# *Advanced Fuel Cycle Cost Basis Report: Module F1 Spent Nuclear Fuel Aqueous Reprocessing Facility*

## Nuclear Fuel Cycle and Supply Chain

***Prepared for***
***U.S. Department of Energy***
***Systems Analysis and Integration***
***April 2021***
**INL/EXT-21-62313**
***Revision 0***

# REVISION LOG

| Rev. | Date | Affected Pages | Revision Description |
|---|---|---|---|
| | 2004 | All | **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. |
| | 2009 | All | **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. |
| | | All | **New technical/cost data which has recently become available and will benefit next revision:**<br>- 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<br>- 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. |
| | 2021 | All | Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020. |
| | | | |
| | | | |

*Page intentionally left blank*

# ACKNOWLEDGEMENT

This latest version of the Module F1 Spent Nuclear Fuel Aqueous Reprocessing Facility is the result of the cumulative effort of many authors that have contributed to the Advanced Fuel Cycle Cost Basis Report (AFC-CBR). It is not possible to identify and acknowledge all those contributions to the AFC-CBR and this module. All the authors, including the four primary authors, fifteen contributing authors, the twelve contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to the development and writing of this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. J. Hansen (INL) and E. Hoffman (ANL) can be contacted with any questions regarding this document.

jason.hansen@inl.gov; ehoffman@anl.gov

**Suggested Citation:**

DOE-NE Systems Analysis & Integration Campaign, *Advanced Fuel Cycle Cost Basis Report: Module F1 Spent Nuclear Fuel Aqueous Reprocessing Facility*. Idaho Falls: Idaho National Laboratory, 2021.

# CONTENTS



# FIGURES

# TABLES

# ACRONYMS

| | |
|---|---|
| ACF | autocorrelation function |
| AIC | Akaike Information Criterion |
| ANL | Argonne National Laboratory |
| BMMR | Brownian Motion Mean Reversion |
| DOE | U.S. Department of Energy |
| DOE-EIA | U.S. Department of Energy-Energy Information Administration |
| EAR-I | Estimated Additional Resources Category I |
| HEU | highly enriched uranium |
| IAEA | International Atomic Energy Agency |
| IMF | International Monetary Fund |
| INL | Idaho National Laboratory |
| LEU | Low-Enriched Uranium |
| MA | moving average |
| MAPE | Mean Absolute Percentage Error |
| MOX | mixed oxide fuel |
| NEA | Nuclear Energy Agency |
| NUEXCO | Nuclear Exchange Corporation |
| OECD | Organization for Economic Cooperation and Development |
| PACF | partial autocorrelation function |
| RAR | Reasonably Assured Resources |
| RepU | reprocessed uranium |
| SR | Speculative Resources |
| TMI | Three Mile Island |
| USAEC | US Atomic Energy Commission |
| USD | uranium price data |
| WIT | What-It-Takes |
| WNA | World Nuclear Association |

*Page intentionally left blank*

# 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 2020 for this FY21 update.**
- **Nature of this FY21 update from previous AFC-CBRs:** Escalation only.
- **Estimating Methodology for latest (2009 AFC-CBR) technical update from which this FY21 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 AFB-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.

## F1-1. 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 $UF_6$) and $PuO_2$, 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.

