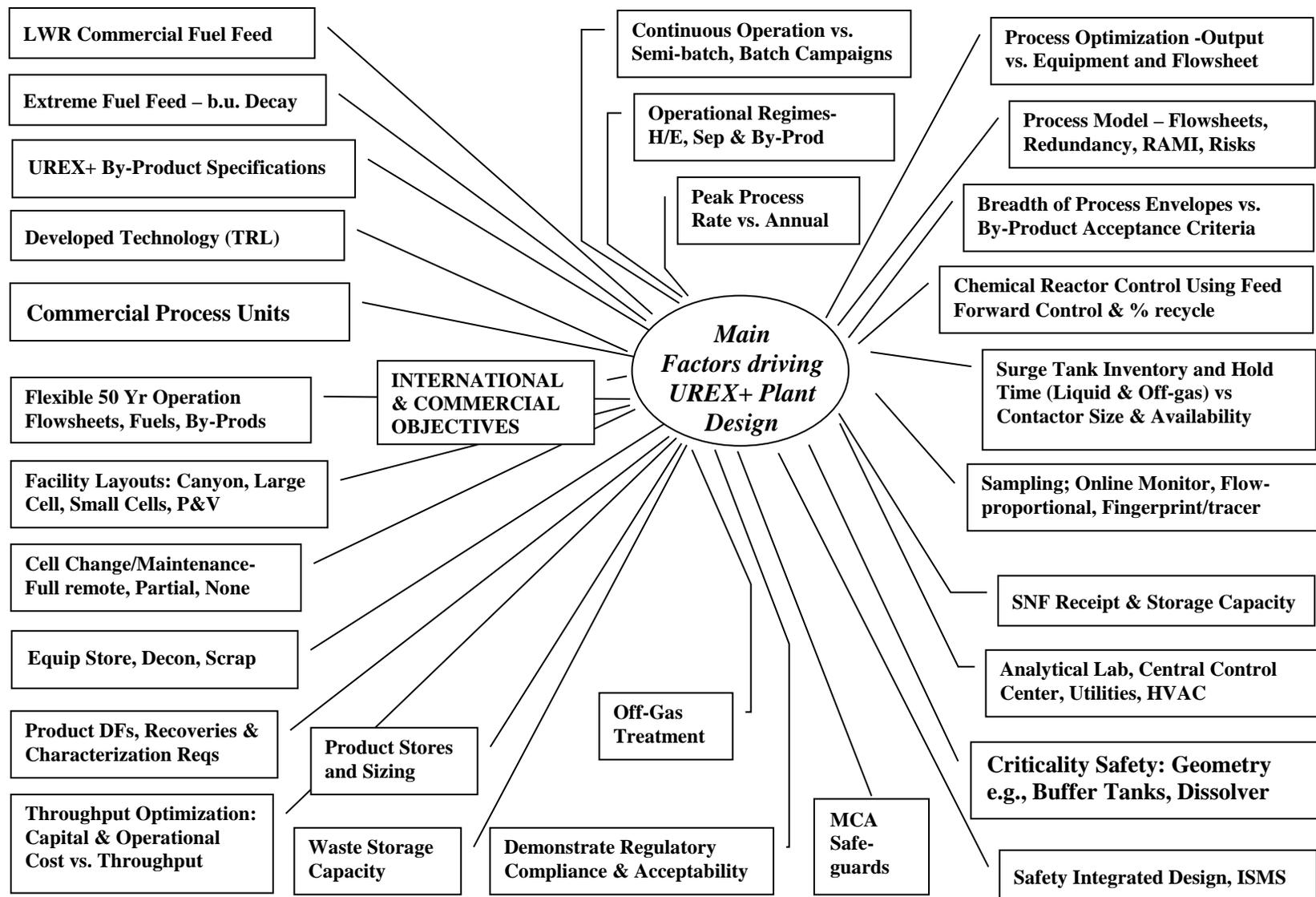


Figure F1-5. Schematic of drivers for UREX+ Plant Concept Design.

Haire also noted two maintenance approaches. The first approach involved a “canyon-type” facility allowing for remote equipment replacement via overhead cranes. The second approach, which was to be used in the Barnwell, South Carolina, reprocessing plant, is to place failure-prone equipment in shielded alcoves for easier access in a primarily contact handling-based maintenance mode. While the fully remote maintenance approach involves larger facilities, and therefore higher costs, the canyon design for small throughput plants may require fewer changes with scale-up and provides flexibility to adapt to process evolution, changing fuel or product specifications, or other requirements. However, the progressive reduction in permissible dose levels and the application of “as low as reasonably achievable” now further restricts the use of this second approach.

An additional third approach, which has been used in Europe for chemical separations in particular, is to use “dark cells,” which require no planned maintenance for several decades, but may require tailored remote intervention afterward if initial design and operation is unsuccessful. THORP designed in the 1980s generally favored this approach by adopting remote maintenance of the massive shear/shear pack and full-life-of-plant “zero-maintenance” chemical separation equipment using airlifts, vacuum-operated slug lifts, reverse flow diverters, steam ejectors, vacuum lifts and through-wall drives for CVFs, and non-wetted flow actuators using compressed air. Valveless maintenance-free diverters and distributors are used. There is limited hot-cell access for maintenance work. Overall commercial facility design is often a hybrid of these. However, it should be noted that a fully remote canyon facility has never been constructed for the commercial nuclear fuel sector, but only for defense applications, which may be less cost sensitive.

The final factor noted by Haire is a difference in the scaling of facilities that process thermal and fast reactor fuel. The lower total heavy metal content and higher fissile content (fraction) of fast reactor fuels results in relatively larger front-end processes and the need for more criticality control features. This added complexity may result in additional unit cost for both capital and operations, though Haire added that this effect becomes insignificant at lower design throughputs (e.g., 300 MTHM/year), which is substantial for a FR processing plant [e.g., supports about 15 commercial scale fast reactors, each of ~1 GW(e)].

For the above and additional reasons, Haire differs with several other authors in avoiding the use of a constant 0.6 scaling factor as is commonly used in non-nuclear industry sectors (e.g., chemical and oil) (NAS 2000; Bunn et al. 2003). Instead he notes, “In the familiar rule of thumb scaling law, capital costs are proportional to the  $n$ th powers of capacity; however,  $n$  is not a constant. The value of  $n$  approaches 0.1 for very small-capacity plants and 0.9 for very large plants” (Haire 2003). This results in diminishing returns for scale-up. Haire recommended an optimal size for a reprocessing plant of ~2,500 MT/yr. Spencer et al. (2003) extended Haire’s work to include several additional plant designs, supporting the development of a scaling curve, showing the difference in plant cost versus design throughput (Haire 2003). This curve is provided in Figure F1-6. While the bottom of the curve is at ~7,000 MT/yr, they noted very little unit cost difference between 2,000 and 10,000 MT/yr. A throughput of 7,000 MTHM/yr may require four to seven solvent extraction lines. Data for capacities beyond 10,000 MT/yr are questionable or suggest a capacity point where multiple plant locations become the only practical siting means, thus the unit cost increases.

However, the influence of line throughput and solvent exchange contactor types was not explicitly recognized. For a low burn-up fuel and use of mixer-settlers, where criticality safety restrictions from the relatively low Pu level are less significant, the actual throughput may be 1,500 MTHM/yr using a single line of contactors, for example the British Nuclear Fuels plc (BNFL) Magnox B205 plant at Sellafield. Cap La Hague, Thermal Oxide Reprocessing Plant (THORP), and now Rokkasho show that throughputs of 800–1,000 MTHM/yr are achievable with LWR oxide fuels using pulse columns of diameters in the range 300–500 mm. Beyond this, criticality safety restrictions become dominant and multiple-line plants or multiple single-line plants seem to be required. Given the complexity of reprocessing technology and relative lack of design standardization and operating experience, at least compared to LWR technology,

the tendency has been to minimize risk to capital by constructing independent reprocessing plants. It is arguable that with current practice the minimum of the cost curve shown in Figure F1-6 should appear near the single line value, probably in the range 1,000 to 2,000 MTHM/yr. The latest generation U.S. designs appear to build on Savannah River Site (SRS) DuPont philosophy by extensive use of centrifugal contactors with their operational benefits of high availability and rapid re-start of processing, but concomitant requirement for fully remote operation and maintenance. While SRS has used designs of centrifugal contactor banks that appear to support single line throughputs of 1,000 MTHM/yr, the safety limit of centrifugal contactor diameter and associated throughput does not appear to have been established. Optimization, concerning process remote equipment versus capital cost and throughput, needs further development and appears critical to future plant design.

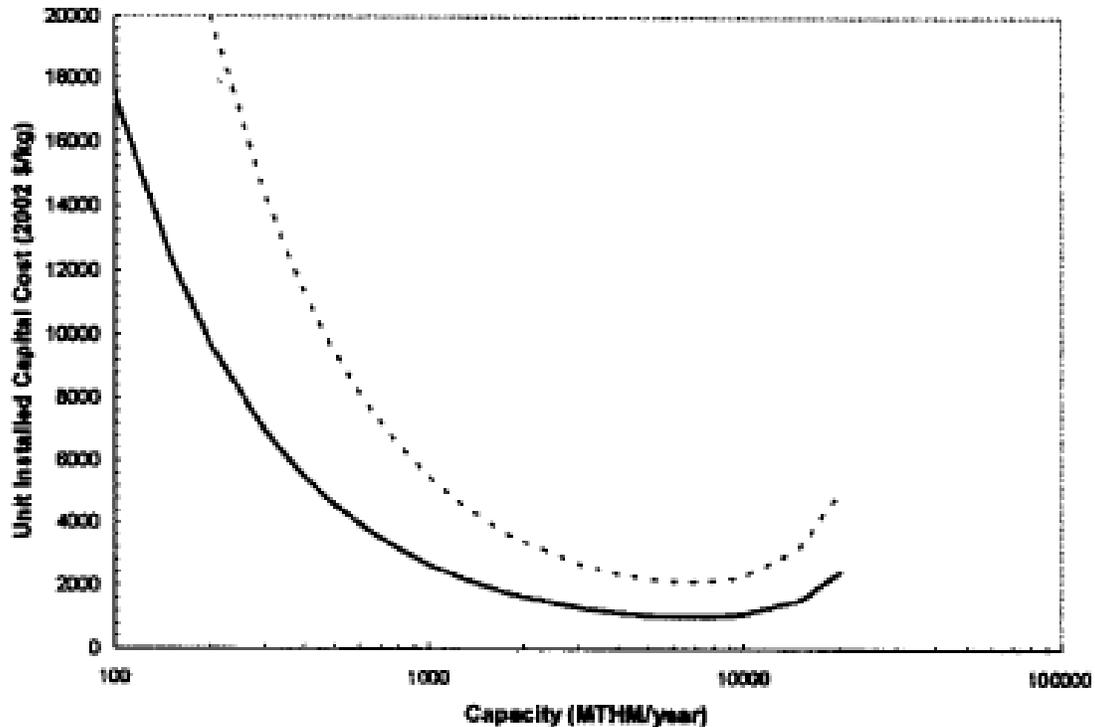


Figure F1-6. Reprocessing unit installed capital cost versus capacity (Haire 2003).

The four Cap La Hague and Sellafield operating PUREX reprocessing plants are at coastal sites and use sea discharges of low-level liquid wastes. The processing plant for these at Sellafield is significant in cost. (Alpha discharges decreased by 100-fold over past 10–20 years due to pressure from Eire and Scandinavia.) This cost should be included in reprocessing since it is affected by reprocessing plant design (e.g., salt-free flowsheet and degree of recycle to high-level liquid waste). If, as expected, UREX+ were to be a zero liquid discharge plant with inland siting, this may well increase costs. Rokkasho is also at a coastal site and may have liquid discharges.

It may be worth noting that PUREX and UREX+ processes were developed in different historic time periods with different aims and design requirements. There are also potential processes intermediate in complexity to PUREX and UREX+ that use tributyl phosphate (TBP) and complexants to form uranium and mixed TRU products together with HLW. AREVA and British Nuclear Group (formerly BNFL) already store vitrified HLW in passive air-cooled vaults for decay of high heat, intermediate half-life emitters such as cesium and strontium.

A factor further affecting scaling is the number of separations to be handled by the design. In a small plant, each additional separation stage adds an increment of complexity, including the separation equipment, process control, additional in-process holdup, and product storage. However, since the latter separations typically involve small volumes (once the uranium, which is over 92% of the heavy-metal mass, is removed), considerable scale-up can be accommodated without substantial additional complexity provided that close coupling of process steps can be tolerated, flexible process envelopes are available, criticality safety and mal-operation scenarios, and process analytical requirements can be met. For UREX+, where there are a larger number of specified products (each by-product or “waste” stream has a specification rather than being a residual). The early removal of uranium is helpful in reducing chemical process mass, but it may be more valuable to remove Pu with some U/MA (for non-proliferation reasons), and then the buffer tanks presently needed between separation areas would be much less expensive (presently a significant contributor to overall capital cost) as they may not need to be safe regarding criticality. Also removing U does not necessarily substantially reduce the liquor volumes and equipment/cell sizing since these may now be governed by Pu concentrations and flowsheet chemistry to achieve desired decontamination factors (DFs).

Using data from the Consolidated Fuel Treatment Center (CFTC) studies the cost was fitted using the logarithmic relationship:

$$CostofA = CostofB \left( \frac{CapacityofA}{CapacityofB} \right)^n$$

Where, capacity is expressed as instantaneous design capacity (MT/yr), and the exponential factor, *n*, is typically in the range of about 0.6. However, based on the considerations discussed above, the power law exponent is expected to be less than 0.6. The preceding equation indicates that a log-log plot of the capacity versus cost should be a straight line with the slope equal to the exponent. Therefore, the CFTC reprocessing Total Project Cost (TPC) estimates for different UREX+1 capacities shown below were used to determine the power law factor was equal to about 0.42 over the range of capacities from 800 to 3000MT/yr.

## **F1-6. COST BASES, ASSUMPTIONS AND DATA SOURCES**

### **F1-6.1 HISTORICAL COST OF EXISTING FACILITIES**

The cost basis for aqueous reprocessing should be straightforward because several facilities have been built and run in the last 50 years, and there are current contracts for reprocessing services. However, most of these facilities were related to military programs, and little information is available for them. The two existing commercial reprocessing sites have published only rather limited cost data because the information is considered proprietary.

Current prices charged for spent nuclear fuel reprocessing services at La Hague are ~\$900/kgHM (NAS 2000). This should provide a base cost from which to work. However, the above price includes other services such as transportation, storage, and some waste disposal. Thus the reprocessing service alone is a lesser scope than this. The term “reprocessing service” is used to distinguish from the actual cost of reprocessing. Bunn notes the prices of reprocessing services at existing facilities in Europe were initially artificially high to cover capital costs, and prices have come down as the capital costs have been recovered and demand has reduced (Bunn et al. 2003). But these may now be coming below long-term economic cost, for example leading to the planned closure of THORP in 2010. A number of European countries have removed the legal duty on their electric utilities to contract for reprocessing of their spent fuels. The fact that one of these services is being offered at a particular price does *not* in itself demonstrate that its full cost must be at that price or below.

The UREX+ suite of processes are much different from the traditional PUREX. The UREX+ processes use multiple solvents and complexants increasing the number of separations stages required to meet the objectives of the program, which are quite different from the traditional reprocessing in Europe and Japan. The main transuranic product of the UREX+ process is also a significant heat generator that adds complexity. Therefore, there is no direct comparison that would seemingly match. Even the proposed initial front-end shearing, voloxidation, and dissolution is more complex in UREX+ due to higher TRU recovery requirements.

While direct construction and operating cost information on the THORP and La Hague plants are limited, there are a large number of independent cost studies of reprocessing facilities with various functional and operational requirements. There are also a number of studies of designs that were not built or operated. Rather than assess each of these studies, the work of others is referenced in integrating these different sources (Spencer 2003; AREVA 2004). Also, the 2004 scoping study is referenced for a UREX+ Spent Fuel Treatment Facility (SFTF) conducted for the Advanced Fuel Cycle Initiative (AFCI) program. And, the more detailed information available is used from this source to establish the code of accounts relative cost splits (WGI 2004).

The scaling studies cited previously recommended the optimal size of a reprocessing facility to be approximately 2,500 MT/yr. The design life of an aqueous processing facility has not been well established. The cost studies referenced above are based on a range of operating lives from 15 to 30 years. A longer life stretches out repayment of capital, reducing per unit cost, but it increases the risk of substantial equipment replacement and changed regulatory and commercial requirements. Given the large amounts of commercial spent nuclear fuel projected, any new reprocessing facility developed in the U.S. should be designed for a long life. The most economical would be a plant size of at least 2,500 MT/yr and an operating life of at least 40 years, resulting in a total processing throughput of 100,000 MTHM (or more).

However, an operating lifetime of 40 years may not always be desirable given that parts of the plant see aggressive conditions and that plants are normally designed to be economic for particular flowsheets and not easily converted to new standards such as much higher fissile contents/burnups. It may be reasonable and conservative to assume a 20-year economic lifetime since this period is likely to be met, and then further operation involving replacement of equipment to continue processing or meet a new flowsheet can be considered. At commercial interest rates, any operation after 20 years has lower impact, but it does reduce unit costs for near-zero interest rates.

## **F1-6.2 STUDIES OF ADVANCED REPROCESSING FACILITIES**

DOE has conducted two pre-conceptual design studies for reprocessing. The Engineering Alternative Study (EAS) developed Life Cycle Cost (LCC) estimates for a 3,000MT/yr UREX+1 based reprocessing center. The facility included segments to receive and manage SNF, dissolve the fuel core from inside the cladding material, and use the UREX+1a process to separate the various components of the SNF. In addition, the facility treated all product and waste streams to acceptable forms either for further processing into a proliferation-resistant fast reactor fuel, or for disposal. The design concept included a fully remote canyon-type operation. LCC estimates were developed assuming a 40-year life. The LCC included extended product and waste storage facilities to allow, for example, the HLW and Cs/Sr waste to decay prior to disposal.