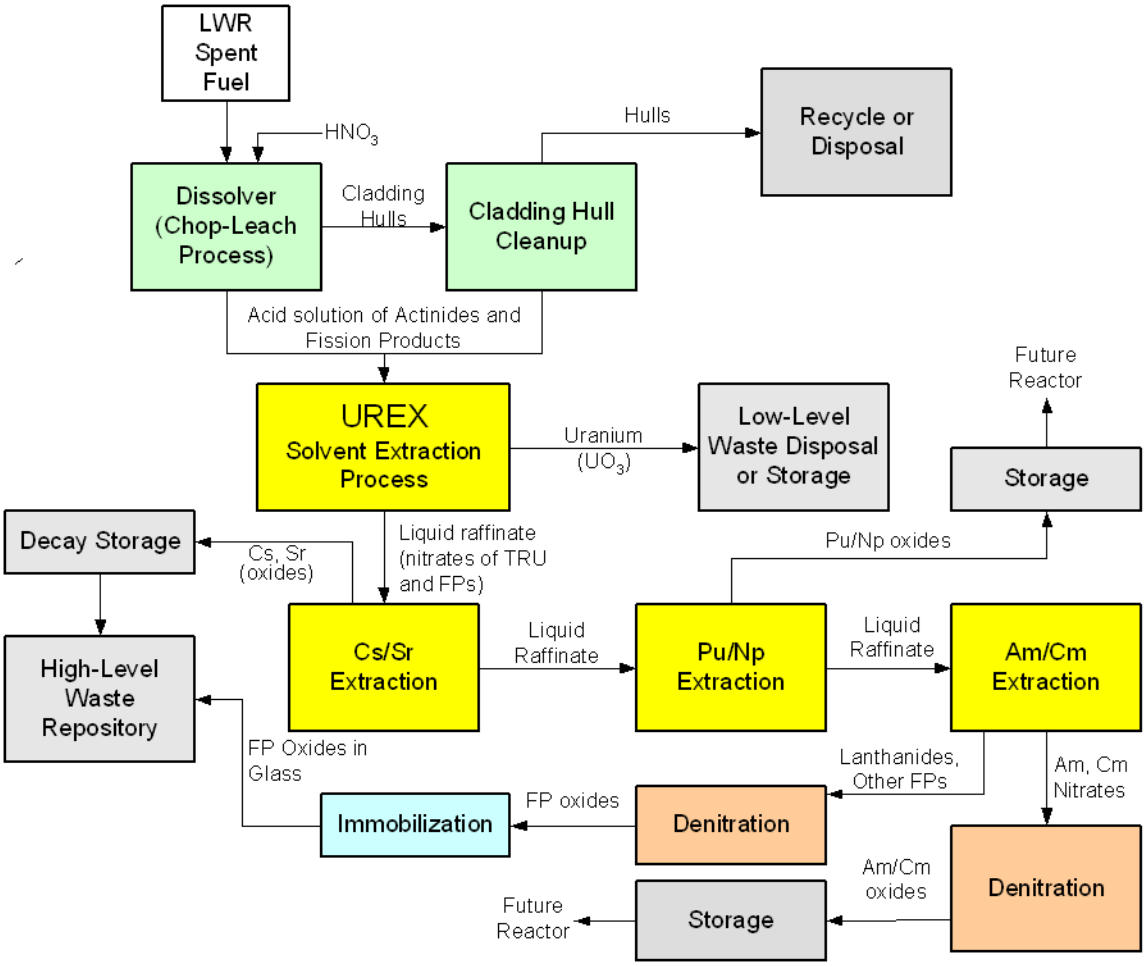


Figure F1-1. Example of UREX+ aqueous reprocessing process flow (Laidler 2003).

## 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 colocate 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.

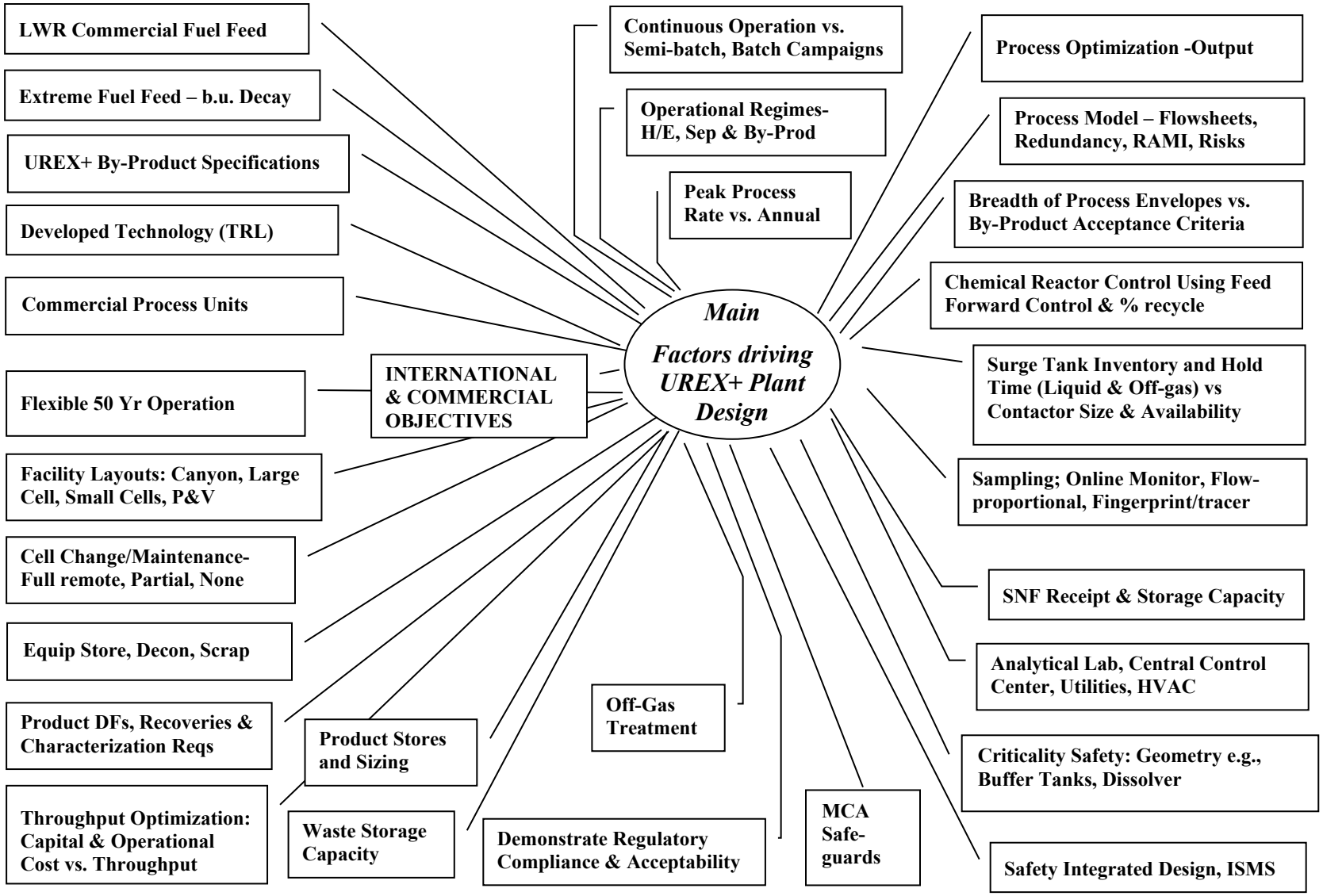


Figure F1-5. Schematic of drivers for UREX+ Plant Concept Design.