The second study or Follow-on EAS (FOEAS) modified a number of programmatic and engineering assumptions used in the EAS. This included the waste and product disposition paths, which were assumed to be available so that storage facilities were limited to those required for buffer storage, the canyon concept was optimized to allow better utilization of the shielded space, the ventilation system sand filters were replaced with HEPA filters, and the Cs/Sr treatment process was revised to reduce the waste storage requirements.

The FOEAS also developed LCC estimates for a number of alternative processes, including a UREX+3 in which U/Pu/Np and Am/Cm are separate products, and a simpler processing scheme in which only the U/Pu are recovered and the minor actinides are combined into a single HLW borosilicate glass. An electrochemical alternative was also developed (see Module F2/D2).

A number of capital cost estimates have been included as part of the studies in the referenced analyses. For example, Haire includes reference capital costs for facilities ranging in capacity from very small (15 MTHM/yr) to large facilities (3,000 MTHM/yr) (Haire 2003). The National Academy of Sciences study on “Nuclear Wastes: Technologies for Separations and Transmutation” also has numerous tables with cost data in its Appendix J (NAS 1996). This study along with that of Bunn et al. are the most comprehensive studies to date in the area of reprocessing costs (Bunn et al. 2003). Table F1-1 provides the reference capital costs along with the inflator factor and the equivalent costs for 2005.

Significantly larger escalated capital costs (from \$5B to \$7B) for some of the facilities above are reported in the National Academy of Sciences article. These values may include some costs for onsite facilities covered in other modules, such as vitrification of high-level reprocessing wastes (G Module). The estimated actual costs for the La Hague (France) and the Rokkasho-mura (Japan) plants are reported (1996) in this range in a report from The National Academy of Sciences (NAS 1996). However, more recent capital costs for Rokkasho-mura are estimated at over \$20B.

Data from the EAS and FOEAS have been adjusted from those provided in the references reports (WSRC 2007, 2008a). These costs have been distributed within the various modules in this report. The data presented in Table F1-1 for the 3000 MT/yr reprocessing alternative have also been adjusted from that presented in the reference document (WSRC 2007). Adjustments were made to ensure the assumptions and design attributes were consistent with the 800 MT/yr cases. These adjustment include the elimination of sand filters and inclusion of additional footprint for HEPA filters, a reduction in the hardened footprint to reflect an optimized canyon equipment arrangement developed as a part of the FOEAS, and elimination of future project cost from the LCC to reflect a consistent assumption that waste disposal facilities were available such that multiple waste glass storage buildings were not required.

The most recently constructed reprocessing facility is the 800 MT/yr Rokkasho-mura facility with a stated capital cost of \$20B including MOX fuel fabrication and other associated reprocessing facilities. Using values from the EAS studies for activities/costs defined in other modules (MOX fuel fabrication [\$4B to \$5.1B], the HLW vitrification [\$3B to \$4.4B], the U/Pu vault [\$0.75B to \$1.0B] and U solidification and storage costs [\$0.25B to \$0.33B]) provides a Rokkasho reprocessing core plant cost of \$9.2B to \$12.0B. This compares to about 15% of the core FOEAS Co-Extraction (Co-Ex) reprocessing plant with an estimate range of \$10.2B to \$14.2B.

Table F1-2 provides the LCC estimates for the principle EAS and FOEAS alternatives.

Table F1-1. Capital cost and throughput estimates for various reprocessing plants design studies and actual facilities (prepared in 2005).

Plant or Design Study (Complete construct/ operate/design study) <sup>24</sup>	Design Rate MT/day (days/yr)	Planned Throughput MTHM/yr	Actual Throughput MTHM/yr	100% Capacity MTHM/yr	Ref. Capital Cost (\$B)	m.v. Basis Year	Inflator Factor	Capital Cost 2005 (\$B)
<b>Windscale B205(1964- )<sup>1</sup></b>	<b>7 (214)</b>	<b>1,500</b>	<b>~500-1,500</b>	<b>2,555</b>	-	-	-	-
<b>West Valley (1966-72)<sup>2</sup></b>	<b>1 (300)</b>	<b>300</b>	<b>~110 (640 – 6y)</b>	-	-	-	-	-
HTGR Ref. RP (1969) <sup>3</sup>	-	260	Design/cost	-	0.060	1969	~4	0.24
<b>GE Morris (1974)<sup>4</sup></b>	<b>3</b>	<b>(900)</b>	<b>Inoperable</b>	<b>1,095</b>	<b>0.064</b>	-	<b>~4</b>	<b>0.26</b>
<b>AGNS Barnwell (1974) <sup>5</sup></b>	<b>5 (300)</b>	<b>1,500</b>	<b>Not operated</b>	<b>1,825</b>	<b>1.50</b>	<b>1983</b>	<b>1.8</b>	<b>2.7</b>
Exxon (1976) <sup>6</sup>	Est. 1.7 (300)	500	Design/cost	-	0.99	1978	2.6713	2.64
Exxon (1976) <sup>6</sup>	Est. 5 (300)	1,500	Cost estimate	-	1.5	1983	1.8	2.7
IAEA (1976) <sup>7</sup>	-	300	Cost estimate	-	0.48	1976	3.0786	1.48
IAEA (1976) <sup>7</sup>	-	750	Cost estimate	-	0.70	1976	3.0786	2.16
IAEA (1976) <sup>7</sup>	-	1500	Cost estimate	-	1.05	1976	3.0786	3.23
IAEA (1976) <sup>7</sup>	-	3000	Cost estimate	-	1.72	1976	3.0786	5.30
<b>Tokai RP (1977- )<sup>8</sup></b>	<b>0.7 (143)</b>	<b>100</b>	<b>40 (1,123 -28 y)</b>	<b>255</b>	-	-	-	-
<b>RT-1 Mayak (1977- )<sup>9</sup></b>	<b>1 (200)</b>	<b>200</b>	<b>146 (3,500 -24y)</b>	<b>400</b>	-	-	-	-
DuPont (1978) <sup>10</sup>	5 (300)	1,500	Design/cost	1,825	2.4	1983	1.8	4.3
DuPont (1978) <sup>10</sup> inc. fab	10 (300)	3,000	Design/cost	3,650	3.7 inc fuel fab	1978	2.6713	9.0
CFRP FR Dem (1979) <sup>11</sup>	0.1 (150)	15	Design/cost	30	0.80 ± 0.2	1982	1.8808	1.50
CFRP Hot Exp (1979) <sup>12</sup>	0.5	-	Design/cost	183	1.0 ± 0.25	1982	1.8808	1.88
EDRP FR UK (1984) <sup>13</sup>	0.3 (250)	75	Design/cost	110	0.42 (£0.24B)	1982	1.8808	0.79
GE ALMR (1990) <sup>14</sup> fab	-	2,700	Design/cost	-	5	1990	1.4	7
EPRI Study (1990) <sup>15</sup>	-	1,500	Cost study	-	3.0	1990	1.4	4.2
<b>UP-3 (1990- )<sup>16</sup></b>	<b>5 (160-200)</b>	<b>800 (1,000)</b>	<b>800+</b>	<b>1,825</b>	<b>6.2 (28BFF'92)</b>	<b>2003</b>	<b>1.1</b>	<b>6.8</b>
OECD study (1994) <sup>17</sup>	~5 (180)	900	Cost study	1,825	4.1B (£2.7B)	~1993	1.3623	5.5
<b>THORP (1994- )<sup>18</sup></b>	<b>5 (120)</b>	<b>600</b>	<b>600</b>	<b>1,825</b>	<b>4.1 (£2.3B)</b>	<b>1992</b>	<b>1.37</b>	<b>5.6</b>
<b>UP2-800 (1994- )<sup>19</sup></b>	<b>5 (160-200)</b>	<b>800 (1,000)</b>	<b>800+</b>	<b>1,500</b>	<b>5.8 (37BFF'00)</b>	<b>1990</b>	<b>1.4</b>	<b>8.1</b>
SFTF – UREX+ (2004) <sup>20</sup>	7.4 (270)	2,000	Design/cost	2,700	3.0	2004	1.05	3.2
<b>Rokkasho (2007-8)<sup>21</sup></b>	<b>5 (160)</b>	<b>800</b>	<b>Commission</b>	<b>1,500</b>	<b>5.2-6.5</b>	<b>1992</b>	<b>1.37</b>	<b>(~20)</b>
COEX <sup>TM</sup> –AREVA (2006) <sup>22</sup>	8.3 (300)	2,500	COEX <sup>TM</sup> design	3,030	16.2 inc fuel fab	2005	1	(~13)
EAS – UREX+1a	12.5(240)	3,000	Design Study	4,500	\$26.6 to \$39.2B	2007	1	
FOEAS - UREX+1b	3.34(240)	800	Design Study	1,200	\$14.5 to \$21.2B	2007	1	
FOEAS – UREX+3	3.34(240)	800	Design Study	1,200	\$17.2 to \$25.6B	2007	1	
FOEAS – Co-Ex	3.34(240)	800	Design Study	1,200	\$10.2 to \$14.2B	2007	1	

**NOTE:** See Section F1-16.3 for additional notes to this table.

Table F1-2 CFTC TPC and LCC Estimates for Reprocessing Module

Millions of 2007 Dollars	Benchmark 2 800 MT/yr UREX+1		SA4 800 MT/yr UREX+3		SA5 800 MT/yr Co-Ex	
	Low	High	Low	High	Low	High
Annual Operations Cost (nominal year) Labor	194	288	214	322	195	293
Utilities	17	28	17	28	20	33
Materials	22	33	23	34	20	26
Misc contracts	6	6	6	6	7	7
Misc Projects	17	22	17	23	13	20
<b>Total Annual Operations Cost</b>	<b>254</b>	<b>376</b>	<b>277</b>	<b>412</b>	<b>254</b>	<b>377</b>
40-year LCC						
Labor	9822	14734	10852	16278	9805	14707
Materials	1048	1573	1223	1835	938	1406
Utilities	956	1434	967	1450	1107	1660
Contracts	180	270	182	273	208	313
Misc. Projects	531	796	576	864	547	820
<b>Subtotal: 40-year Operations</b>	<b>12,538</b>	<b>18,807</b>	<b>13,800</b>	<b>20,700</b>	<b>12,604</b>	<b>18,906</b>
Future Capital Projects	0	0	0	0	0	0
D&D	1690	2545	2032	3079	1156	1714
<b>Subtotal LCC O&amp;M &amp; D&amp;D</b>	<b>14,228</b>	<b>21,352</b>	<b>15,832</b>	<b>23,779</b>	<b>13,760</b>	<b>20,620</b>
Early Life Cycle	201	300	262	407	187	270
TPC	14453	21202	17193	25656	10211	14186
<b>Total LCC</b>	<b>28,882</b>	<b>42,853</b>	<b>33,287</b>	<b>49,842</b>	<b>24,158</b>	<b>35,076</b>
LCC Unit Cost (\$/kg HM)	903	1,339	1,040	1,558	755	1,096

A recent re-examination of the original EAS and FOEAS cost estimates (Washington Savannah River Company 2007, 2008a and 2008b) concluded that there may be scope for a reduction in the originally estimated capital costs, based on a comparison of the non-direct costs with the nuclear industry experience in building LWRs.

A brief summary of those considerations is provided here, after an introduction explaining the main quantitative findings with regards to direct and non-direct costs for PWR.

#### **Direct and non-direct costs from the LWR experience**

This section presents a summary of a quantitative analysis of direct and non-direct costs from the LWR historical experience.

Direct construction costs include the cost of bulk commodities, equipment and their installation labor. All other costs are included here in the “non-direct” cost category: those include indirect costs (which in

turn typically include the cost of the architect/engineer services, including construction services, engineering, construction management, quality assurance, field supervision, startup, and testing); owner's costs, contingencies and startup costs.

In the actual construction experience, Indirect Costs were found to be the dominant cost component at the two-digit level: 31% of total costs (and approximately 60% of direct costs) in the EEDB Better Experience (EEDB 1988) (i.e. the actual observed construction costs in the 1970s and 1980s of the nuclear plant construction projects that ended without substantial cost overruns) and 42% of total costs (and approximately 120% of direct costs) in the EEDB Median Experience (EEDB 1988) (i.e. the actual observed average construction costs in the 1980s of the nuclear plant construction projects). The indirect costs in the latter case were substantially larger than the entire combined direct costs. This finding is consistent with the framework proposed in (Ganda 2014) to explain the cost overruns observed historically in nuclear construction, based on changes required during the construction phase and associated inefficiencies: the following is a quote from (EEDB 1988): *“The un-distributable indirect costs account for over half of the total cost change [between 1978 and 1987, in constant dollars] and of this amount about 70 percent is for engineering and field supervision increases. Consequently, the major cost drivers over the first nine EEDB updates appear to be those activities and practices related to meeting accountability type requirements. Accountability encompasses such topics as regulatory reviews, design review, project control, analysis verification, procedure development and implementation, equipment qualification, inspection, testing and similar or related activities.”* (EEDB 1988).

Owner's costs were estimated at about 10% of total overnight costs in all the construction estimates analyzed in (Ganda 2014), without significant variations in the percentages. Owner's costs include land, substation, transmission facilities, generator step-up transformer, nuclear insurance, taxes, fees, permits, owner's engineering, supervision and quality assurance, roads, ancillary buildings (e.g. visitor's centers, cafeterias, parking lots etc.), training of operations staff, owner's general and administrative overhead, and licensing with all the local regulatory agencies.

The contingency rate was estimated at ranges of between 8% and 14% in the various construction estimates analyzed in Ganda (2014).

### **Re-examination of the EAS and FOEAS cost estimates**

The 2007 low estimate for the total construction cost of the EAS 3000 MT/y UREX +1 facility was \$42 billion in the 2007 EAS. The vast majority of the costs (\$35 billion) out of a total of \$42 billion for the low estimate (i.e. about 83%) are for the “Process facilities/buildings”. Additionally, 90% of the “Process facilities/buildings” costs are from the 7 most expensive process facilities, with the first 3 comprising almost 60% of the total costs. Those are “Fuel”, “Extraction” and “U/TRU storage” buildings. The “Fuel” building is the largest and most expensive part of the facility, with an estimated “low” construction cost of approximately \$7.8 billion (Washington Savannah River Company 2007). It hosts the following functions:

- Fuel Receipt & Storage, Fuel Shearing;
- Off-gas Removal / Capture;
- Fuel Dissolution;
- Hull Treatment;
- Tc Alloying.

The direct construction cost of the fuel building structures was estimated at approximately \$1 billion, while the installed cost (including of installation labor and material) of the building's equipment was estimated at approximately \$0.8 billion. Therefore, of the total of between \$7.8 and \$10.8 billion (the low and high estimates), only about \$1.9 billion in both cases are the direct construction costs, while an additional \$0.8-0.9 billion are the startup costs (a detailed breakdown of the costs from (Washington Savannah River Company 2007) is provided in Table F1-1).

Moreover, about \$1 billion is for design costs that were included in the original \$7.8 billion estimate. While it is important to inform on the design costs, a reader would be well served by clearly citing those costs separately from the “construction” costs, if the objective is to inform on the actual cost of constructing a reprocessing facility, as is the purpose of the present module.

The non-direct costs were revised as shown in Table F1-1, as compared to the original estimate derived in the EAS (Washington Savannah River Company 2007) and used in previous versions of the CBR, based on a comparison of the non-direct costs with the nuclear industry experience in building LWR (discussed briefly above).

The “Project Support Services, Project Management and Administrative Costs” are compared to the typical indirect costs for LWR: it was found that the ratio of “indirect/direct” costs is approximately 60% for a well-executed PWR construction project, including a large cost contribution from home-office services, which would not need to be repeated for projects that replicate the design of existing facilities and are well-executed. Excluding this cost, the fraction of indirect/direct costs for LWR would be approximately 40%. However, in the case of the Fuel Building, the fraction of indirect/direct costs is 96% (for the low cost case) to 124% (for the high cost case) in the study by Washington Savannah River Company (2007).

Further, the need for additional “Supplementary Costs” (at \$745 million for the “Total Estimated Cost Subfield”, i.e. at about 40% of the \$1.855 billion of direct construction costs) is not clear. “Supplementary Costs” include “General and Administrative” expenses (about 23% of direct construction costs) and a contractor “fee”, of about 17% of the direct construction costs. Administrative expenses were already included in the “Project Support Services, Project Management and Administrative Costs”, and that account was found to be larger than typical with LWR: therefore, it is inferred that this cost should not be included. Additionally, the estimates provided here are for a well-executed FOAK project, awarded on a fixed price contract basis, as opposed to the typical cost-plus-fixed fee contract basis that appears to have been assumed in EAS (Washington Savannah River Company 2007). Under fixed price contracting, contractors’ fees are not explicitly included in the estimates. In summary, it appears that “Supplementary Costs” should not be included in the total cost estimate.

Also, contingency costs of about 58% of direct construction appear high, when compared to a typical value of about 8-14% of direct construction costs for LWR construction, even when considering that this would be a “first of a kind” plant. Regarding an appropriate contingency rate for the construction of the building, it can be argued that construction of massive concrete buildings has been done multiple times before, and should not present an extraordinary, first-of-a-kind challenge, so perhaps a contingency of 10% on the direct construction costs of the building would be more appropriate. The equipment part would be relatively new, even though complex chemical plants have been constructed before. Therefore, even allowing a 50% contingency on the equipment part of the building, one would reach a total (i.e. building and equipment) contingency cost of approximately 50% of the value utilized in (Washington Savannah River Company 2007) (\$100 million for the construction and approximately \$400 million for the equipment). This would give a contingency rate of approximately 27% on the total direct costs. It is noted in (Washington Savannah River Company 2007), that contingencies in this estimate are mainly due to uncertainties other than “Process/Equipment Uncertainty”.