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 F1-1. 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.

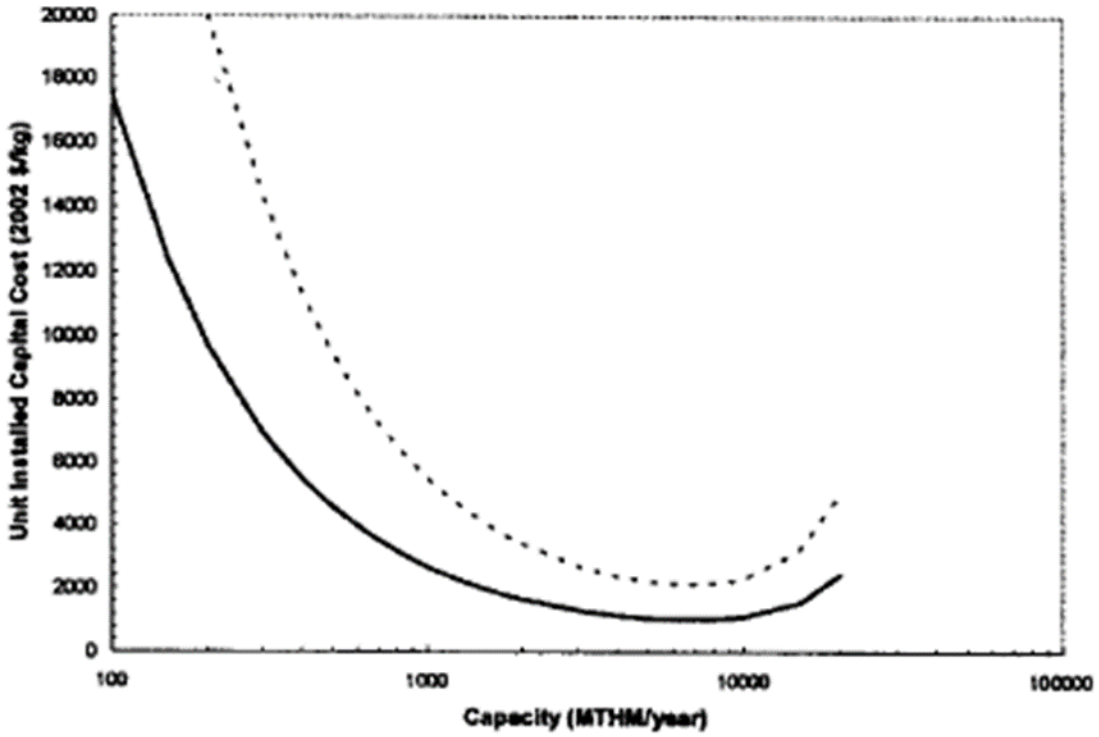


Figure F1-6. Reprocessing unit installed capital cost versus capacity (Haire 2003).

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:

$$CostofA = CostofB\left(\frac{CapacityofA}{CapacityofB}\right)^{n} \quad (1)$$

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 sited 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)[24] | 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) |
|---|---|---|---|---|---|---|---|---|
| **Windscale B205(1964- )[1]** | **7 (214)** | **1,500** | **~500-1,500** | **2,555** | **-** | **-** | **-** | **-** |
| **West Valley (1966-72)[2]** | **1 (300)** | **300** | **~110 (640 – 6y)** | **-** | **-** | **-** | **-** | **-** |
| HTGR Ref. RP (1969)[3] | - | 260 | Design/cost | - | 0.060 | 1969 | ~4 | 0.24 |
| **GE Morris (1974)[4]** | **3** | **(900)** | **Inoperable** | **1,095** | **0.064** | **-** | **~4** | **0.26** |
| **AGNS Barnwell (1974) [5]** | **5 (300)** | **1,500** | **Not operated** | **1,825** | **1.50** | **1983** | **1.8** | **2.7** |
| Exxon (1976)[6] | Est. 1.7 (300) | 500 | Design/cost | | 0.99 | 1978 | 2.6713 | 2.64 |
| Exxon (1976)[6] | Est. 5 (300) | 1,500 | Cost estimate | - | 1.5 | 1983 | 1.8 | 2.7 |
| IAEA (1976)[7] | - | 300 | Cost estimate | - | 0.48 | 1976 | 3.0786 | 1.48 |
| IAEA (1976) [7] | - | 750 | Cost estimate | - | 0.70 | 1976 | 3.0786 | 2.16 |
| IAEA (1976) [7] | - | 1500 | Cost estimate | - | 1.05 | 1976 | 3.0786 | 3.23 |
| IAEA (1976) [7] | - | 3000 | Cost estimate | - | 1.72 | 1976 | 3.0786 | 5.30 |
| **Tokai RP (1977- )[8]** | **0.7 (143)** | **100** | **40 (1,123 -28 y)** | **255** | **-** | **-** | **-** | **-** |
| **RT-1 Mayak (1977- )[9]** | **1 (200)** | **200** | **146 (3,500 -24y)** | **400** | **-** | **-** | **-** | **-** |
| DuPont (1978)[10] | 5 (300) | 1,500 | Design/cost | 1,825 | 2.4 | 1983 | 1.8 | 4.3 |
| DuPont (1978)[10]inc. fab | 10 (300) | 3,000 | Design/cost | 3,650 | 3.7 inc fuel fab | 1978 | 2.6713 | 9.0 |
| CFRP FR Dem (1979)[11] | 0.1 (150) | 15 | Design/cost | 30 | 0.80 ± 0.2 | 1982 | 1.8808 | 1.50 |
| CFRP Hot Exp (1979)[12] | 0.5 | - | Design/cost | 183 | 1.0 ± 0.25 | 1982 | 1.8808 | 1.88 |
| EDRP FR UK (1984)[13] | 0.3 (250) | 75 | Design/cost | 110 | 0.42 (£0.24B) | 1982 | 1.8808 | 0.79 |
| GE ALMR (1990)[14] fab | - | 2,700 | Design/cost | - | 5 | 1990 | 1.4 | 7 |
| EPRI Study (1990) [15] | - | 1,500 | Cost study | - | 3.0 | 1990 | 1.4 | 4.2 |
| **UP-3 (1990- )[16]** | **5 (160-200)** | **800 (1,000)** | **800+** | **1,825** | **6.2 (28BFF'92)** | **2003** | **1.1** | **6.8** |
| OECD study (1994) [17] | ~5 (180) | 900 | Cost study | 1,825 | 4.1B (£2.7B) | ~1993 | 1.3623 | 5.5 |
| **THORP (1994- )[18]** | **5 (120)** | **600** | **600** | **1,825** | **4.1 (£2.3B)** | **1992** | **1.37** | **5.6** |
| **UP2-800 (1994- )[19]** | **5 (160-200)** | **800 (1,000)** | **800+** | **1,500** | **5.8 (37BFF'00)** | **1990** | **1.4** | **8.1** |
| SFTF – UREX+ (2004)[20] | 7.4 (270) | 2,000 | Design/cost | 2,700 | 3.0 | 2004 | 1.05 | 3.2 |
| **Rokkasho (2007-8) [21]** | **5 (160)** | **800** | **Commission** | **1,500** | **5.2-6.5** | **1992** | **1.37** | **(~20)** |
| COEX™–AREVA (2006)[22] | 8.3 (300) | 2,500 | COEX™ 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 |
| **Total Annual Operations Cost** | **254** | **376** | **277** | **412** | **254** | **377** |
| | | | | | | |
| 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 |
| **Subtotal: 40-year Operations** | **12,538** | **18,807** | **13,800** | **20,700** | **12,604** | **18,906** |
| Future Capital Projects | 0 | 0 | 0 | 0 | 0 | 0 |
| D&D | 1690 | 2545 | 2032 | 3079 | 1156 | 1714 |
| **Subtotal LCC O&M & D&D** | **14,228** | **21,352** | **15,832** | **23,779** | **13,760** | **20,620** |
| | | | | | | |
| Early Life Cycle | 201 | 300 | 262 | 407 | 187 | 270 |
| TPC | 14453 | 21202 | 17193 | 25656 | 10211 | 14186 |
| **Total LCC** | **28,882** | **42,853** | **33,287** | **49,842** | **24,158** | **35,076** |
| | | | | | | |
| | | | | | | |
| 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$^{nd}$ most expensive building, the "Extraction Building", and to the 3rd 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 F1-3. 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 |
|---|---|---|
| Total Estimated Costs (TEC) | | |
| Engineered Equipment Costs | 817,837 | 817,837 |
| Structures & Improvements Costs | 1,037,622 | 1,037,622 |
| Subtotal Field Directs | 1,855,460 | 1,855,460 |
| 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 |
| Subtotal TEC | 6,484,078 | 3,481,417 |
| Other Project Costs (OPC) | | |
| 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 |
| Subtotal OPC | 1,291,226 | 522,213 |
| Subtotal - Fuel Building -Total Project Costs (TPC) | 7,775,304<br><br>Design costs of $1bn are included in this number | 4,003,629<br><br>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, ≤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 Plantwas 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, 2nd 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 levelized 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-TRUEX 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 $PuO_2$ 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 New 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 F1-4. 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 19.3% escalation) from the previous version (2009) of the cost basis report where the EAS comprehensive cost estimates were presented..