Regarding startup costs, it was found in a DOE project cost estimating guide (DOE 2016), that *“construction startup costs can range from 0.5 to 10 percent of the installed cost for the conventional construction facility.”* (Chapter 8, DOE 2016). While it can be argued that the Fuel Building is not a “conventional” facility, it can also be argued that the facility is a large chemical plant, and that the “unconventionality” of the facility has already been included in a large allowance for contingency for the equipment installation. For this reason, it appears advisable to follow the guideline on startup costs, perhaps to the upper range, of the “installed” costs including “direct, indirect and contingencies.

In summary, installed costs would be about \$3.4 billion, and the startup costs would be \$350 million instead of the \$815 million estimated in (Washington Savannah River Company 2007). A contingency value for startup costs of 50% would be about \$175 million. It is noted that the high percentage value of the contingencies for the startup costs includes conservatism in the estimate.

By applying all of the above considerations, the total construction cost of the Fuel Building for the 3000 MT/y UREX+1A plant would be reduced by about 48% to about \$4 billion, of which about half are direct costs (similarly to the historical experience with well executed construction of PWRs), about \$1 billion would be for indirect costs, about \$500 million would be for construction contingency and about \$500 million would be for startup costs and associated contingencies. A design cost of about \$1 billion is reported separately and is therefore not included in this construction estimate. It is also noted that the modified estimate of Table F1-1 includes substantial conservatism in the contingencies, to allow for the fact that this unit would be a FOAK. While it would be un-likely that several of these large (i.e. 3000 MT/year) facilities could be constructed in sequence, a NOAK facility should have lower contingency costs, perhaps as much as \$400 million less, if the contingency rates that were set at 50% would instead be lowered to 10%. Additionally, a NOAK facility could re-use the design that were developed for the FOAK facility, and thus could avoid design costs. Additionally, a NOAK facility could avoid the home-office engineering services (typically about 25% of indirect costs for a LWR, please see (Ganda 2016)), which would not need to be repeated for projects that replicate the design of existing facilities and are well-executed.

The same logic that was applied to the cost estimate of the fuel building has been applied also to the 2<sup>nd</sup> most expensive building, the “Extraction Building”, and to the 3<sup>rd</sup> most expensive building, the “U/TRU Storage Building”. In both cases, the modified estimate is about 55% of the low estimate costs of (Washington Savannah River Company 2007), excluding design costs, which in turn are about 14% of the original Low Estimate, also similar to the values estimated for the Fuel and Extraction buildings.

Since the combined construction costs of the Fuel, Extraction and U/TRU storage buildings comprise almost 60% of the total cost of the project, the analysis performed on these three buildings can be considered representative enough to be extensible to the entire facility using the same fractional costs, using the average cost reduction of three buildings of 52.7%.

Using this fraction, the new updated cost estimate for the “Process facilities/buildings” excluding design costs is \$18.4 billion.

Table F1-1 Detailed breakdown by construction cost categories for the “Fuel Building” and modified estimate for the 3000 MTHM/yr fuel building according to the logic described in this Section.

All costs are in (1000s)	Low estimate (Washington Savannah River Company 2007)	Modified estimate
<b>Total Estimated Costs (TEC)</b>		
Engineered Equipment Costs	817,837	817,837
Structures & Improvements Costs	1,037,622	1,037,622
<b>Subtotal Field Directs</b>	<b>1,855,460</b>	<b>1,855,460</b>
Preliminary & Final Design Costs	1,009,370	0
Preliminary Design Costs	296,874	0
Final Design Costs	712,497	0
Project Support Services, Project Mgmt. & Admn. Costs	1,792,374	1,113,276
Supplementary Costs	745,153	0
Escalation	0	0
General and Administrative	419,148	0
Fee	326,004	0
Contingency Costs	1,080,471	512,681
<b>Subtotal TEC</b>	<b>6,484,078</b>	<b>3,481,417</b>
<b>Other Project Costs (OPC)</b>		
Start-up Costs	815,011	348,142
Supplementary Costs	260,803	0
Escalation	0	0
General and Administrative	203,753	0
Fee	57,051	0
Contingency Costs	215,163	174,071
<b>Subtotal OPC</b>	<b>1,291,226</b>	<b>522,213</b>
<b>Subtotal - Fuel Building -Total Project Costs (TPC)</b>	<b>7,775,304</b>	<b>4,003,629</b>
	Design costs of \$1bn are included in this number	Design costs of \$1bn are not included in this number

The total cost of design (including both preliminary and final design) was estimated in (Washington Savannah River Company 2007) at 13% of the original Low Cost Estimate of \$35 billion, resulting in an additional \$4.7 billion in design costs.

No basis was found yet to revise the costs of the Balance of Plant and of the site improvements, at \$3.2 b and \$4.1 b respectively: therefore, the costs estimated for those parts in (Washington Savannah River Company 2007) remain applicable also in this analysis.

In summary, the updated total project cost is approximately \$25.7 billion excluding design, and \$30.4 billion including preliminary and final design, instead of a range of \$42 billion to \$61 billion reported in (Washington Savannah River Company 2007).

Since the estimated construction cost of Table F1-2 is based on the EAS estimate, including the non-direct costs that are being revised here, the same reduction to 52.7% of the construction costs of Table F1-2 is applied here.

For the “low” and “high” costs of \$14453 and of \$21202 million for the benchmark 800 MT/y UREX +1A facility, the reduction would then lead to \$7616 and \$11173 million. The “LLC O&M and D&D” costs have not been changed in this CBR revision, and it will be revised in future revision if necessary.

Therefore, the resulting summary cost for a facility lifetime of 40 years and zero discount rate, would be reduced from a range of 903-1339 \$/kgHM to 689-1026 \$/kgHM.

Additionally, the following is noted:

- The O&M costs of the EAS and FOEAS designs have not been revisited yet, since insufficient information was found in the original sources of the EAS and FOEAS (Washington Savannah River Company 2007, 2008a and 2008b) to re-evaluate this information.
- The direct construction costs have not been revisited yet since the works of Washington Savannah River Company (2007, 2008a and 2008b). It is possible that a cost reduction could be obtained also in this area.

### F1-6.3 NOTES FOR TABLE F1-1

1. The UK Windscale B205 reprocessing plant for Magnox,  $\leq 8$  GW(t)d/t burnup, gas-cooled, natural uranium metal-fuelled (Gen I) reactors originally operated at over 1,000 t/yr throughput and is still operating at around 500 t(HM)/yr (one of two head-end decanning lines closed down as reactor fleet decreased) and planned for closure after 2012, when all reactor-lifetime fuel arising has been reprocessed. Decommissioning of this plant is envisioned around 2020. The plant is described in the Nuclear Power Technology article (Marshall 1983).
2. Nuclear Fuel Services (NFS) West Valley, New York reprocessing plant is the only plant in the U.S. to have reprocessed commercial reactors fuels. During its 6-year period of operation it separated 1,926 kg of plutonium from a mixture of Atomic Energy Commission and commercial utility fuels. Process losses, discharges, and exposures became higher than planned and final product sometimes did not meet expected quality levels. The plant was permanently shut down in 1976 after it was determined that stricter regulatory requirements could not be met (DOE 1996).
3. A conceptual design and capital cost estimate (INEEL 1969) for a High-Temperature Gas-Cooled Reactor (HTGR) Reference Fuel Reprocessing Plant was prepared for Idaho Nuclear Corporation by Bechtel (Bechtel: August 1969, INEEL Report No. IN-1451.) The plant design includes a crush-burn head-end process for removing the bulk of graphite: fuel particles are separated by screening, crushed to break SiC coatings, again burned and Th, U and FP are separated using an acid-thorex solvent extraction process.
4. The Midwest Fuel Recovery Plant (MFRP) hybrid aqueous/electrochemical nuclear fuel reprocessing plant was constructed at Morris, Illinois, near the Dresden Nuclear Power Station. When in final cold testing in 1974, General Electric (GE) determined that its performance would not be acceptable without extensive modifications. The combination of complex processing equipment with higher expected failure rates and close coupling of process steps, which required much longer time to resume operation after shutdown, would permit only a low throughput. The request for a reprocessing plant operating license was withdrawn and the plant was licensed only to store spent fuel (700 t) (DOE 1996.)
5. The Allied-General Nuclear Services (AGNS) Barnwell Plant was due to begin operation in 1974, but by 1977 was not completed or licensed when the U.S. decided to defer indefinitely all reprocessing of commercial irradiated fuel. It was technically unproven since it never operated with spent fuel, and it has since been decommissioned. A technical description is given in Nuclear Chemical Engineering (Benedict 1981), pp. 491–501, M. Benedict, T. Pigford, H. Levi, 2<sup>nd</sup> Ed, McGraw-Hill, 1981. The flow-sheet gives a chemical separations feed of 5 t(HM)/d and the plant is described by Haire (2003)

as having an annual capacity of 1,500 t(HM). It should be noted that to achieve this annual throughput, the availability would need to be nearly twice that of the French and UK plants, THORP, UP-2, and UP-3.

6. Exxon undertook conceptual design and capital cost estimates for oxide reprocessing plants with a period of 7 years of design effort, including 200 man-years of architect engineering (Exxon Nuclear Company 1976). Also see Exxon nuclear fuel recovery and recycling center process description (Ritter 1979). Capital cost for 1,500 t/yr plant is quoted by Haire (2003). One of the proposed sites was in Eastern Tennessee south of Oak Ridge.
7. IAEA PUREX-based reprocessing plant cost studies to scope against plant scale (Meckoni et al. 1977). Approximate capital costs may be derived from unit and leveled costs, but it is not clear whether costs were derived from bottoms up estimates or expert judgment.
8. Tokai Reprocessing Plant–PUREX thermal oxide uranium reprocessing pilot plant, no longer operating commercially for Japanese electric utilities, but is reserved for test runs, mainly with MOX fuels.
9. Mayak RT-1 at Ozersk, R. F. was commissioned in 1977 to reprocess spent fuel from VVER-440, BN-350, BN-600, research, and naval propulsion reactors. Most of the feed is from VVER-440 reactors and this is the only Russian facility that reprocesses spent power reactor fuel. The plant's nominal reprocessing capacity (based on spent fuel from the VVER-440 reactors) is 400 tons of spent fuel per year, The RT-1 facility is made up of a spent fuel storage pool, three chopping-dissolution process lines, and a modified PUREX process. High-level liquid radioactive waste from the reprocessing is vitrified (NTI 2009).
10. Dupont design studies completed around 1978. These used canyon design with rapid equipment replacement, selective centrifugal contactor placement and rapid startup compared to other plants. Haire (2003) quotes the capital cost of the smaller plant. Bastin (2000) quotes the capital cost for the larger plant that also includes MOX fuel fabrication. This cost was reduced by 10% (\$0.9B) in Table F1-1 to account for removal of MOX fabrication scope. The plant is described in DuPont de Nemours 1979 article (DuPont 1979). Detailed flow-sheets were prepared by Savannah River Laboratory for a conceptual 10 MT/day reprocessing facility. These plants were considered conservative and designed with stronger engineering emphasis on availability and capacity factor, design value of 80%, than the AGNS Barnwell and Exxon Nuclear Company designs. Haire (2003) quotes the Dupont 1,500 t/yr plant as being 60% higher capital cost than the AGNS Barnwell and Exxon Nuclear Company designs, both also of nominal 1,500 t/yr throughput.
11. Oak Ridge National Laboratory (ORNL) studies performed under the Consolidated Fuel Reprocessing Program (CFRP) during the late 1970s and early 1980s as quoted by Haire (2003). The cost of a small-scale fast reactor reprocessing plant to support one or two demonstration fast reactors was scoped. Calculations showed almost no difference in capital cost of reprocessing plant for thermal and fast reactor fuels at throughputs <300 t(HM)/yr. FR reprocessing then becomes more costly than thermal oxide fuel when expressed as per t(HM), but may be less expensive per kW(e)hr.
12. ORNL studies performed under the CFRP during the late 1970s and early 1980s as quoted by Haire M. J. (2003). Except in throughput, the design basis of Hot Experimental Facility (HEF) is similar to that of the 1,500 t(HM)/yr LWR oxide fuel PUREX reprocessing plant and design was performed to obtain a direct comparison of capital costs.
13. Outline Planning Application for a European Demonstration Fast Reactor Reprocessing Plant (EDRP) at Dounreay at Caithness, Scotland, UK was prepared in May 1985, by United Kingdom Atomic Energy Authority (UKAEA), to treat fuel from four commercial fast reactors, but plant construction did not take place. The design used batch dissolvers, sulphate flowsheet for U-Pu partitioning, and liquid waste treatment by flocculation prior to sea discharge.

14. GE advanced liquid metal reactor (ALMR) reprocessing plant. The NAS (1996) provides an estimate of \$6.1B (1990) capital cost for PUREX-TRUOX reprocessing plant (2,700 t/yr throughput) for high recovery of transuranic actinides for transmutation in the ALMR and includes plant for fabrication of TRU MOX fuel. An earlier separate estimate for the same throughput and believed without MOX fuel fabrication was lower at a quoted value of \$4.25B (Salerno et al. 1989).
15. The Electric Power Research Institute (EPRI) 1990 study for a generic U.S. site estimated reprocessing plant capital costs ranging from \$2.73B (government-owned plant) to \$3.00B (privately-owned plant) with a planned annual throughput of 1,500 t/yr (Gingold 1991).
16. AREVA (formerly Compagnie générale des matières nucléaires [COGEMA]) thermal oxide reprocessing plant constructed in France for foreign customers. The capital cost value for UP-3 is quoted in a 2003 article) Bunn et al. The capital costs provided for UP-3 and THORP plants do not include interest during construction, which were borne by reprocessing customers. In 1998, Cogéma submitted dossiers seeking authorization to reprocess up to 1,000 metric tons of heavy metal per year in UP2-800 and up to 1,000 in UP-3 (previously 800 t/yr each). COGEMA committed not to reprocess a total of more than 1,700 t per year. In 2003, permission was given, subject to the overall limit, for up to 1,000 t(HM)/yr for each plant.
17. OECD-NEA 1994, “The Economics of the Nuclear Fuel Cycle”; Cost data supplied by BNFL, capital cost includes reprocessing, fuel receipt and storage, intermediate level waste encapsulation and associated research and development (R&D), but excludes vitrification and HLW management (likely higher cost in pounds sterling than THORP due to need for design modification and additional facilities for increased throughput as compared to THORP). The 1993 Great Britain Pound exchange rate was approximately \$1.50 USD—markedly weaker pound than 1992.
18. THORP is part of the UK Sellafield site, 988 acres. Capital Cost - THORP-only GBP £1.85B (1992 m.v.), THORP and associated waste facilities £2.85B. BNFL (1993) states that the “construction cost of THORP, spread over the ten years 1983–1992, equates to around £1.9B. However, taking account of other projects which are directly related to THORP, the overall capital cost of the programme was around £2.85 B.” Part of the stated £1B for associated waste facilities covers items (excluding vitrification of HLW) that are needed for a standalone reprocessing plant (e.g., receipt pond, liquid waste treatment, degraded solvent treatment, ILW encapsulation). The judgment is that a capital cost for THORP “reprocessing and excluding high level waste treatment” of £2.3B (1992 m.v.) would be reasonable (low rather than high). Using a mean historic exchange rate for 1992 of 1.77 and an inflator factor of 1.37 [approximately Engineering New Record’s “Construction Cost Index History” (ENG 2009)] gives a capital cost for THORP of \$5.7B (1992 mv). Like Bunn, it is judged that use of a Construction Cost Index may underestimate costs of unique facilities such as a reprocessing plant. Originally THORP was planned to have a throughput of 6,000 MTHM in 10 years. This figure was later revised to 7,000 MTHM in 10 years, but the higher throughput was not achieved. Of current generation, operating PUREX plants, THORP has published the most detailed economic data. The figure provided here is consistent with the OECD-NEA hypothetical for which BNFL provided cost input and COGEMA input on basic design and future improvements. Also similar to value given by Bunn et al. (2003).
19. AREVA (formerly COGEMA) thermal oxide reprocessing plant constructed at Cap La Hague site (717 acres) in France for Electricite de France (EDF). UP-2 commenced operation in 1966 as a reprocessing plant for Gaz-Graphite (Gen I reactor) metallic fuels, was converted in around 1976 to UP2-400 plant (400 t/yr) for oxide reprocessing (addition of UP2-HAO) and later still (1994) to UP2-800 (800 t/yr) LWR oxide fuel deriving from EDF French national electric utility. It seems unlikely that a definitive capital cost value can be given for this plant that evolved over many years. However, Bunn et al. quote a capital cost for UP-2. They also quote a combined capital cost for UP-2 and UP-3 facilities at Cap La Hague as FF90B (equated to \$16B in 2003 m.v.). It is not clear whether this

includes vitrification and other supporting requirements to oxide reprocessing or not (Bunn et al. 2003). The report “Economic assessment of Used Nuclear Fuel Management in the United States,” by Boston Consulting Group (BCG 2006) for AREVA, July 2006, quotes a capital cost of \$17.8B (2005 money value and assuming 1€ ≡ 1\$[USD]) for oxide fuel reprocessing, HLW vitrification and MOX fuel fabrication (essentially Cap La Hague [UP-3, UP-2, etc.] and Melox). On this basis, a capital cost of UP-3 (new, as-built plant rather than modified) would be \$6B– \$7B (2005 m.v.).

20. The UREX+ process design, which is more complex than PUREX, provides for five distinct solvent extraction processes that yield the separation of uranium, technetium, cesium with strontium, plutonium with neptunium, and americium with curium (WGI 2004). Some volatile fission products are also separated and residual fission products including rare earths are immobilized. The cost is described as rough order of magnitude (ROM) value.
21. Rokkasho reprocessing plant (RRP), part of the 939-acre fuel cycle center, was originally planned to operate in 2000, but it is likely to be about 8 years late. Capital costs are reputed to have trebled from \$7.6B to around \$21B, but no official estimates were obtained. RRP uses the PUREX process as exemplified by French reprocessing technology, but will mix U and Pu streams to avoid separation of a pure PuO<sub>2</sub> solid product.
22. The report “Economic assessment of Used Nuclear Fuel Management in the United States,” by Boston Consulting Group [BCG] (2006) for AREVA, quotes a capital cost of \$16.2B (2005 money value and assuming 1€ ≡ 1\$[USD]) for an integrated facility for fuel reprocessing, HLW vitrification and MOX fuel fabrication (essentially Cap La Hague [UP-3, UP-2, etc.] and Melox). A capital cost of \$13B (2005 m.v.) for reprocessing alone (removal of remote fuel fabrication, vitrification and interim storage components) was quoted. But, it is noted that the days/yr of full-effective operation for reprocessing has been raised from 200 (UP-3 recent increased value, formerly 160) to 300. Also a long period of operation, 50 years, is assumed. In the Co-Ex flowsheet, irradiated fuel is separated into three main streams: plutonium-uranium oxide, which is then fabricated into fuel on site in the MOX fuel fabrication unit; recycled uranium oxide, which is purified, converted, and re-enriched outside the integrated recycling plant and fabricated into conventional uranium-based fuel; and mixed fission products and minor actinides, which are considered HLW and vitrified. Subsequent updates to the costs in 2008 indicate the potential for cost growth (WSRC 2008b).
23. The Systeme Internationale (SI) symbol for metric ton is t (i.e., t ≡ MTHM).
24. In the first column of Table F1-1, the names of plants actually constructed are shown in bold; some of these operated and some were never operated. The names of cost and design studies that were not used to construct actual plant are shown in normal font.
25. The EAS and FOEAS studies represent the cost associated with this module only, U/transuranic (TRU) storage costs have been reported in Module E-3; U/Tc Separations and Tc Solidification, HLW vitrification and storage, Cs/Sr Solidification and Storage costs have been reported in Module G-1; GTCC and TRU secondary waste treatment costs have been reported in Modules G4 and G-5; LLW treatment and packaging costs have been reported in Module G-3.

## F1-7. DATA LIMITATIONS

Direct construction and operating costs of commercial facilities are not available from the construction and operating companies. Even if direct costs were available, they would provide only around four data points for one technical approach (PUREX) under one financing scheme for one facility size (though near optimal scale using pulse column technology with “dark cells”).

The number of cost estimates for the UREX + technology is more limited. There are also a number of options of technologies for waste processing, including collection and stabilization of key fission products (e.g., cesium, iodine, strontium, and technetium) and stabilization of the HLW component. Many of the

newer technologies have high technical uncertainty that equates to high uncertainty in the limited cost data.

Technical improvements are possible and even probable after a facility is completed. One study estimated process improvements, and improved operating experience at La Hague would result in an 85% reduction in waste volume per unit processed over a 10-year period (OECD-NEA 1994). Such dynamics can result in changes in operating costs over time for the same facility, making comparisons between facilities even more difficult, though these changes may be more for environmental and acceptability reasons and could possibly lead to increased costs.

Given the size of reprocessing facilities and the long construction time, financing is the major cost. The difference in financing costs alone of a government-financed facility and a for-profit private facility of the same size can result in a factor of approximately 2.5 increase in the total facility cost (Bunn et al. 2003; WGI 2004). The existing commercial facilities in France and the U.K. were developed under unique customer financing arrangements. New facilities are likely to also be developed with special financing, including heavy government involvement.

While the costs for this module are based on 2005 dollars, this adjustment provides an incomplete picture. The prevailing interest rates at the time and place of the cost estimate are potentially a larger impact than changes due to inflation. Most of the studies referenced here used a 5% discount rate, but some other earlier studies assumed interest rates as high as 12%. Given construction periods of 6 to 10 years or longer, this difference from 5 to 12% was estimated to increase unit costs by 70% (WGI 2004).

The method used to adjust costs to current year dollars can also impact cost estimates. For example, Bunn's use of a gross domestic product deflator approach (Bunn et al. 2003) results in ~20% higher adjusted costs from the Nuclear Energy Agency, Organization for Economic Cooperation and Development study (WGI 2004) than is developed by using the Engineering News Record's "Construction Cost Index History" (ENR 2009).

## **F1-8. COST SUMMARIES**

The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table F1-3. The summary shows the reference cost basis (constant year U.S. dollars), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Based on the agreement of the FOEAS estimates with industry and the most recently deployed commercial reprocessing facilities, the FOEAS is used as the basis for selected values for reprocessing.

Section F1-6.2 include new analyses that suggest that the cost for this module should be lower than what is presented here, (which is based primarily on the un-adjusted EAS cost analysis). However, we feel that additional evaluations of all the available data are needed before implementing those changes in the WIT table and accompanying distributions, which therefore remains un-changed (except for 14% escalation) from the previous version (2009) of the cost basis report where the EAS comprehensive cost estimates were presented..

Table F1-3. Cost summary table. (Note that 2012 WIT values were same as 2009 WIT values)

<b>What-It-Takes (WIT) Table: 2009 AFC-CBD values and escalation to year 2017\$</b>				
Reference Cost(s) Based on Reference Capacity	Low Cost	Mode Cost	Mean Cost	High Cost
Co-Ex 800 MT/yr (2009\$)	\$755/kg HM	\$925/kg HM		\$1,096/kg HM
<b>Esc to 2017\$&gt;&gt;</b>	<b>\$861/kgHM</b>	<b>\$1055/kgHM</b>	<b>\$1055/kgHM</b>	<b>\$1250/kgHM</b>
UREX+1a 800 MT/yr (2009\$)	\$903/kg HM	\$1,120/kg HM		\$1,339/kg HM
<b>Esc to 2017\$&gt;&gt;</b>	<b>\$1030/kgHM</b>	<b>\$1277/kgHM</b>	<b>\$1277/kgHM</b>	<b>\$1526/khHM</b>
UREX +3a 800 MT/yr (2009\$)	\$1040/kg HM	\$1,300/kg HM		\$1,558/kg HM
<b>Esc to 2017\$&gt;&gt;</b>	<b>\$1156/kgHM</b>	<b>\$1482/kgHM</b>	<b>\$1482/kgHM</b>	<b>\$1776/kgHM</b>
	Facility scales are based on 800 MT/yr. Capacity scaling is limited to a single train due to criticality.			

Facility costs for such things as waste disposition and fabrication would be additional costs as provided by other cost modules. The triangular distribution used for modeling purposes is shown in Figure F1-7.

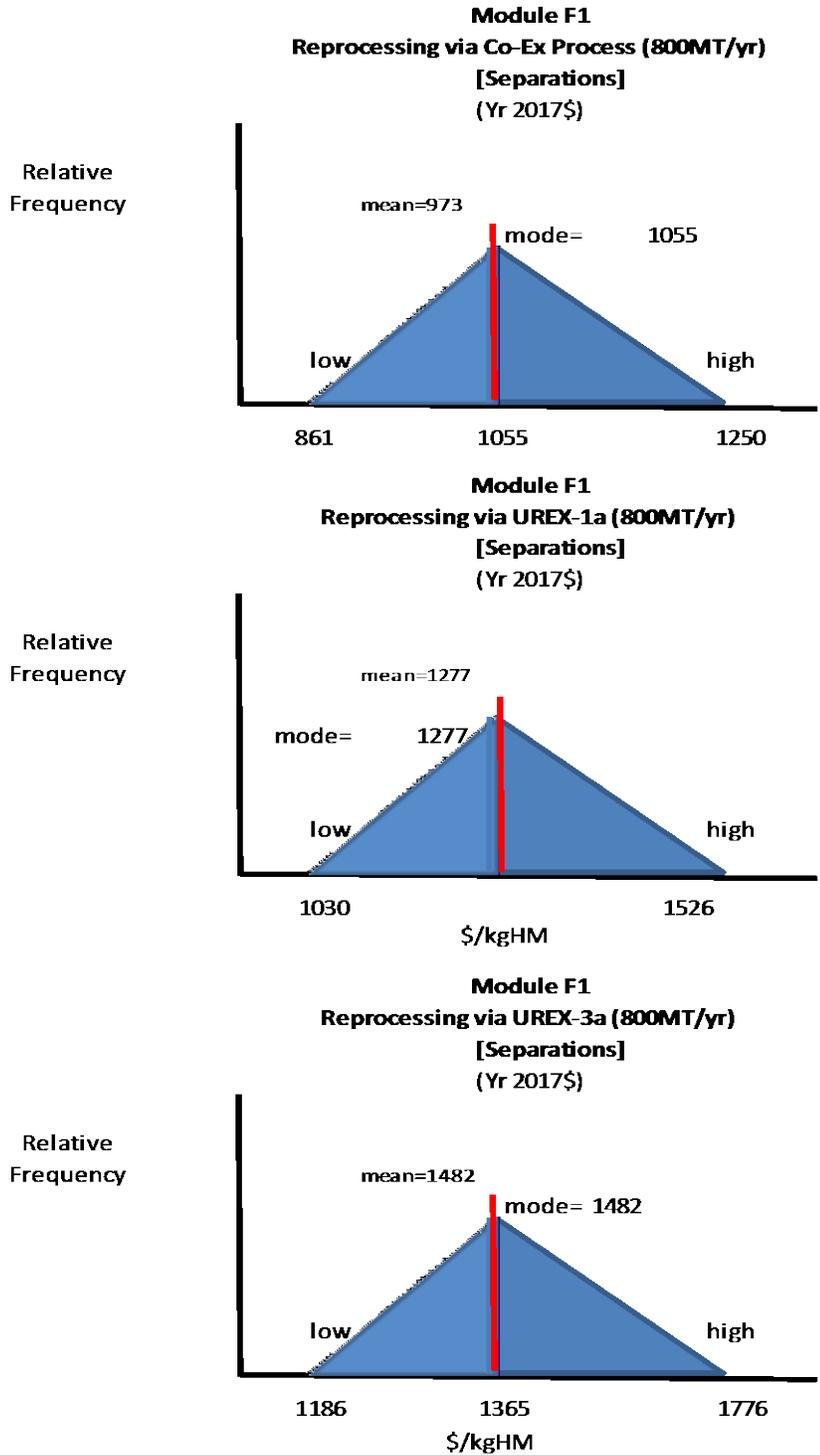


Figure F1-7. Aqueous **separations** estimated cost frequency distributions for three processes.

The extensive analyses, in Appendix J of the 1996 NAS report (NAS 1996), warn that cost experience with existing facilities, rather than estimates for new facilities, should be the basis for realistic estimates. It also warns that only government financing (in the U.S.) will keep the costs low enough to be competitive with the once-through fuel cycle. The 1996 NAS report suggests that aqueous reprocessing of

UOX fuel will cost well over \$1,000/kgHM and that reprocessing of light-water reactor or fast reactor MOX fuel will cost even more because of the more complex flowsheets. If costs for Rokkasho-mura were recovered in the manner of a private facility in the U.S., over \$2,000/kgHM would be required.

The unit costs for all required modules are combined in Table F1-4. These costs do not include MOX fuel fabrication or extended waste storage for decay, but do include the cost for all product and waste processing to a final form and buffer storage. (See Modules G1, G3, G5, K2 and E3 for additional details.) The total cost of reprocessing is similar to the values in the National Academy of Science study (NAS 1996) with more complex processing adding additional cost. Figure F1-8 shows the probability distributions for these total reprocessing costs

Table F1-4. Total reprocessing, waste conditioning, and storage unit costs.

<b>What-It-Takes (WIT) Table: 2009 AFC-CBD values + Escalation to Year 2017\$</b>				
Reference Cost(s) Based on Reference Capacity	Low Cost	Mode Cost	Mean Cost	High Cost
Co-Ex 800 MT/yr	\$1,108/kg HM	\$1,370/kg HM		\$1,619/kg HM
<b>Esc to 2017\$&gt;&gt;</b>	<b>\$1263/kgHM</b>	<b>\$1562/kgHM</b>	<b>\$1557/kgHM</b>	<b>\$1846/kgHM</b>
UREX+1a 800 MT/yr	\$1,494/kg HM	\$1,850/kg HM		\$2,214/kg HM
<b>Esc to 2017\$&gt;&gt;</b>	<b>\$1703/kgHM1</b>	<b>\$2109/kgHM</b>	<b>\$21125/kgHM</b>	<b>\$2523/kgHM</b>
UREX +3a 800 MT/yr	\$1,670/kg HM	\$2,080/kg HM		\$2,488/kg HM
<b>Esc to 2017\$&gt;&gt;</b>	<b>\$1904/kgHM</b>	<b>\$2371/kgHM</b>	<b>\$2371/kgHM</b>	<b>\$2836/kgHM</b>

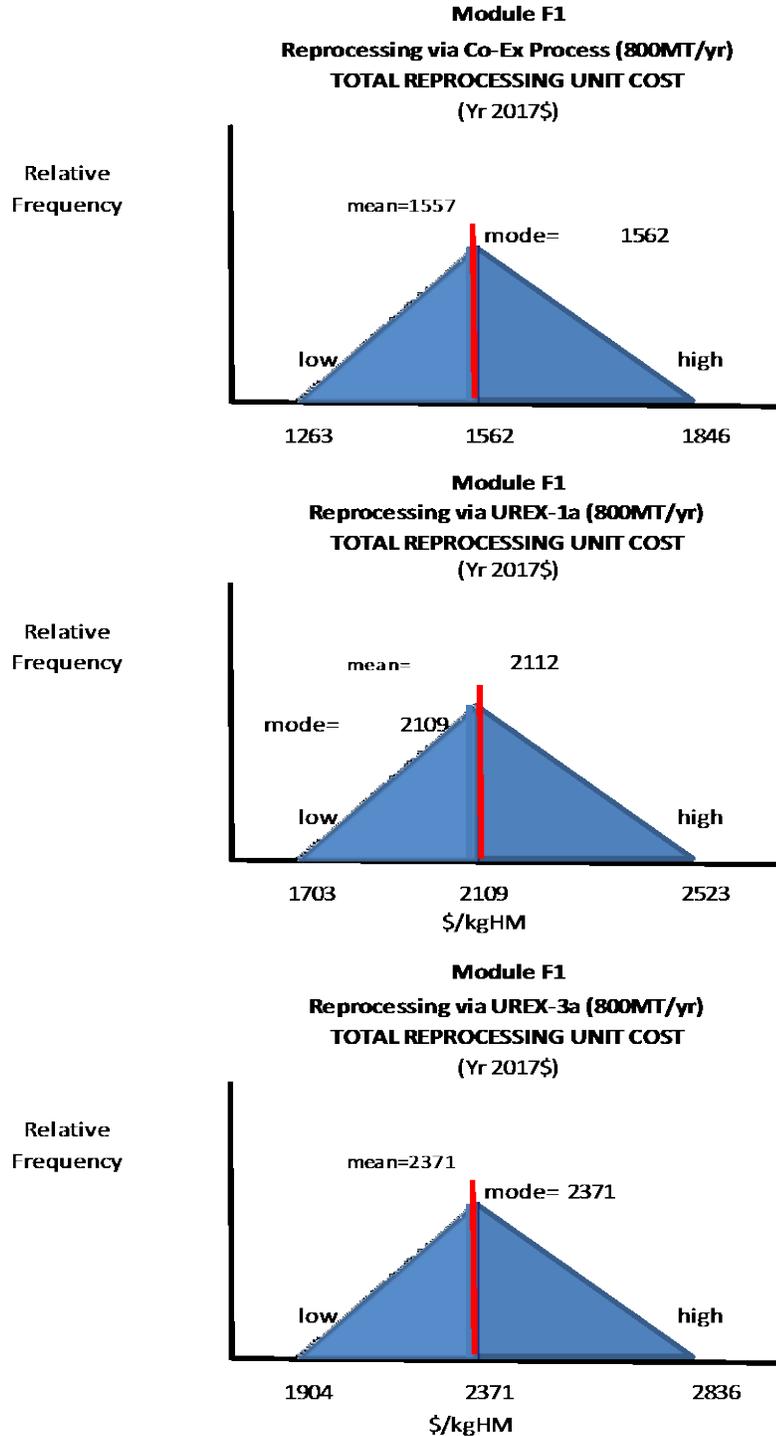


Figure F1-8. **Total reprocessing** estimated cost frequency distributions for three processes.

In May of 2007 Areva and Societa Gestione Impianti Nuclear Spa (Sogin) signed a contract for reprocessing 235MT of used fuel from shutdown Italian nuclear power plants (World Nuclear News, 2007). The contract value was reported as \$340million or \$1445/kg of heavy metal. The contract includes transportation, reprocessing, and packaging of used nuclear fuel. The vitrified waste will be returned to

Italy. The contract price is within the established range of the Co-Ex reprocessing cost in Table F1-4 and only slightly higher than the nominal cost recommended. This difference is likely the cost of transportation which is not included in the combined cost in Table F1-4. The report confirms Table F1-4 as reasonable estimates for aqueous reprocessing.

### **F1-8.1 SPECIAL NOTE ON THE REPROCESSING OF THORIUM-CONTAINING FUELS**

It was not possible to identify recent documents or references containing cost data for the aqueous reprocessing of thorium-containing fuels, nor detailed cost studies. However, based on discussion with the National Technical Director of the Fuel Cycle Technology’s Separation Campaign, it was possible to obtain the following information. As compared to the aqueous reprocessing of uranium-based fuels, thorium-based fuel is harder to dissolve, requiring the use of the hydrofluoric acid, and resulting in larger waste quantities. Both of these would increase the costs. Also, because of the use of the hydrofluoric acid, the dissolver (and possibly other components) would need to be fabricated from more expensive alloys, such as hastelloy. Further increasing the process equipment cost, components would have to be larger for the same heavy metal throughput, because of the slower dissolution rate. It is therefore clear that the cost of reprocessing thorium fuels is expected to be higher than the cost of reprocessing uranium fuel; however, quantifying the incremental cost with any degree of precision is not possible without a detailed study. **The expert opinion is that a cost increment of 5% to 10% would be a reasonable estimate.**

**What it takes.**

It is therefore suggested the range for the cost of aqueous reprocessing of thorium based fuels, where the low values are increased by 5% as compared to the values of Table F1-3, the high values are increased by 10% and the nominal values are also increased by 10%. The results are shown below in Table F1-5. Figure F1-9 shows the aqueous reprocessing separations cost distributions for the three processes above treating thorium-based fuels.