Table F1-4. Cost summary table.

| **What-It-Takes (WIT) Table: 2009 AFC-CBD values and escalation to year 2020$** | | | | |
|---|---|---|---|---|
| Reference Cost(s)<br>Based on Reference Capacity | Low Cost | Mode Cost | Mean Cost | High Cost |
| Co-Ex 800 MT/yr (2009$) | $755/kg HM | $925/kg HM | | $1,096/kg HM |
| **Esc to 2020$>>**<br>**F1-1coex** | **$900/kgHM** | **$1100/kgHM** | **$1100/kgHM** | **$1300/kgHM** |
| UREX+1a 800 MT/yr (2009$) | $903/kg HM | $1,120/kg HM | | $1,339/kg HM |
| **Esc to 2020$>>**<br>**F1-1a** | **$1100/kgHM** | **$1350/kgHM** | **$1350/kgHM** | **$1600/khHM** |
| UREX +3a 800 MT/yr (2009$) | $1040/kg HM | $1,300/kg HM | | $1,558/kg HM |
| **Esc to 2020$>>**<br>**F1-3a** | **$1250/kgHM** | **$1550/kgHM** | **$1550/kgHM** | **$1850/kgHM** |
| | Facility scales are based on 800 MT/yr. Capacity scaling is limited to a single train due to criticality. Escalated from 2009$ estimates with 19.3% escalation to 2020$ then rounded to the nearest 50. Mean is average of {high, low, mode}. | | | |

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.

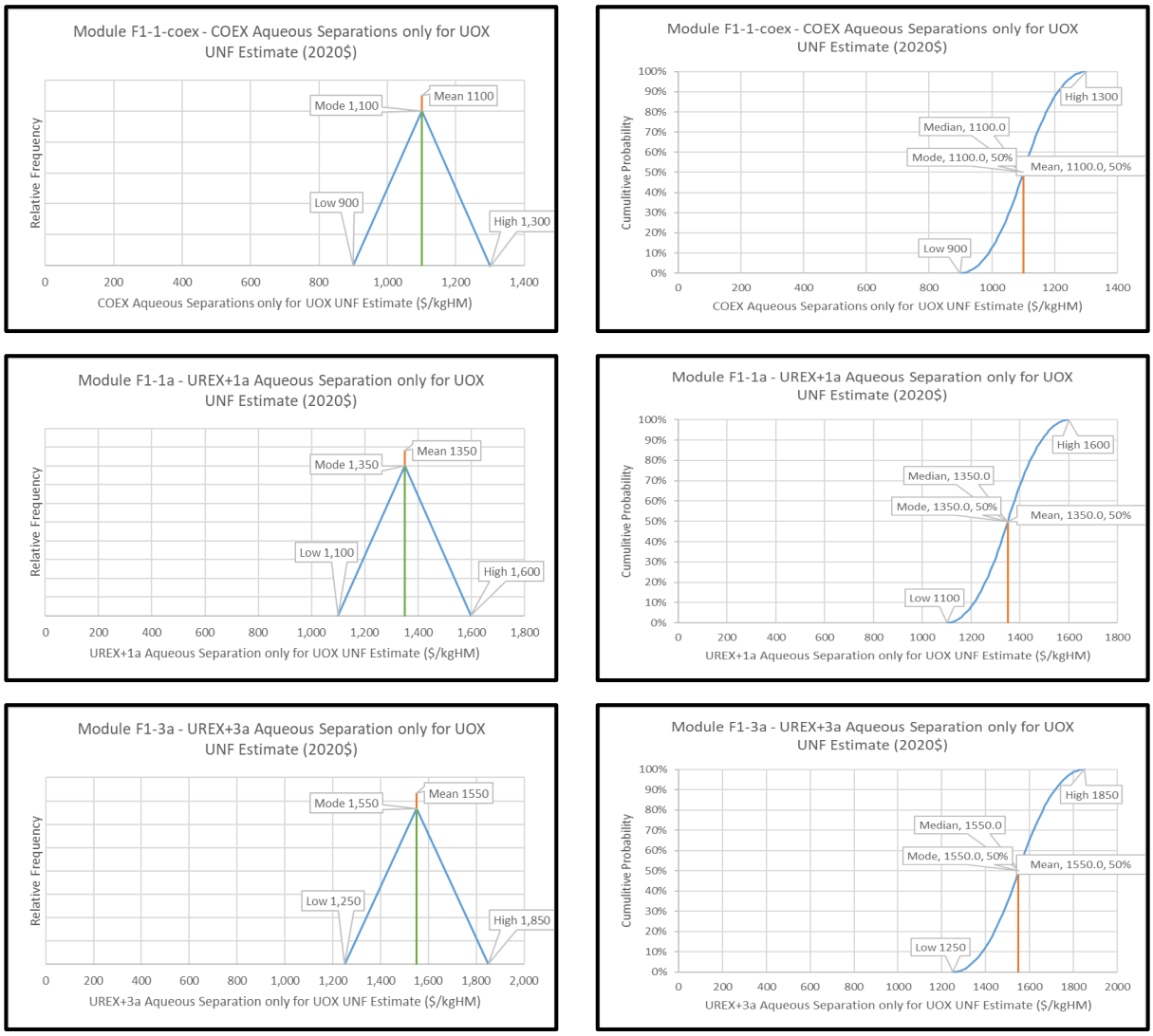


Figure F1-7. Aqueous **separations** estimated cost frequency distributions for three processes.