Table F1-5. Reprocessing (aqueous separations) unit cost for Thorium-containing oxide fuels (2009 AFC-CBD values plus escalation to year 2017\$).

Process and Plant Capacity	Low (\$/kgHM)	Mode (\$/kgHM)	Mean (\$/kgHM)	High (\$/kgHM)
Co-Ex 800 MT/y	793	1018		1206
<b>Escalated 2017\$ &gt;&gt;</b>	<b>904</b>	<b>1161</b>	<b>1147</b>	<b>1375</b>
UREX+1a 800 MT/y	948	1232		1473
<b>Escalated 2017\$ &gt;&gt;</b>	<b>1080</b>	<b>1405</b>	<b>1388</b>	<b>1680</b>
UREX +3a 800 MT/y	1092	1430		1714
<b>Escalated 2017\$ &gt;&gt;</b>	<b>1245</b>	<b>1630</b>	<b>1610</b>	<b>1954</b>

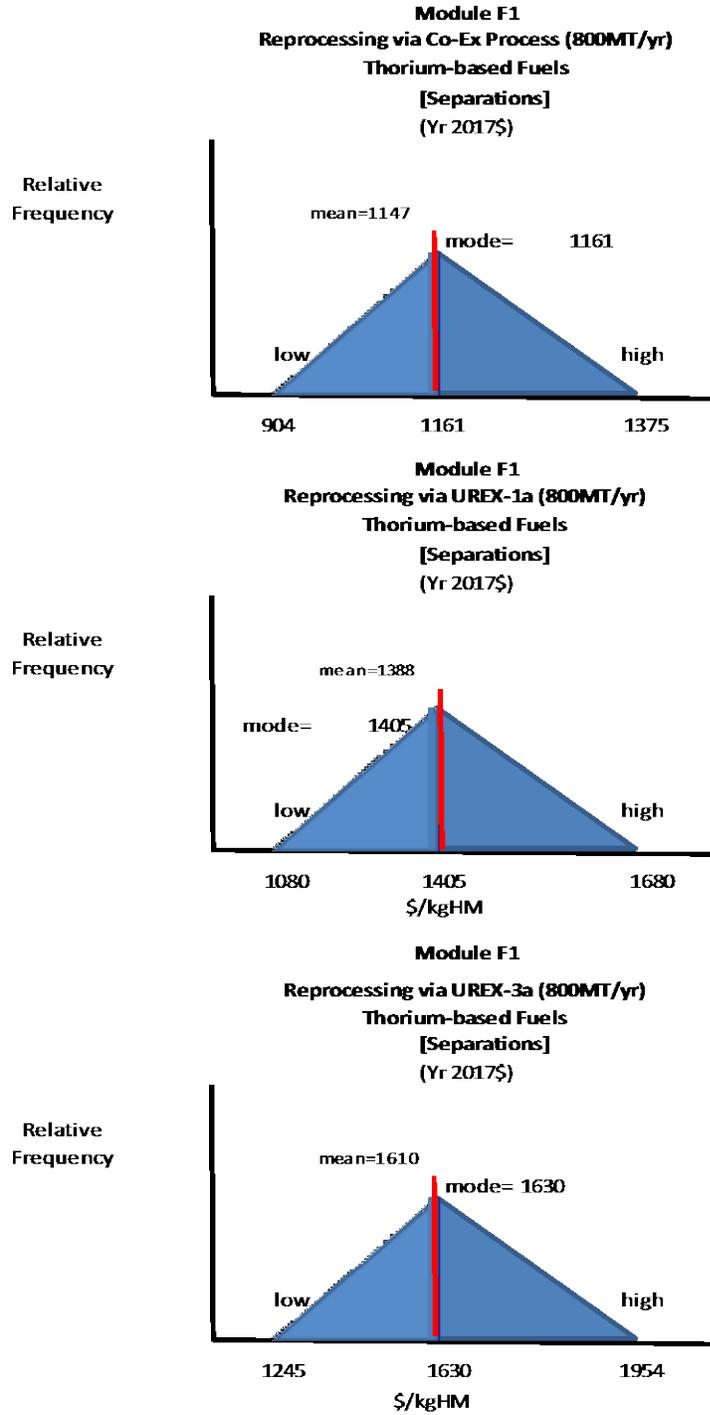


Fig F1-9. Aqueous **separations** estimated cost frequency distributions for three processes.

The costs including all products and waste processing to a final form or buffer storage are shown in Table F1-6, where the costs are also increased by 5% (low value) and 10% (high and nominal values), based on the fact that Th-fuel reprocessing likely will produce a larger amount of wastes.

Table F1-6. Total reprocessing: separations, waste conditioning and storage unit costs of aqueously processed thorium-containing fuels (2012 AFC-CBD values plus escalation from year 2009\$ to year 2017\$).

	Low (\$/kgHM)	Mode (\$/kgHM)	Mean (\$/kgHM)	High (\$/kgHM)
Co-Ex 800 MT/y (2009\$)	1163	1507		1781
<b>Escalated 2017\$ &gt;&gt;</b>	<b>1326</b>	<b>1718</b>	<b>1691</b>	<b>2030</b>
UREX+1a 800 MT/y	1569	2035		2435
<b>Escalated 2017\$ &gt;&gt;</b>	<b>1789</b>	<b>2320</b>	<b>2295</b>	<b>2776</b>
UREX +3a 800 MT/y	1754	2288		2737
<b>Escalated 2017\$ &gt;&gt;</b>	<b>2000</b>	<b>2608</b>	<b>2583</b>	<b>3142</b>

Figure F1-10 shows the total reprocessing related cost distributions for the three processes above treating thorium-based fuels, including waste conditioning and storage.



It should be noted that on-line reprocessing has been suggested for Th-232/U-233 fuel cycles utilizing liquid-fueled molten salt reactors (MSRs). Such a reprocessing scheme has been discussed in Module R7.

## **F1-9. SENSITIVITY AND UNCERTAINTY ANALYSIS**

A sensitivity analysis was provided in previous releases of this report based on the SFTF cost data. Since more current and detailed information is now being used in this module, this earlier analysis is no longer provided.

## F1-10. REFERENCES

- AREVA, 2004, Press release, “EDF and AREVA Sign a Contract for Managing EDF Used Nuclear Fuel,” August 24, 2004.
- Bastin, C., 2000, *Global Foundation*, 22 *Int. Energy Forum*, Nov 5–6, 1999, ed. B. Kurosumnoaeglu, S. Mint and A. Permuter, Pub. Springer, 2000.
- BCG, 2006, “Economic Assessment of Used Nuclear Fuel Management in the United States,” Prepared by Boston Consulting Group for AREVA, July 2006.
- Benedict, M., T. Pigford, H. Levi, 1981, *Nuclear Chemical Engineering*, 2<sup>nd</sup> Ed, McGraw-Hill, pp. 491–501, 1981.
- British Nuclear Fuels Limited (BNFL), 1993, “The Economic and Commercial Justification for THORP,” Risley, UK, BNFL, p. 22, 1993.
- Bunn M., S. Fetter, J. P. Holdren, and B. van der Zwaan, 2003, “The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel,” Harvard University, DE-FG26-99FT4028, p. 29, December 2003.
- DOE, 1996, “Plutonium Recovery from Spent Fuel Reprocessing by Nuclear Fuel Services at West Valley, New York from 1966 to 1972,” U.S. Department of Energy, February 1996.
- DOE (2016), John Makepeace, “Cost Estimating Guide”, DOE G 430.1-1, February 22, 2016.
- DuPont de Nemours, 1979, “3,000 t/a Reprocessing and Fabrication Plant,” *Nuclear Technology*, Vol/Issue: 43:2, 1979.
- EEDB, (1988), “Nuclear Energy Cost Database - A reference data base for nuclear and coal fired power plant power generation cost analysis”, September 1988, DOE/NE-0095
- ENR, 2009, “Defense and General Construction Escalation Indices based on an average of the Engineering News Record Construction Cost Index and Building Cost Index,” <http://enr.construction.com/features/coneco/subs/recentindexes.asp>, Web page accessed August 17, 2009.
- Exxon Nuclear Company, 1976, “Nuclear Fuel Recovery and Recycling Center Preliminary Safety Analysis Report,” XN-FR-32, U.S. Nuclear Regulatory Commission, Docket No. 50-564 (filed June 1976).
- Ganda, (2014). Ganda, F., Schneider, E., Williams, K., Kim, T.K., Taiwo, T.A., “Identification and analyses of fuel cycle economic issues,” Fuel Cycle Research and Development, US Department of Energy Fuel Cycle Options Campaign, FCRD-FCO-2014-000402, 2014.
- Gingold, J. E., R. W. Kupp, D. Schaeffer, and R. L. Klein, 1991, “The cost of reprocessing irradiated fuel from light water reactors: an independent assessment,” (S. M. Stoller), EPRI Report NP-7264, Palo Alto, California, Electric Power Research Institute.
- Haire M. J., 2003, “Nuclear Fuel Reprocessing Costs,” American Nuclear Society Topical Meeting on Advances in Nuclear Fuel Management III, Hilton Head Island, South Carolina. October 5–8, 2003.
- INEEL, 1969, Conceptual design and capital cost estimate for High-Temperature Gas-Cooled Reactor (HTGR) Reference Fuel Reprocessing Plant, INEEL Report No. IN-1451, prepared for Idaho Nuclear Corporation by Bechtel, August 1969.
- Laidler, J. J., 2003, “AFCI Separations Overview,” PowerPoint presentation, AFCI Semiannual Review, Santa Fe, New Mexico, August 2003. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)

- Marshall, W., ed. "Nuclear Power Technology," 1983, Volume 2, Fuel Cycle, Edited W. Marshall, Clarendon Press, Oxford, 1983.
- Meckoni, V., R. J. Catlin, L. L. Bennett, 1977, "Regional Nuclear Fuel Cycle Centres," IAEA Study Project, International Atomic Energy Agency, Vienna, Salzburg, International Conference on Nuclear Power and its Fuel Cycle, 1977.
- NAS 1996, "Nuclear Wastes—Technologies for Separations and Transmutation," Committee of Separations Technology and Transmutation Systems, National Research Council, Washington D.C., 1996.
- NTI, 2009, "RT-1 Spent Fuel Reprocessing Facility," <http://www.nti.org/db/nisprofs/russia/fissmat/pumayak/spentfue.htm>, Web page accessed August 17, 2009.
- OECD-NEA 1994; Nuclear Energy Agency, 1994, The Economics of the Nuclear Fuel Cycle, Appendix 3, "Reprocessing Option Cost Estimates and Future Trends, Nuclear Energy Agency Organization for Economic Cooperation and Development, Paris, France, 1994.
- Ritter, G. L., 1979, Nuclear Technology, Vol./Issue: 43:2, April 1979.
- Salerno L. N., M. L. Thompson, B. A. Hutchins, and C. Braun, 1989, "ALMR Fuel Cycle Economics," Paper presented at the small and medium reactors seminar, San Diego, California, August 1989.
- Spencer, B. B., D. D. Guillermo, E. D. Collins, 2003, "Effect of Scale on Capital Costs of Nuclear Fuel Reprocessing," American Nuclear Society Winter Meeting, November, 2003.
- Vandegrift, George F., Monica C. Regalbuto, et al., 2004, Argonne National Laboratory, LAB-SCALE Demonstration of the UREX+ process, WM'04 Conference, Tucson, Arizona February 29–March 4, 2004.
- Washington Group International (WGI), 2004, "Spent Fuel Treatment Facility Scoping Study," Job No. 26861 004, Washington Group International under contract to Bechtel BWXT, Idaho, LLC, Contract #17157, SOW-1113, Rev. 2, Denver, Colorado, January 29, 2004. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- Washington Savannah River Company, 2007, "Engineering Alternative Studies for Separations Summary Report," EAS-G-ESR-G-00049, June 2007. (This document has a restricted distribution, may be proprietary, or both: and is not publicly releasable.)
- Washington Savannah River Company, 2008a, "Follow-on Engineering Alternative Studies Summary Report," GNEP-CFTC-PMO-MI-DV-2008-00087, March 2008. (This document has a restricted distribution, may be proprietary, or both: and is not publicly releasable.)
- Washington Savannah River Company, 2008b, "CFTC Cost and Schedule Review Summary Report," CFTC-RPT-00001, November 2008. (This document has a restricted distribution, may be proprietary, or both: and is not publicly releasable.)
- World Nuclear News, 2007, "Areva and Sogin sign reprocessing contract" at <http://www.world-nuclear-news.org/newsarticle.aspx?id=13372>, web page accessed May 8, 2012, article dated May 9, 2007.



**Combined Module F2/D2-1**

**Electrochemical Reprocessing and  
Remote Fuel Fabrication**



# Module F2/D2-1

## Electrochemical Reprocessing and Remote Fuel Fabrication

### F2/D2-1-MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Significant revisions based on new analysis and new data.
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:** Preconceptual design report based on bottom-up estimating (Landmark Study 2015).

### F2/D2-1-RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module R2. In later AFC-CBRs the Module was renamed D2/R2 to recognize the fact that separated reprocessing (R2) and fuel refabrication (D2) information was not available.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2017.
- **New technical/cost data which has recently become available and will benefit next revision:** Research on pyrochemical/electrochemical methods of fuel reprocessing and refabrication continues in the US, Russia, and South Korea. New reports and technical papers may become available.

### F2/D2-1-1. BASIC INFORMATION

This module discusses electrochemical reprocessing of spent nuclear fuel, and remote fuel fabrication with recycled material.

Since remote fuel fabrication is an integral part of the overall recycle system, it is generally envisioned to be housed in the same facility as the reprocessing step. Therefore, the associated remote fuel refabrication step is also included in this module. The technical reasons for such integration are considered in the module. Additionally, while the need for remote fabrication can arise also after aqueous reprocessing, no cost studies were found for remote fabrication only, while few cost studies have been performed on (a) electrochemical reprocessing and (b) on electrochemical reprocessing with integrated remote fabrication. Unfortunately, it was not possible at this point to deduce, by comparison of those costs, the cost of remote fabrication alone, for reasons that will be explained in the module. Therefore, the following approach will be proposed: a best estimate of costs, based on existing studies, will be derived for integral electrochemical reprocessing/remote refabrication (IRRF), and the simple difference between the cost of IRRF and that of UREX+1a, discussed in module F1, will be suggested as the cost of remote fabrication. This approach is obviously imprecise, and likely to understate the cost of remote fabrication only, since synergies between reprocessing and refabrication will be present that lower the cost of the combined step, as compared to each of the two processes alone. The main reason is that in the integrated plants, process operations generally occur in one or two remotely-operated hot cells, making it impossible to delineate processing operations and cost from those of fabrication. These estimates should be updated in the future, if detailed studies on the cost of remote fabrication alone will be produced.

## F2/D2-1-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

### Reprocessing Step.

Sometimes the variants of this generic step are called pyrochemical, pyroprocessing, pyrometallurgical, pyrolytic, or molten salt methods. In this document, the term electrochemical is used to encompass all of these terms. Their distinguishing characteristic is that they do not employ aqueous solution chemistry; therefore, they fall into the class of what are called “dry” processes. All processes of this type involve molten salt chemistry at elevated temperatures. While this type of process has never been applied on a commercial scale, it has been demonstrated for research reactor fuel.

In early research, spent nuclear fuel (oxide and carbide) was treated in gaseous reducing and oxidizing environments. The resulting chemical and physical changes in the fuel structure breaks it down to release many of the fission products. Remaining material was subjected to a final reduction step to create the necessary composition for use in recycled fuel. Neither of these gaseous electrochemical processes (sometimes called “volatility” processes) was applied on a large scale, and no production facility was built. A good history on such processes was prepared by Benedict, Pigford, and Levi (1981). Note that electrochemical processes were seriously considered in the UK for the reprocessing of magnox and AGR fuels.

More recent references to electrochemical processing relate to molten salt electrolytic treatment of fast reactor metal and oxide fuels, such as that developed at Argonne National Laboratory (ANL).<sup>1</sup> Fuel is separated electrochemically into waste and product streams via a molten salt electrolyte. Various types of separation are possible, depending on the fuel cycle needs and potential for chemical separations. Interim storage, waste stabilization, and recycle fuel refabrication may also occur in the same plant, and for nonproliferation, radiation safety, and cost minimization purposes, such consolidated operations are the recommended deployment path. This process has been successfully demonstrated on a small scale through treatment of the sodium-bonded metal fuel from Experimental Breeder Reactor-II (EBR-II). Future research and design efforts at the Materials and Fuels Complex (MFC) will eventually result in a pre-conceptual design and preliminary costing for a molten salt electrochemical processing facility to treat current commercial spent nuclear fuel. At an electrochemical processing facility, spent nuclear fuel would be received, unloaded, and temporarily stored until treatment (see sample flow sheet in Figure F2/D2-1). The general treatment involves spent fuel element disassembly and/or shearing followed by steps in preparation for electro-refining. Metal fuel, such as that which is processed at MFC, is chopped into small segments before immersion in LiCl-KCl salt within an electro-refiner vessel. In order to be compatible with electro-refining, spent oxide fuel would first undergo chemical or direct electrolytic reduction to the metallic form.

Uranium, fission products, transuranics (TRU), and unreactive metals can be separated from each other in the electrorefiner. In a separate process, the uranium may be removed from the electrorefiner and processed into a metal product to be stored as waste (likely to be Greater-Than-Class-C) or recycled into new fast reactor fuel (see Module K-3 for a detailed description of these options). Unreactive metals, including cladding and fuel components, may be removed from the electrorefiner and processed with other waste metals for creation of a metal, high-level waste form. Cleanup (refining) of this metal is another option that prevents the need to deal with high-level waste. Fission products, which largely remain in the electrorefiner and are dissolved in the salt electrolyte solution, may be extracted from the salt and immobilized in a ceramic high-level waste form. Short-term (in terms of geologic time) storage (many decades) of the ceramic high-level waste form would allow for decay of fission products cesium and strontium, which are heat-load concerns for a geologic repository. The salt can then be recycled for reuse

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1. Beginning February 1, 2005, the name of the Idaho National Engineering and Environmental Laboratory (INEEL) was changed to Idaho National Laboratory (INL). Argonne National Laboratory-West was renamed the Materials and Fuels Complex (MFC).

in the electrorefiner. Transuranics may be treated as a high-level waste, sent for decay storage, or returned to a reactor in the form of refabricated fuel. The nature of this treatment is dependent on the chemical and radioactive characteristics of the specific transuranic mix and the type of reactors available for fuel recycle (fast versus thermal).

**The Fuel Fabrication or Refabrication Step.**

As defined in the introduction to Module D1, fuel fabrication represents the set of chemical, ceramic/metallurgical, and mechanical steps that take a basic chemical form of the fissile material and convert it to finished fuel assemblies and associated hardware ready for insertion into the reactor. In F2/D2, however, the fissile material is assumed to arise from back-end fuel cycle steps (i.e., reprocessing or transmutation/separation: Modules F1 or F2/D2) and to require remote fabrication, due to the high radiotoxicity and radioactivity of the fuel, that prevents glove-box handling rather than from front-end fuel cycle steps such as mining, conversion, and enrichment (Modules A, B, and C).

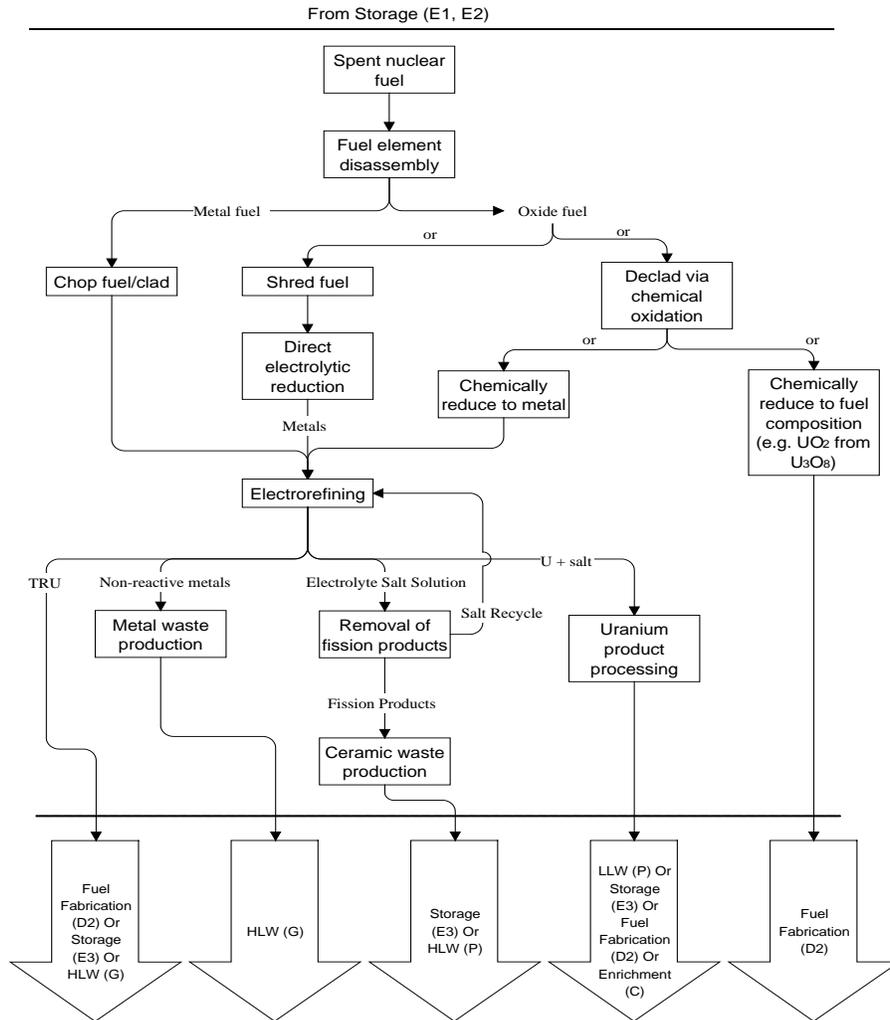


Figure F2/D2-1. Example of electrochemical processing flow sheet for spent nuclear fuel. (Note: HLW metal waste might be diluted with DU to form Class C low-level waste or might be re-refined.)

In general, the fuel refabrication step is generally envisioned as very likely to be totally integral to the reprocessing technology. The nature of these fuel fabrication operations and the associated facility is affected by the following factors:

1. If a fuel comes from front-end fuel cycle steps or has its uranium and/or plutonium separated out in a PUREX or Co-Ex-type aqueous reprocessing step, it is likely to have such low radioactivity that it can be handled in glove boxes. Low-enriched uranium (LEU) and thermal and fast mixed oxide (Pu, U, Np mixed oxide [MOX]) fuel fall in this category and are described in the Module D1 series. Fuels that are refabricated from reprocessing steps can contain grouped higher actinides, including Cm (curium) and Am (americium), or even some fission products, which are recycled into a reactor for destruction. Such grouped actinides and some fission products can originate from an aqueous spent LWR fuel reprocessing scheme such as uranium extraction (UREX) 1a from which highly radioactive mixed actinide oxide powder would be a product. (Such fuel cycles can have nonproliferation advantages because no weapons-useable fissile materials, such as plutonium, are separated out, and the refabricated fuel rods are self-protecting from theft or tampering because of their high radiation fields.) Any stand-alone fuel fabrication plant that fabricates such higher actinide-laden (or fission product-laden) material, whether derived from spent light-water reactor (LWR) or fast-reactor fuel, into drivers or targets for either reactor type will need to incorporate a remote-handling process in a very robust building. Since the building radiation safety and security requirements for such a remote-handling fabrication facility are much like a reprocessing plant, economics drives one to integrate fabrication and reprocessing into one building. These types of fuels, when used in tandem with fast reactor (FR) systems, also allow for destruction of selected long-lived fission products by transmutation and long-lived actinides by transmutation or fission. Because of the high gamma/neutron-radiation fields associated with the fuel material, the refabrication process must be contained in a highly shielded hot cell and is generally highly automated while, at the same time, being simple enough for cost-effective robotics to be used.
2. The regulatory and quality assurance requirements for such refabricated fuel are not yet available in the form of a fuel specification, such as that available for enriched UO<sub>2</sub> and LWR-MOX fuel. Considerable research and development (R&D) and fuel qualification demonstration will be needed before these types of fuels reach this stage, but the reasons for quality assurance remain the same (i.e., fuel reliability, meaning prevention of fission-product) and actinide releases from the fuel form.
3. The fuel form must be capable of safe transport and storage both before and after each irradiation cycle. The integrity of the cladding or fuel matrix must be maintained at all times. If the reprocessing and refabrication facility is collocated with the reactors, such as in a multireactor park, transport concerns are obviated or minimized.

Some reactors and fuel cycles will have fuel components in the reactor simultaneously, some of which are contact-handled (Module D-1) such as driver fuel or blankets, and some of which are remote-handled (this Module F2/D2) such as grouped-actinide driver fuel or targets for long-lived radionuclide destruction. This will depend on whether the reactor core or a given fuel assembly is homogeneous or heterogeneous. A heterogeneous-core fast reactor, which burns actinides and also breeds some new plutonium, may have depleted-uranium blankets. The blankets can be produced in a relatively inexpensive contact-handling facility. A driver fuel, which contains significant amounts of recycled higher actinides and makeup uranium and/or plutonium, must be produced in an expensive remote-handling facility. There is even the option of putting all the minor actinides (Am and Cm) and long-lived fission products in separate rods called "targets." Fabrication of these highly radioactive rods would require a robust remote-handling facility. A homogeneous core for a "burner" fast reactor would have the driver fissile material (recycled and make-up) and higher actinides together in the same fuel rods, and would not include blanket fuel, since the intent is to destroy actinides (burn) and not to produce new ones (breed).

It can be seen that the fuel type (D Modules) and reprocessing scheme (F Modules) are intimately linked. Definition of the fueling scheme for the reactor will determine which components must be separated in the reprocessing plant and sent to the appropriate refabrication facilities or processed in integral refabrication facilities. Even thermal reactors can be configured to burn minor actinides by use of specially fabricated target rods that are interspersed among the more conventional UOX and/or U, Pu MOX rods in a given LWR fuel assembly. Unlike the UOX and U Pu MOX rods, the target rods would require remote refabrication, unless the concentrations of Am, Cm, and carried over fission products are very low.

**Fuel Form.** The fuel form most commonly envisioned today consists of thin, cylindrical, cast rods consisting of a uranium and plutonium (with some minor actinides and trace fission products) metal alloyed with a metal such as zirconium. The fuel material originates most likely from an electrochemical reprocessing scheme with the possible addition of some makeup plutonium (with possible other actinides) from storage and/or makeup uranium. These thin rods are then clad in stainless steel and inserted into a fast-reactor fuel assembly, which appears from the outside much like the fast-reactor oxide pellet (Module D1-4) or vibropacked (VIPAC; Module D1-5) fuel assembly. This is the fuel type envisioned for liquid metal reactor concepts such as the GE Super-Power Reactor Inherently Safe Module (S-PRISM) and the ANL Fast Burner Reactors. The metal-fuel fast reactor option is the best known in the U.S., since it is supported by GE in the PRISM reactor program. By adding steps at each end, oxide fuels can also be accommodated by pyrochemistry; and considerable R&D has been performed for the electrochemically compatible oxide fuel type in Russia. It also turns out that VIPAC fuels fit in well with electrochemical reprocessing schemes, since the powder morphology required for VIPAC fuel is well-accommodated by electrolytic electrochemical processing steps. For purposes of unit costing, it is very difficult to separate the reprocessing from the refabrication steps. Ceramic remote-handled fuel (such as [U, Pu, MA] oxide) feed materials could originate from either an integral electrochemical or stand-alone aqueous reprocessing scheme. UREX 1-a is an example of the latter. (Note: a ceramic fuel refabrication plant could be located within the same building as an aqueous reprocessing plant; however, the two processes are not “integral” in the same process-chemistry sense as pyroprocessing and pyro-refabrication.)

**Status of the Industry.** Reprocessing and production of remote-handled metal fast reactor fuels is not yet done on an industrial scale; however, a large central plant may not be needed. Proponents suggest that it will be best to keep this operation on a small scale, where refabrication is collocated with the electrochemical reprocessing step dedicated only to the onsite reactors. ANL-West successfully demonstrated such technology at their Idaho Integral Fast Reactor facility adjacent to EBR-II. (Nearly all of this work was discontinued in the mid-1990s as a result of policy decisions made by the U.S. government to discourage plutonium recycle and fast reactors in general.) Work on fast reactor fuel cycles continues mainly in Russia, France, India, and Japan. The Generation IV program is also considering the Sodium-cooled Fast Reactor and its fuel cycle as one of the six concepts to be studied. K. Abney et al. (1997), provides a good assessment of the technology status of electrochemical processing and the International Atomic Energy Agency (IAEA) provides a good country-by-country assessment of reprocessing in general, including R&D on electrochemical processing (IAEA 2005).

## F2/D2-1-3. PICTURES AND DIAGRAMS

**Process Diagrams.** For the metal remote-fabricated fuel option, the refabrication and electrochemical spent fuel reprocessing steps are part of one synergistic process (see Figure F2/D2-2).

Figures F2/D2-3 and F2/D2-4 provide a conceptual drawing of a proposed molten salt electrochemical processing facility for treating commercial spent nuclear fuel. This concept is the subject of a pre-conceptual design effort at the INL. Results from this study (Frigo et al. 2003) provide some preliminary cost estimates.

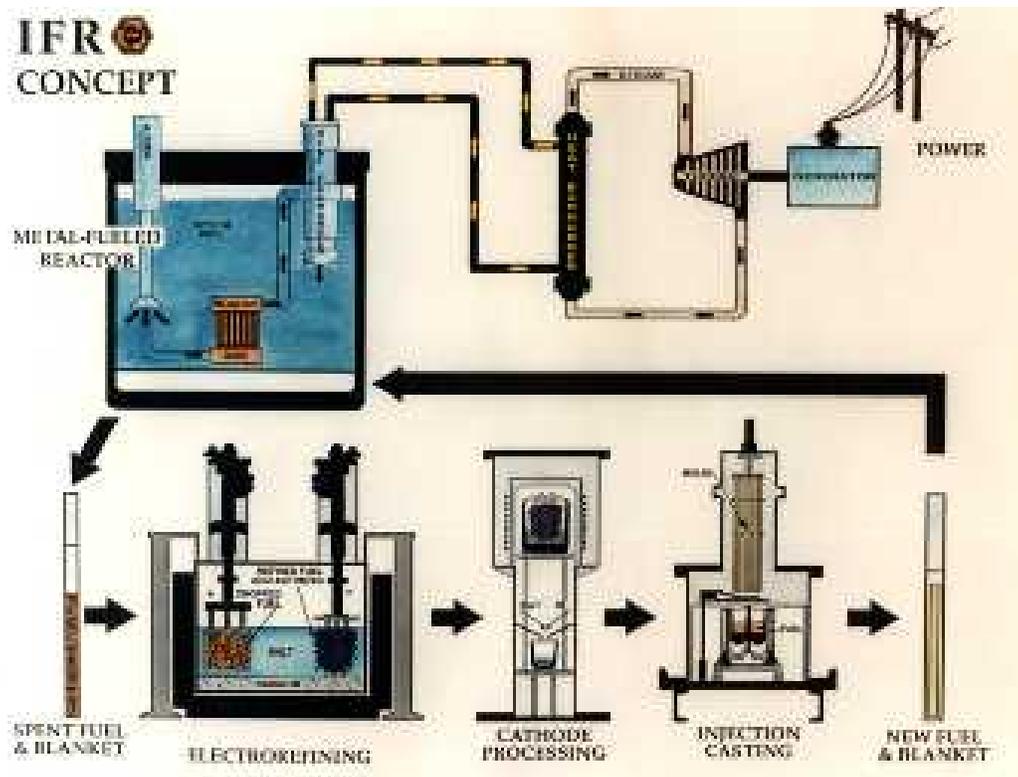


Figure F2/D2-2. ANL Integral Fast Reactor concept showing last three refabrication steps.

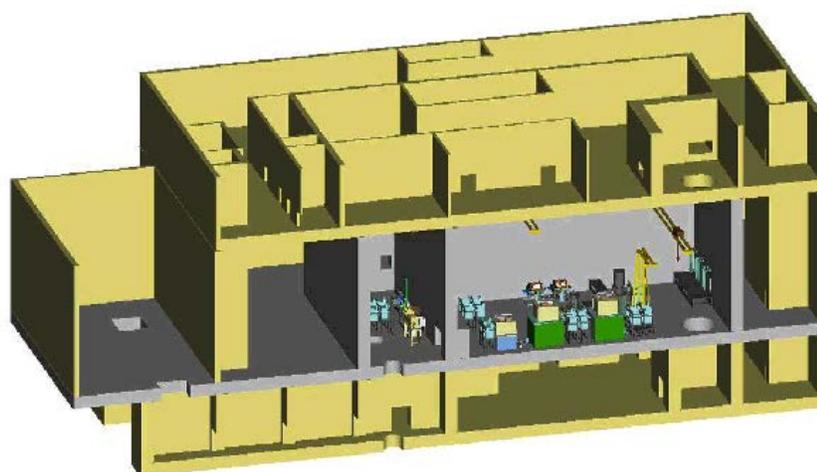


Figure F2/D2-3. Three-dimensional conceptual rendering of the Advanced Pyroprocess Recycle Facility (Frigo et al. 2003).



Figure F2/D2-4. Three-dimensional conceptual rendering of the air and process cells (Frigo et al. 2003).

## F2/D2-1-4. MODULE INTERFACES

This F2/D2 module interfaces with upstream reactor (R1 for irradiated targets in thermal reactors and R2 for irradiated fast-reactor driver fuel and/or targets) and possible upstream makeup actinide storage modules (E modules), and waste disposal modules (Module G). The fast reactor (R2) is also the downstream recipient of the integrated facility's refabricated fuel product. In practice, a small throughput electrochemical processing facility may be immediately collocated with a fast reactor (or multiple small, modular fast reactors) as an integrated recycle function along with the fuel fabrication facility. Alternatively, a higher throughput centralized electrochemical processing facility might be integral to a larger group of fast reactors.

When considering costs for such facilities, care must be taken to differentiate between separation and waste management functions. This must be done to avoid double counting costs for waste management (Module G) that might already be in the integral reprocessing/refabrication facility Module F2/D2 cost breakdown.

**Metal Fuel Considered.** Nearly all the remotely handled fuels addressed in this section will be metal fuels for sodium-cooled fast reactors (such as the PRISM Advanced Liquid Metal Reactor [ALMR]) arising from electrochemical reprocessing. Early fuels are likely to have higher actinides blended with uranium and plutonium and small amounts of carried-over fission products such as lanthanides. Later, fuels may have some fabricated long-life fission product target rods slated for fission product destruction by transmutation. These rods would be produced in the same highly-shielded refabrication facility. Accommodation for the production of fast reactor first cores is also an interface issue, since a separate larger fabrication facility may be required, and the initial fuel may contain fewer actinides.

**Dirty MOX Considered Elsewhere.** The use of thermal or fast-reactor MOX containing plutonium, neptunium, and very small amounts of the highest actinides, Am, and Cm, (sometimes called dirty MOX) is considered in Modules D1-2 and D1-4. It is possible that such MOX fuel could be handled in special shielded gloveboxes designed for maximum personnel protection, however, a full-fledged, hot-cell-type, remote-handling facility will be needed if Am and Cm concentrations are sufficiently high. If higher concentrations of Am and Cm (and/or fission products) require destruction, LWR or FR target rods would definitely have to be fabricated in a remote-fabrication, hot cell environment. This is the type of facility envisioned for LWR-derived, grouped actinide (Pu, Np, Am, Cm) oxides arising from a UREX-1a reprocessing facility.