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 F1-5. 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 F1-5. Total reprocessing, waste conditioning, and storage unit costs.

| What-It-Takes (WIT) Table: 2009 AFC-CBD values + Escalation to Year 2020$ | | | | |
|---|---|---|---|---|
| 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 | | $1,619/kg HM |
| **Esc to 2020$>> F1-1coex_T** | **$1300/kgHM** | **$1650/kgHM** | **$1633/kgHM** | **$1950/kgHM** |
| UREX+1a 800 MT/yr | $1,494/kg HM | $1,850/kg HM | | $2,214/kg HM |
| **Esc to 2020$>> F1-1a_T** | **$1800/kgHM1** | **$2200/kgHM** | **$2217/kgHM** | **$2650/kgHM** |
| UREX +3a 800 MT/yr | $1,670/kg HM | $2,080/kg HM | | $2,488/kg HM |
| **Esc to 2020$>> F1-3a_T** | **$2000/kgHM** | **$2500/kgHM** | **$2483/kgHM** | **$2950/kgHM** |
| | Escalated from 2009$ estimates with 19.3% escalation to 2020$ then rounded to the nearest 50. Mean is average of {high, low, mode}. | | | |

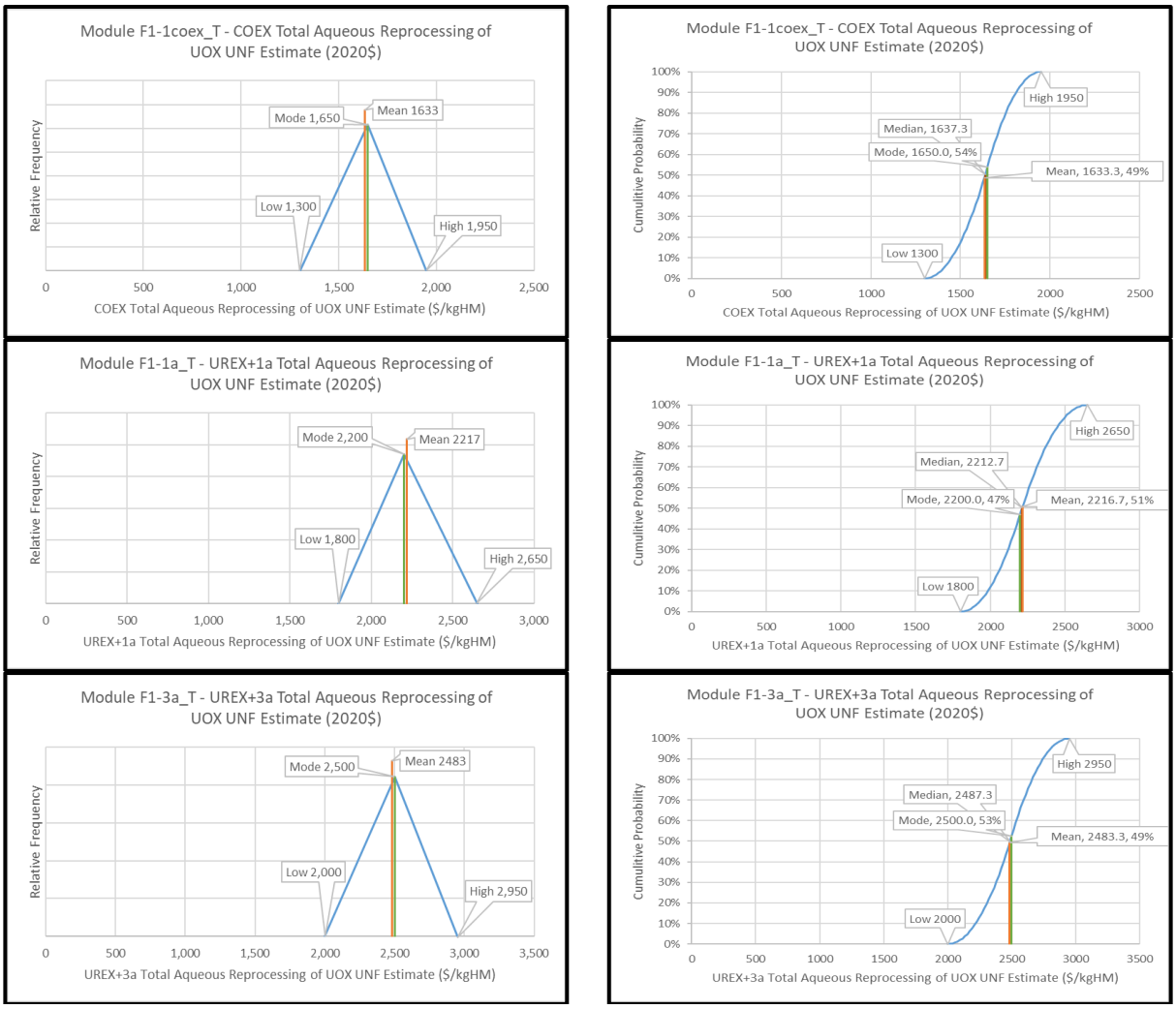


Figure F1-8. **Total reprocessing** estimated cost frequency distributions for three processes.

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 F1-5 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 F1-5. The report confirms Table F1-5 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 F1-6. Figure F1-9 shows the aqueous reprocessing separations cost distributions for the three processes above treating thorium-based fuels.

Table F1-6. Reprocessing (aqueous separations) unit cost for Thorium-containing oxide fuels (2009 AFC-CBD values plus escalation to year 2020$).

| Process and Plant Capacity | Low ($/kgHM) | Mode ($/kgHM) | Mean ($/kgHM) | High ($/kgHM) |
|---|---|---|---|---|
| Co-Ex 800 MT/y | 793 | 1018 | | 1206 |
| **Escalated 2020$ >> F1-coexTh** | **950** | **1200** | **1200** | **1450** |
| UREX+1a 800 MT/y | 948 | 1232 | | 1473 |
| **Escalated 2020$ >> F1-1aTh** | **1150** | **1450** | **1450** | **1750** |
| UREX +3a 800 MT/y | 1092 | 1430 | | 1714 |
| **Escalated 2020$ >> F1-3aTh** | **1300** | **1700** | **1683** | **2050** |
| | Escalated from 2009$ estimates with 19.3% escalation to 2020$ then rounded to the nearest 50. Mean is average of {high, low, mode}. | | | |

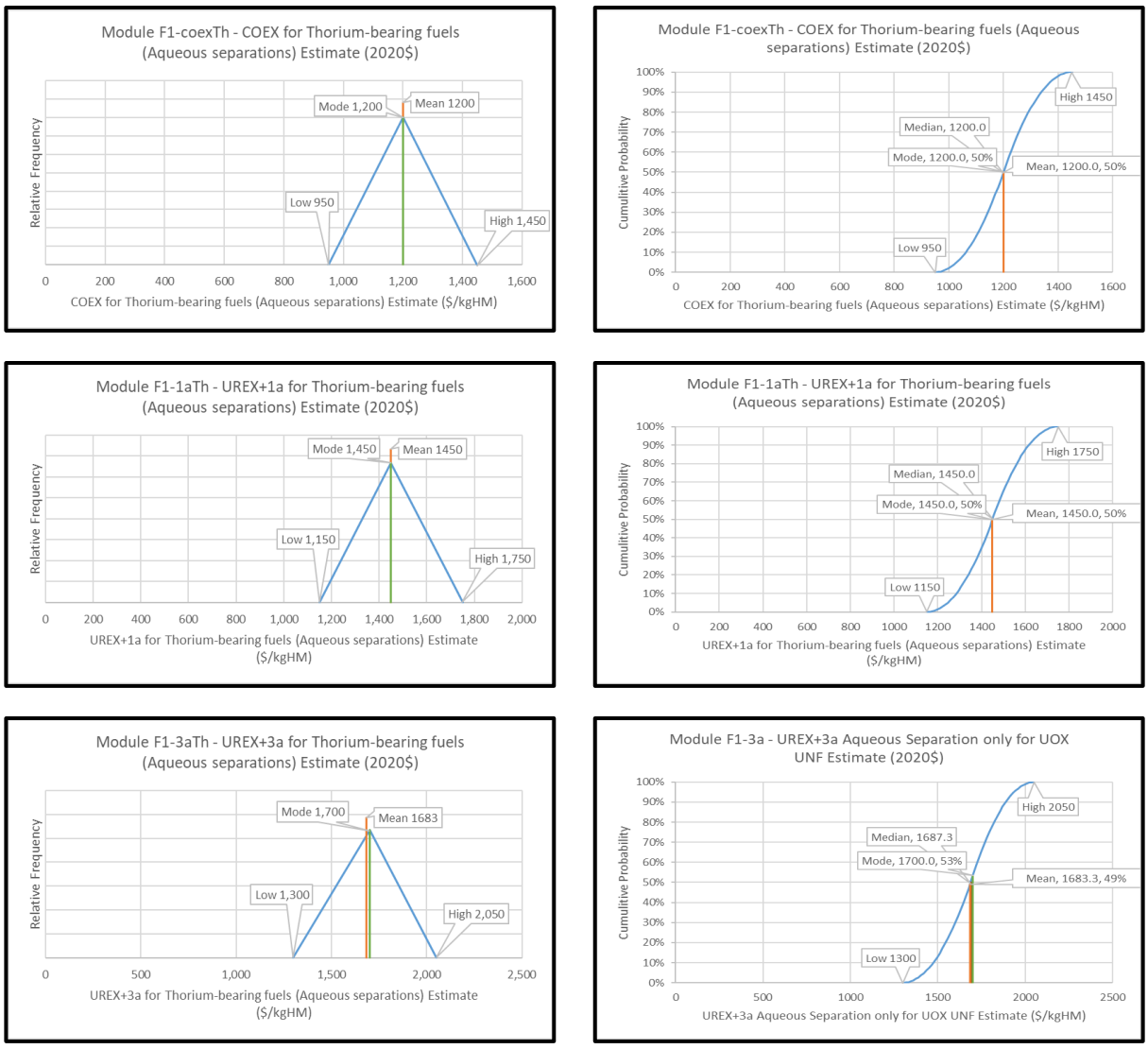


Figure F1-9. Aqueous **separations** estimated cost frequency distributions for three processes.