## F2/D2-1-5. COST BASES, ASSUMPTIONS, AND DATA SOURCES

### Costs of Some Early Electrochemical Processes

The Atomics International Reduction OXidation (AIROX) process was developed for treatment of  $\text{UO}_2$  fuel. Heat is applied in an oxidizing atmosphere to create  $\text{U}_3\text{O}_8$ , which results in breaking open the cladding and pulverizing the fuel due to material volume increase. Chemical reduction by reaction with hydrogen returns the uranium to  $\text{UO}_2$ . Most fission products are removed during a series of these oxidation-reduction reactions, and the final  $\text{UO}_2$  product can be reformed into fuel pellets for recycle. Similarly, the CARBothermic-reduction OXidation (CARBOX) process was developed for UC fuel. Again, a series of oxidation and reduction reactions are performed, resulting in lower fission product concentrations. Costing for these two pioneer electrochemical processes was estimated in 1963 and 1965 government reports (Colby, et al. 1963, 1965). Given the age of the estimates and the significant changes in technology and regulation, not to mention cost escalation during the intervening 40 years, values given in the reports are not considered useful for the purpose of AFCI system studies.

### ANL-GE Estimates from 1985-1993

Additional electrochemical processing facility cost estimates are based on the fundamental technology developed at ANL. A detailed conceptual design study was performed for a commercial-scale electrochemical processing facility to serve a collocated 1,400 MWe fast breeder reactor. Annual processing of at least 25% of the full core metal fuel (reload minimum of 20 MTHM/yr) is necessary for reactor refueling. Recycled fuel is also fabricated in this facility. One-year decay storage of the fuel was assumed, and reactor plant services were shared. Bottom-up cost estimates for this facility are provided in a 1985 publication by ANL (Lineberry et al. 1985). While the estimate was performed by a government entity and based on government experience, no assumption was made on whether government or private funding/operation of the proposed facility is assumed.

Based on the ANL technology, GE's ALMR more recently prepared a conceptual design and conducted a cost study for a more advanced electrochemical processing facility (Delene et al. 1993; Taylor et al. 1991; ORNL 1992). This is a bottom-up cost estimate assuming private/utility ownership and operation, a 200-MTHM/yr spent metal-fuel treatment, recycle fuel production, and a 15-month fuel cycle time. A report by the National Academy of Sciences uses this conceptual design and cost study in a 1996 economic assessment of fuel reprocessing technologies (NAS 1996).

Table F2/D2-1 shows the projected capital and life-cycle costs for both a central facility and collocated (at reactor) fuel recycle facility. The highlighted numbers come from a conceptual design report prepared by Oak Ridge National Laboratory (ORNL) in 1981 and 1991 GE assessment data (Jones 1981; Taylor et al. 1991). The other plant life, discount rate, etc., data were added so that a unit cost of refabricated fuel in \$/kgHM could be calculated.

A later generation ALMR system, the S-PRISM, incorporated a hybrid recycle scheme with facilities that processed oxide and metal fuel in parallel. A bottom-up cost estimate was performed for a 100-MTHM/yr metal fuel recycle facility. The LWR oxide fuel facility was cost estimated with a top-down approach for 1,000-MTHM/yr throughput. These two plants are similar in design and function but significantly differ in heavy metal throughput rates. Cost references for these designs could not be found in the public domain.

Separately, the U.S. Department of Energy (DOE) has a multiyear program to debond and partially reprocess some of the sodium-bonded irradiated EBR-II fuel in the adjacent FCF using electrochemical techniques. A DOE report describes the anticipated cost and schedule for this activity (DOE 2003). A section below will show the calculated unit costs for this activity. Projected costs (DOE 2003) for the ongoing processing of EBR-II driver fuel are \$94,000/kgHM (\$282M to process 3,000 kgHM). Blanket fuel processing will cost \$13,000/kgHM (\$260M for 20,000 kgHM). However, such high costs appear to

be driven primarily by the small mass of fuel to be processed, leading to a very small throughput or to a very short facility lifetime; in either cases a sub-optimal utilization of the facility.

Table F2/D2-1. Unit cost data on two ALMR-Integral Fast Reactor recycle plant concepts: central and collocated. The input parameters in blue are [from (Delene et al. 1993; Taylor et al. 1991; ORNL 1992) and from (Jones 1981) or (Lineberry et al. 1985)] while in black are derived value.

Throughput	200	20	MT/y	
Throughput	200000	20000	kg/y	
Overnight capital cost	5.18E+08	1.05E+08	\$ of 1991	
Time for construction	3	3	years	
Interest during construction	2.36E+07	4.79E+06	\$ of 1991	
Total capital cost	5.42E+08	1.10E+08	\$ of 1991	
Facility lifetime	50	50	years	
Discount rate	3.0%	3.0%		
Lev. factor	0.038617	0.038617		
Annual capital charges	2.09E+07	4.24E+06	\$ of 1991	
<b>Capital unit cost</b>	<b>105</b>	<b>212</b>	<b>\$/kgHM</b>	
Annual O&M cost	1.76E+08	2.78E+07	\$ of 1991	
<b>O&amp;M unit cost</b>	<b>879</b>	<b>1390</b>	<b>\$/kgHM</b>	
<b>TOT unit cost (in 1991 \$)</b>	<b>984</b>	<b>1602</b>	<b>\$/kgHM</b>	
Inflation/escalation from 1991 to 2017 (CPI)	1.82	1.82		
<b>TOT unit cost (in 2017 \$)</b>	<b>1790</b>	<b>2916</b>	<b>\$/kgHM</b>	

### Cost studies from other countries

The French and Japanese nuclear industries have also pursued development of molten salt electrochemical process technology from the ANL basis, but have not published cost estimates on their designs. The Russian institute RIAR at Dimitrovgrad is also active in this area and has linked their vibrocompaction method (Module D1-6) for fast reactor fuel fabrication to electrochemical fuel reprocessing.

### More recent cost studies

Three detailed cost studies, all based on ANL technology, were performed in recent years for pyroprocessing and/or remote fabrication facilities. In chronological order:

1. (WSRC 2008). This study is for a 300 MT/y pyroprocessing facility without refabrication, but including oxide reduction in order to be able to reprocess LWR spent fuel.
2. (Carter 2010). This cost study is for a 21.7 MT/y facility that includes both reprocessing and refabrication.
3. (Landmark 2015). This cost study is for a 100 MT/y pyroprocessing facility with oxide reduction before reprocessing, but no refabrication of the reprocessed fuel.

In the following, each study is analyzed in detail. Each of the study provide the construction costs, (in the form of overnight cost) and occasionally the operation and maintenance costs. In order to generate a unit cost in \$/kgHM however, assumptions must be made on the discount rates and on the facilities expected lifetimes. A common set of assumptions applied here are:

- Facility lifetimes of 50 years: These types of facilities are designed with a high degree of redundancy and reliability, and they could therefore be operated for a long time. However, since no commercial pyroprocessing facility has been constructed thus far, it has not been determined yet how long could the expected lifetime be. Other nuclear facilities, such as reactors, have received licenses for life extension of up to 60 years, and other types of chemical plants, such as

refineries, have been in operations for more than a century. Fifty years was chosen here as representative of a “long lifetime”, until more accurate data becomes available.

- Discount rate of 3%: It was chosen here as representative of a discount rate that would be appropriate for a government project. According to Section 8 of Office of Management and Budget (OMB) Circular A94, which specifies which discount rates should be used for government projects, the treasury borrowing rates (currently about 3%) should be used for discounting if performing “cost-effectiveness analyses”. “Cost effectiveness analysis”, defined in Section 5, bullet b, of OMB Circular A94, could include various types of reprocessing facilities, under the assumption that the objective is to compare alternative ways to achieve the same benefits to society (such as for example a lower waste heat and volume after reprocessing), and it is impractical to consider the dollar value of those benefits.

### **The (WSRC 2008) cost study**

This study on pyroprocessing cost was performed as part of a “follow-on” study of a UREX+1a cost study performed the year before (WSRC 2007). The (WSRC 2008) study includes two “benchmark cases”, (1) an 800 MT/year plant using the UREX+1b solvent extraction process; and (2) a 300 MT/year plant based on electrochemical separations technology. In addition, a series of deployment alternatives to the benchmarks listed above are studied in (WSRC 2008). Because of the large number of alternative scenarios studied in (WSRC 2008), including the pyroprocessing alternative, few bottom-up cost estimates were performed in that work. Instead, “*the cost estimate details from the original EAS (June 2007) were used as a starting point and adjustment factors were then applied to account for changes in facility footprint sizes and process modifications.*” (WSRC 2008). However, the electrochemical process is an exception, for which some bottom-ups estimates were performed, due to the difference in technology and equipment to aqueous separation. In particular, an “engineering analysis” was performed for pyroprocessing to adjust the estimates based only on \$/ft<sup>2</sup>, although the details of the engineering analysis are not provided in (WSRC 2008).

In summary, the pyroprocessing costs developed in (WSRC 2008) appear to be largely based on the previous detailed costs estimates developed in 2007 for an aqueous 3000 MT/y UREX+1a facility (WSRC 2007), the cost of which is discussed extensively in Section F1. A recent re-examination of the original EAS and FOEAS cost estimates (WSRC 2007, 2008), also discussed in Section F1, with more details in (Ganda 2016), concluded that there may be scope for a large reduction in the originally estimated capital costs, based on a comparison of the non-direct costs with the nuclear industry experience in building LWRs, to 52.7% of the capital cost estimates in (WSRC 2007). The same fractional cost reduction is consequently applied to the estimates reported here from (WSRC 2008).

The (WSRC 2008) total construction cost for a 300 MT/y pyroprocessing facility without refabrication, of between \$11.4B and \$16.5B (low and high estimates in 2008-year dollars), was adjusted as discussed above to between \$6.0B and \$8.7B. For a facility lifetime of 50 years and a 3% discount rate, the unit capital cost would therefore be between 770 \$/kgHM and 1120 \$/kgHM. O&M was reported in (WSRC 2008) as between \$270M and \$410M annually, resulting therefore in a unit O&M cost of 900 \$/kgHM to 1370 \$/kgHM. It is noted that these reported annual O&M costs would be therefore between 4.5% and 6.8% of the adjusted capital costs, but a much lower amount (2.4% to 3.6%) of the un-adjusted capital costs, even of the low estimate for capital costs. The un-adjusted range appears low, as compared to a typical range of 4% to 7% annual O&M costs as a fraction of the original construction cost, as reported in (Bunn 2016), based on historical evidence and a number of specific estimates for aqueous reprocessing facilities. It is noted that the adjusted values, instead, fall within the values reported in (Bunn 2016). This gives additional support to the adjustment performed on the capital costs. While (Bunn 2016) does not provide ranges or O&M cost estimates for pyroprocessing facilities, the range applicable to aqueous facilities is used here as the closest approximation available, considering the similar functionality between the two types of facilities.

The total adjusted pyroprocessing cost of this study are therefore between 1670 \$/kgHM (assuming the low of capital and the low of O&M costs) and 2480 \$/kgHM (assuming the high capital and the high O&M costs), approximated as 1700-2500 \$/kgHM.

### **The (Carter 2010) cost study**

The (Carter 2010) study is for an integrated facility performing both electrochemical separation and remote fabrication of the separated material. As for the (WSRC 2008), the cost estimates for this facility is largely based on the previous detailed costs estimates developed in 2007 for an aqueous 3000 MT/y UREX+1a facility (WSRC 2007), the cost of which is discussed extensively in Section F1. Therefore, the same fractional cost reduction applied to the original EAS and FOEAS cost estimates (WSRC 2007, 2008) (and discussed in the F1 section) and to the (WSRC 2008), in the previous subsection, is applied also to the construction costs estimates reported in (Carter 2010).

The un-adjusted total construction cost was found to be between \$2.6B and \$3.8B (low and high estimates) for a 21.7 MT/year facility. After the capital cost adjustment discussed above, the expected construction cost was reduced to between \$1.4B and \$2.0B. Additionally, it was noted in (Carter 2010) that, because of the sub-optimal use of space and equipment, the throughput could be increased to 70 MT/y with little or no additional capital spending “*The capacity can be increased to 70 MT/year within the indicated TPC [Total Project Cost] range.*” (Carter 2010, page 18). Therefore, 70 MT/year is used here as the reference throughput.

Consequently, for a facility lifetime of 50 years and a 3% discount rate, the unit capital cost would be between 750 \$/kgHM and 1100 \$/kgHM. These values are very close to those obtained in (WSRC 2008), at 770 \$/kgHM and 1120 \$/kgHM, for the larger facility of 300 MT/year, without refabrication but with oxide to metal conversion at the front end of the process. The larger facility without refabrication would instead be expected to have a lower construction unit cost because of (1) larger size, with possible economies of scale; and (2) added remote refabrication step. However, a few considerations are provided here in light of this result.

- While the two estimates have been made by the same research groups, the one in 2010 (Carter 2010) has been performed later than the (WSRC 2008). Additionally, the (Carter 2010) was a dedicated cost study, while the (WSRC 2008) was part of a broader set of sensitivity studies and was characterized as “*an initial effort*” (WSRC 2008) to perform a cost estimate for a pyroprocessing facility. Because of this, more conservatism may have been inserted into the earlier estimate, resulting in an effectively larger unit cost. Based on this logic, more weight should be put on the (Carter 2010) estimate than on the FOEAS estimate (WSRC 2008).
- It is also possible that the remote fabrication part of the process may not add substantially to the capital costs, since it would be largely sharing the same expensive, highly shielded and remotely operated processing space as the separation part. This would justify a similar unit cost of the (Carter 2010) and (WSRC 2008) estimates.
- Conversely, it is also possible that the oxide-to-metal reduction step would add similar capital costs as the refabrication part, again justifying a similar unit cost of the (Carter 2010) and (WSRC 2008) estimates.
- Regarding the expected smaller cost due to the larger size of (FOEAS 2008) facility, it is possible that, as discussed above, no substantial economies of scale exist for pyroprocessing facilities (likely due to the batch nature of pyroprocessing, coupled with criticality safety considerations).

O&M costs were not reported in Carter 2010. However, it is possible to estimate approximate values based on the previously described range of 4% to 7% of initial capital costs, from (Bunn 2016). In that case, the annual O&M expenses would be between about \$54M (assuming 4% of the low range of capital cost) and \$140M (assuming 7% of the high range of capital cost), resulting in unit O&M costs of between 770 \$/kgHM and 2000 \$/kgHM.

The total adjusted combined pyroprocessing and refabrication costs of (Carter 2010) can therefore be estimated at between 1525 \$/kgHM (with the low range of capital investment and the low fraction of O&M costs of 4%) and 3083 \$/kgHM (with the high range of capital investment and the high fraction of O&M costs of 7%), approximated as 1500-3100 \$/kgHM. The larger uncertainty range for the (Carter 2010) unit cost reflect the larger uncertainty associated with the fact that O&M costs had not been estimated in the study, and therefore had to be derived from other, only partially related, sources.

### **The (Landmark 2015) cost study**

This is a very recent and detailed bottom-up cost study. Merrick & Company, an architect-engineering firm with experience in heavy industrial construction, was subcontracted to provide construction cost and schedule estimates, based on ANL technology, for the 100 MT/y pyroprocessing facility without refabrication, but with oxide reduction to metal before the processing. The work at both ANL (to provide the facilities design) and at Merrick & Company (to perform the economic evaluation) was sponsored by the Landmark Foundation.

The estimated total construction cost was found to be between \$370M and \$450M with and without contingencies, respectively. Design costs were excluded from those estimates. However, it was noted in (Landmark 2015) that *indirect costs* (called “general condition and construction management” costs in (Landmark 2015)) were added as 10% of direct costs. This amount appears inconsistent with the experience of the nuclear industry for the construction of large facilities such as commercial reactors: therefore, the authors of this module revised the indirect costs upwards to make them consistent with the “Better Experience” in PWR construction (EEDB 1988), from 10% to 60% of direct costs.

Direct costs, on the other hand, were based on detailed calculations of each building and associated equipment, so the authors of this module had no reason to alter them. Also, owner’s costs appear to be excluded from those estimates, so owner’s costs were added as 10% of total costs (i.e. both direct and indirect costs) excluding contingencies.

The average contingency is 15% of the combined direct and indirect costs, with different values based on the uncertainty in the estimated cost: 15% for “standard buildings with equivalent industrial examples”, 20% for “site security systems” and 25% for “processing facilities”, for which there is less construction experience.

After the capital cost adjustment was made, the construction cost including direct costs, indirect costs as 60% of direct costs, owner’s costs and contingencies, was calculated at \$720M. For a facility lifetime of 50 years and a 3% discount rate, the unit capital cost would therefore be 378 \$/kgHM. O&M was reported in (Landmark 2015) as \$51M annually, resulting therefore in a unit O&M cost of 510 \$/kgHM. It is noted that these reported annual O&M costs would be 7.1% of the adjusted capital costs, but a much larger amount (11.3%) of the un-adjusted capital costs. The un-adjusted range appears high, as compared to the typical historical ranges for O&M costs as reported in (Bunn 2016), as discussed above. Also, it is noted that the adjusted values, instead, fall within the typical values as reported in (Bunn 2016), of 4% to 7%. This gives additional support to the adjustments performed here on the capital costs.

The total adjusted unit pyroprocessing cost are therefore 788 \$/kgHM, approximated as 800 \$/kgHM, without an uncertainty range available from the (Landmark 2015) report. This value is substantially lower than the unit cost of the functionally-similar but larger facility analyzed in (FOEAS 2008), and of the facility that includes remote fabrication studied in (Carter 2010). The following considerations are proposed here regarding those cost discrepancies:

- The design of the (Landmark 2015) facility has been optimized to reduce costs (e.g. with a square geometry purposely to save on concrete and rebar as opposed to the typical canyon geometry, with cells that allow access to equipment so that it can be repaired remotely rather than having to be over-engineered for no failure, etc...) and the design has advanced enough that the costs estimates in (Landmark 2015) are actually feasible with an effective design.

- The total unit reprocessing cost of (Landmark 2015) is similar to the lower expected cost of UREX+1a, which performs a similar objective, i.e. separating U+TRU. This would indicate that pyroprocessing may have similar costs to aqueous reprocessing.
- If both the (Landmark 2015) and the (Carter 2010) estimates were accurate, the (WSRC 2008) costs would be too high. In that case the difference between (Carter 2010) and (Landmark 2015) would reflect the cost difference between including or not the refabrication stage, and could therefore be used to estimate the cost of remote fabrication, at between 737 \$/kgHM and 2295 \$/kgHM, approximated as 750 \$/kgHM to 2300 \$/kgHM. Under these assumptions, the remote fabrication cost derived here would be an underestimation of the refabrication costs, since it would not account for the fact that a combined facility would have lower costs than a stand-alone facility, due to the sharing of certain functions and services.

## **F2/D2-1-6. SCALING CONSIDERATIONS**

No direct scaling relations were found in the literature. Also, because electrochemical processing is a batch process, as opposed to continuous or semi-continuous aqueous processing, traditional chemical plant cost-scaling factors may not apply well. A pyro-batch line would consist of the largest demonstrated equipment run in a serial batch mode: based on current technology, batch size is limited by the efficiency of electro-refining at large volumes and by criticality concerns for the post-refining process steps. The number of parallel lines would produce the desired throughput, and any capacity additions to an existing line would likely be accomplished by adding more parallel process lines.

However, studies have been performed for facilities of different sizes performing the same functional steps, i.e. Integrated Reprocessing and Remote Fabrication (IRRF), based on the same underlying technology. In particular, Table F2/D2-1 shows the unit cost for a 20 MT/y and a 200 MT/y IRRF facilities, both based on technology developed at ANL. The scaling exponent for the capital cost for the two facilities can be calculated at about 0.7, close to the value of 0.6 typical of chemical plants. However, important caveats should be considered before using this scaling exponent. The two cost studies were performed at different times and by different institutions: the 20 MT/y in 1985 was performed by ANL, and the 200 MT/y in the period 1991-1993 was performed by General Electric, although the facility is also based on ANL technology. Additionally, the 20 MT/y facility was supposed to be collocated at a reactor site, and to share some facilities with the reactor, thus likely reducing its costs, while the 200 MT/y was envisioned as a stand-alone facility. Additionally, in the years between the two studies, the precision of cost estimates may have improved, and the technology may have been better developed, with the aim at reducing the costs.

## **F2/D2-1-7. DATA LIMITATIONS**

No commercial-scale pyroprocessing and remote fabrication facility for nuclear fuel has been built so far, and only one engineering-scale facility has operated: the FCF at MFC processed and fabricated metal fuel for the EBR-II and demonstrated electrochemical reprocessing. In practice, virtually all the cost data that were found and collected here are from studies based on the same technology developed originally at ANL.

A detailed discussion of the available data, including a detailed discussion on the similarities and inconsistencies between recent detailed studies, is provided in Section F2/D2-5. One general problem that arises when analyzing costs from different studies is the homogeneity of basic assumptions, including indirect costs (often underestimated), owners' costs, contingencies, inclusion of cost of capital during construction, amount of "nuclear grade" and "non-nuclear grade equipment" etc...

A general problem is that at this point it was not possible to find defensible data on the cost of remote fabrication alone, and instead it had to be deduced, in a very preliminary and approximate level, from the cost of integrated reprocessing and remote fabrication. How this derivation is performed, together with the limitations of the proposed approach, is discussed in Section F2/D2-5.

In the next Section F2/D2-8, unit costs ranges, including probability distributions to quantify the uncertainty ranges associated with the costs, will be provided. One important consideration regarding unit costs is that cost studies for pyroprocessing facilities generally report the total capital cost, in terms of overnight costs, and the annual O&M costs, but not the unit cost in terms of dollars per kg heavy metal (\$/kgHM). Therefore, in order to arrive at a unit cost, assumptions on facility lifetimes and discount rates are necessary. A discussion of the assumptions on facilities lifetime and discount rate used to arrive at unit costs in this Section is provided in Section F2/D2-5. Additionally, if the construction time is expected to be significant (i.e. more than 2-3 years), the overnight cost needs to be adjusted to include the cost of capital during construction.

History suggests that the uncertainty and cost growth associated with a first-of-a-kind electrochemical processing facility would be the dominant cost factor and, therefore, the cost per MTHM processed would increase, in practice, from the reference value. Both the first-of-a-kind status of the facility and lack of technology scale-up experience would be expected to dominate upward cost changes from the reference value.

## **F2/D2-1-8. COST SUMMARIES**

The module cost information is summarized in the What-It-Takes (WIT) cost summaries in Tables F2/D2-2 (integrated pyroprocessing separation and remote refabrication) and F2/D2-3 (remote refabrication only). The summary shows the reference cost basis (constant year \$U.S.), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated and as a result of sensitivity and uncertainty analysis. Refer to introductory paragraphs in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

As discussed in Section F2/D2-2, the unit costs are derived primarily from a recent study of capital cost of an integrated pyroprocessing and remote fabrication facility for fast reactor metallic fuel (Carter 2010). The O&M costs are derived from ranges reported in (Bunn 2016) for aqueous reprocessing facilities, since the (Carter 2010) study only focused on capital costs. Other assumptions, and cross comparison to other cost studies for similar facilities, are discussed extensively in Section F2/D2-5. Other studies that instead included O&M cost estimates are used to confirm the validity of the ranged provided in (Bunn 2016), as explained in Section F2/D2-5.

Since it was not possible to find defensible data on the cost of remote fabrication alone, it was deduced, in a very preliminary and approximate level, as the difference between the cost of integrated reprocessing and remote fabrication from (Carter 2010) and the cost of UREX+1a, as discussed in Section F2/D2-5.

For a full explanation of the derivation of the cost summaries, as well as the limitation and uncertainty of the data, the reader is strongly advised to read the relevant sections of this module.

Figures F2/D2-5 and F2/D2-5 show the probability distributions for summary the unit costs described in Tables F2/D2-2 and F2/D2-3.

Table F2/D2-2. WIT cost summary table for integrated pyroprocessing separation and remote refabrication (2017\$).

Reference Cost(s) Based on Reference Capacity	Low	Mode (=Mean)	High
Integrated pyroprocessing separation and remote refabrication	2000 \$/kgHM	2600 \$/kgHM	3200 \$/kgHM
Justification	Approximated from 1968 \$/kgHM of (Carter 2010). Reflects the “low” capital cost of the Carter 2010 estimate, and a “low” O&M annual costs of 4% of capital costs (according to Bunn 2016)	Simple average between the two extreme values.	Approximated from 3205 \$/kgHM of (Carter 2010). Reflects the “high” capital cost of the Carter 2010 estimate, and the “high” O&M annual costs of 7% of capital costs (according to Bunn 2016)

Table F2/D2-3. WIT cost summary table for remote refabrication only (2017\$).

Reference Cost(s) Based on Reference Capacity	Low	Mode (=Mean)	High
Remote refabrication only	1000 \$/kgHM	1400 \$/kgHM	1800 \$/kgHM
Justification	Difference from integrated and UREX+1a	Simple average between the two extreme values.	Difference from integrated and UREX+1a

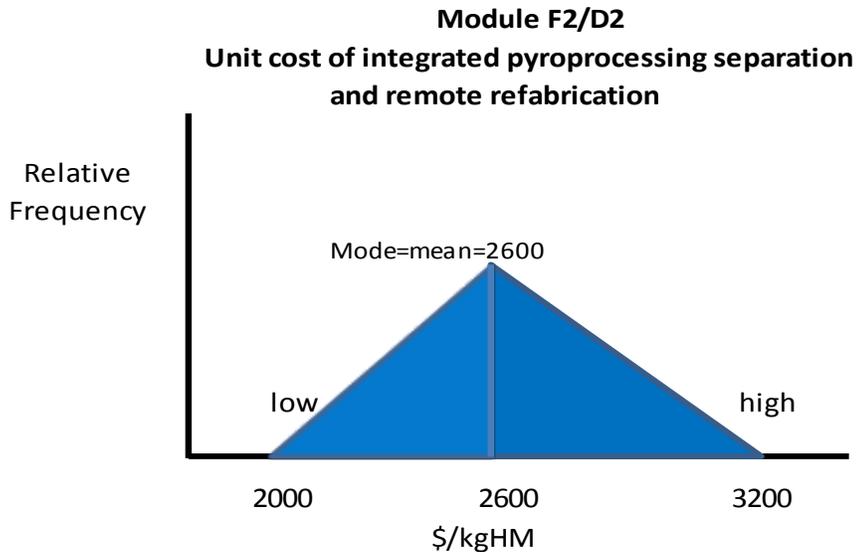


Figure F2/D2-5. Module F2/D2 distribution of combined unit cost for electrochemical reprocessing and remote fabrication of fast reactor metal fuel.

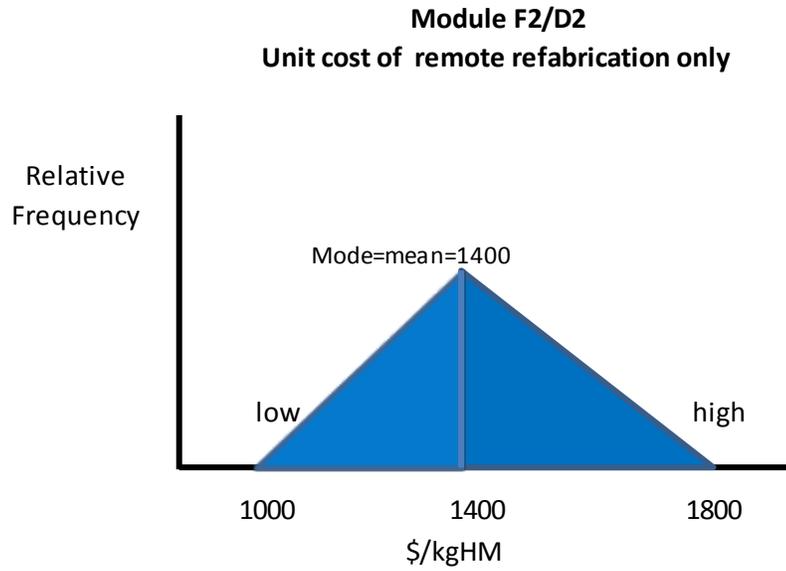


Figure F2/D2-6. Module F2/D2 distribution of unit cost for remote fabrication only.

## F2/D2-1-9. REFERENCES

- Abney, K. et al., 1997, “Advanced Nuclear Fuel Processing Options Final Report,” LA-UR-98-2773, Los Alamos National Laboratory, October 6, 1997.
- Benedict, M., T. Pigford, and H. Levi, 1981, *Nuclear Chemical Engineering: Second Edition*, McGraw-Hill, New York, New York, 1981.
- Bunn M. (2016), Zhang H., and Kang L., “The Cost of Reprocessing in China”, Harvard Kennedy School, Belfer Center for Science and International Affairs, 79 JFK Street. Cambridge, MA 02138, January 2016.
- Carter 2010; Carter, J. T., and Severynse, T. F. 2010; *Electrochemical Reprocessing and Capital Cost Estimate*, Report Number DCRD-SYSA-2010-000107, Savannah River Site, August 2010. [This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.]
- Colby, Jr., L. J., K. L. Mattern, H. Pearlman, E. W. Murbach, G. E. Brand, 1963, *Comparative Fuel Cycle Evaluations, Low Decontamination Pyroprocessing vs Aqueous Reprocessing. Part I. UO<sub>2</sub> Fuel in a Thermal Reactor*, Report No.: NAA-SR-8036, Contract No.: AT-11-1-GEN-8, February 1, 1963. [This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.]
- Colby, Jr., L. J., K. L. Mattern, 1965, *Comparative Fuel Cycle Evaluations, Low Decontamination Pyroprocessing, and Aqueous Reprocessing. Part II. UC Fuel in a Thermal Reactor*, NAA-SR-9335, Contract No. AT-11-1-GEN-8, February 15, 1965. [This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.]
- Delene, J. G., L. C. Fuller, C. R. Hudson, 1993, *ALMR Deployment Economic Analysis*, Oak Ridge National Laboratory, ORNL/TM-12344, June 1993.
- DOE, 2003, *Report on the Preferred Treatment Plan for EBR-II Sodium-Bonded Spent Nuclear Fuel*, Office of Nuclear Energy, Science, and Technology, U.S. Department of Energy, October 2003.
- Frigo, Arthur A., Dale R. Wahlquist, James L. Willit, 2003, “A Conceptual Advanced Pyroprocess Recycle Facility,” *Proceedings of GLOBAL 2003*, ANS, New Orleans, Louisiana, November 2003.
- IAEA, 2005, “Status and Trends in Spent Fuel Reprocessing,” IAEA-TECDOC-1467, International Atomic Energy Agency, Vienna, Austria, September 2005.
- Jones, F. J., 1981, *Conceptual Design Report Hot Experimental Facility for the Consolidated Fuel Reprocessing Program*, ORNL/CFRP-81/4, Oak Ridge National Laboratory, Bechtel Corporation, 1981. [This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.]
- Landmark 2015, Yoon Il Chang, Robert W. Benedict, Javier Figueroa, Joseph E. Herceg, Terry R. Johnson, Eugene R. Koehl, Richard M. Lell, Young Soo Park, Stanley G. Wiedmeyer, Mark A. Williamson, James L. Willit, Merrick and Company Reid James, Steve Meyers, Bryan Spaulding, John Underdahl, Mike Wolf, Summary Report Conceptual Design of a Pilot-Scale Pyroprocessing Facility”, ANL/NE-Landmark-CRADA-12, Prepared by Argonne National Laboratory Merrick and Company for The Landmark Foundation , May 1, 2015.
- Lineberry, M. J., R. D. Phipps, and J. P. Burelbach, 1985, *Commercial-size IFR Fuel Cycle Facility: Conceptual Design and Cost Estimate*, DOE Document No. ANL-IFR-25, October 1985. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- ORNL 1995, *Review of the 1991 Cost Estimates for the Advanced Liquid Metal Reactor*, Report of Team Assembled by ORNL including ORNL, Duke Power, and B&W personnel, Oak Ridge National

Laboratory, Applied Technology, September 1992. [This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.]

Taylor, I. N., M. L. Thompson, and D. C. Wadekamper, 1991, *Fuel Cycle Assessment 1991*, GEFR-00897, Rev 1, GE Nuclear Energy, Applied Technology, September 1991. [This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.]

Washington Savannah River Company, 2007, “Engineering Alternative Studies for Separations Summary Report,” EAS-G-ESR-G-00049, June 2007. (This document has a restricted distribution, may be proprietary, or both: and is not publicly releasable.)

Washington Savannah River Company, 2008, “Follow-on Engineering Alternative Studies Summary Report,” GNEP-CFTC-PMO-MI-DV-2008-00087, March 2008. (This document has a restricted distribution, may be proprietary, or both: and is not publicly releasable.)

## **F2/D2-1-10. BIBLIOGRAPHY**

Boardman, C. E., M. Hui, D. G. Carroll, A. E. Dubberley, 2000, “Economic Assessment of S-PRISM Including Development and Generating Costs,” *Proceedings of the 9th International Conference on Nuclear Engineering (ICONE-9), Nice, France, 2000*.

Ganda, 2016, F. Ganda, R. Wigeland, T. K. Kim, T. A. Taiwo, B. Dixon, “Advances in Developing Improved Fuel Cycle Cost Estimates”, June 1st, 2016, FCRD-FCO-2016-000498. [This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.]

Lauferts, U., et al., 2007, “Economic Assessment of Partitioning, Transmutation, and Waste Reduction Technologies,” *Proceedings of ICAPP 2007, Nice, France, Paper 7382, May 13–18, 2007*.

Lineberry, M. J. *Cost of Fabrication of U-Pu-Zr Metal Fuel versus MOX Pellet Fabrication*, paper from Idaho State University, August 3, 2012

NAS, 1996, “Nuclear Wastes: Technologies for Separations and Transmutation, Appendix J: Fuel Reprocessing Economics,” National Academy of Sciences, 1996, pp 413–446.

NEA/OECD, 2002, *Trends in the Nuclear Fuel Cycle: Economic, Environmental and Social Aspects*, Paris: OECD, 2002.

NEA/OECD, 2005, *Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles: A Comparative Study*, Nuclear Energy Agency/Organization for Economic Cooperation and Development, <http://www.nea.fr/html/ndd/reports/2002/nea3109-ads.pdf>, Web page accessed September 1, 2009.

NEA/OECD, 2006, *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, Nuclear Energy Agency/Organization for Economic Cooperation and Development, Paris, May 2006.

OIA, 1995, *Management and Disposition of Plutonium: Reactor-related Options*, National Academy of Sciences, Washington, DC: National Academy Press, 1995, <http://www.nap.edu/books/0309051452/html/R1.html>, Web page accessed December 21, 2005.

Washington Group International, 2004, “Spent Fuel Treatment Facility Scoping Study,” Job No. 26861-004, Washington Group International under contract to Bechtel BWXT, Idaho, LLC, Contract #17157, SOW-1113, Rev. 2 (10/20/03), Denver, Colorado, January 29, 2004. [This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.]

Zerriffi H. and A. Makhijani, 2000, *The Nuclear Alchemy Gamble: An Assessment of Transmutation as a Nuclear Waste Management Strategy*, August 25, 2000, <http://www.ieer.org/reports/transm/report.pdf>, posted with modifications to Appendix B on IEER Web site May 12, 2005, Web page accessed on September 1, 2009.