The costs including all products and waste processing to a final form or buffer storage are shown in Table F1-7, 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 F1-7. Total reprocessing: separations, waste conditioning and storage unit costs of aqueously processed thorium-containing fuels (2009$ escalated to year 2020$).

| | Low ($/kgHM) | Mode ($/kgHM) | Mean ($/kgHM) | High ($/kgHM) |
|---|---|---|---|---|
| Co-Ex 800 MT/y (2009$) | 1108 | 1370 | 1366 | 1619 |
| **Escalated 2020$ >> F1-CoexTh_T** | **1300** | **1650** | **1633** | **1950** |
| UREX+1a 800 MT/y | 1569 | 2035 | 2013 | 2435 |
| **Escalated 2020$ >> F1-1aTh_T** | **1850** | **2450** | **2400** | **2900** |
| UREX +3a 800 MT/y | 1754 | 2288 | 2260 | 2737 |
| **Escalated 2020$ >> F1-3aTh_T** | **2100** | **2750** | **2700** | **3250** |
| | Escalated from 2009$ estimates with 19.3% escalation to 2020$ then rounded to the nearest 50. Mean is average of {high, low, mode}. | | | |

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

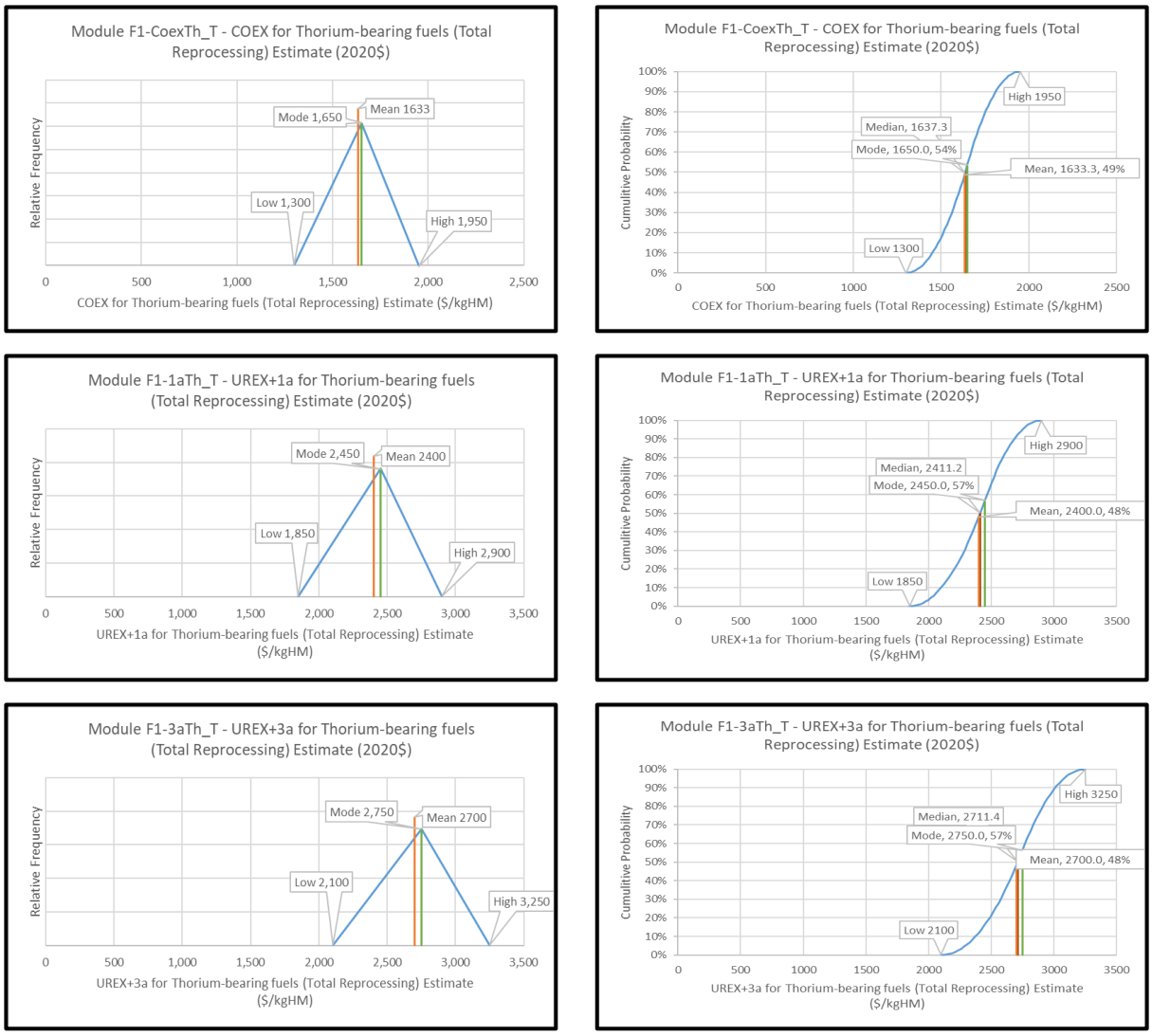


Figure F1-10. Total reprocessing estimated cost frequency distributions for three thorium-related processes.

It should be noted that there are also more difficult environmental, health, and safety considerations for Th-containing fuels than for UOX fuels. The U-232 daughters which build in along with U-233 during irradiation produce very potent gamma radiation. One such daughter is Tl-208 which produces a 2.6 MeV gamma ray upon decay.

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. Permutter, 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*, 2nd 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.