Advanced Fuel Cycle Cost Basis: *Combined Module F2/D2*
Electrochemical and Thermochemical Reprocessing and Associated
Remote Fuel Fabrication

Nuclear Fuel Cycle and Supply Chain

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004	All	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) cost information was not available.
			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.
	2021	All	Latest version of module in which new technical data was used to establish unit cost ranges: FY21.
	2021	All	Module F2/D2 now covers the two major types of non-aqueous (a.k.a. "dry") spent fuel reprocessing. A new technical basis is provided for Electrochemical Reprocessing and Remote Fuel Fabrication (sub-module F2/D2-1); it is based on published studies that are described in the module text. A new submodule F2/D2-2 is added on Gas-Solid Phase Thermochemistry as a reprocessing method with multiple variants. All monetary units are presented in 2020$.

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ACKNOWLEDGEMENT

This latest version of the *Module F2/D2 Electrochemical and Thermochemical Reprocessing and Associated Remote Fuel Fabrication* 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.

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ACRONYMS

AFC-CBR   Advanced Fuel Cycle – Cost Basis Report

AIROX   Atomics International Reduction OXidation

ALMR   Advanced Liquid Metal Reactor

ANL-W   Argonne National Laboratory-West

ASTM   American Society for Testing and Materials

CANDU   Canada Deuterium Uranium

CARBOX   CARBothermic-reduction OXidation

COEX   Co-extraction of uranium and plutonium

D&D   Decontamination and Decommissioning

DOE   U.S. Department of Energy

DUPIC   Direct use of spent PWR fuel in CANDU

EAS   Engineering Alternative Studies

EBR-II   Experimental Breeder Reactor-II

FCF   Fuel Conditioning Facility

FOEAS   Follow-on EAS

FR   Fast Reactor

HALEU   High-assay Low-enriched Uranium

IAEA   International Atomic Energy Agency

IDC   Interest During Construction

IFR   Integral Fast Reactor

IRRF   Integrated Reprocessing and Remote Fabrication

KAERI   Korea Atomic Energy Research Institute

LEU   Low enriched uranium

LUC   Levelized Unit Cost

LWR   Light Water Reactor

MFC   Materials and Fuels Complex

MOX   Mixed Oxide

MTHM   Metric Tons of Heavy Metal

O&M   Operations and Maintenance

OMB   Office of Management and Budget

ORNL   Oak Ridge National Laboratory

PRIDE   PyRoprocess Integrated inactive DEmonstration

PRISM   Power Reactor Inherently Safe Module

PUREX	Plutonium Uranium Reduction Extraction
R&D	Research and Development
RIAR	Russian institute at Dimitrovgrad
SFR	Sodium-cooled Fast Reactor
SNF	Spent Nuclear Fuel
S-PRISM	Super-Power Reactor Inherently Safe Module
TRU	Transuranics
UNF	Used Nuclear Fuel
UOX	Uranium oxide
UREX	Uranium Extraction
VIPAC	Vibration-packing
WIT	What-It-Takes

Module F2/D2-1 Electrochemical Reprocessing and Remote Fuel Fabrication

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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
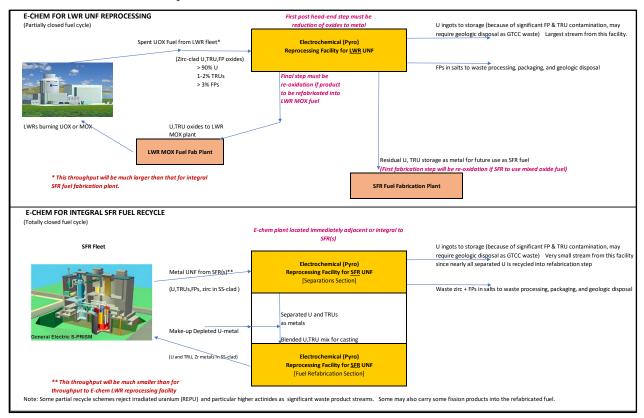
- **Constant $ base year 2020 for this FY21 update.**

- **Nature of this FY21 Module update from previous AFC-CBRs**: Significant revisions based on new analysis of previously unavailable data.

- **Estimating Methodology for latest technical update from which this FY21 update was updated**: Studies that were previously classified as "applied technology" are now publicly available. These studies along with additional studies now underly the basis of the cost estimates reported here. Each of the underlying studies are reviewed in detail then data from them are used to revise reported cost estimates.

F2/D2-1-1. BASIC INFORMATION

This module discusses electrochemical reprocessing (E-chem) of spent nuclear fuel, and remote fuel fabrication with recycled material, also known as re-fabrication.

Since "dry" SNF separations do not have the high decontamination factors of aqueous separations, higher actinides and some fission products are carried over into the heavy metal reprocessing streams, which are ultimately freshly refabricated fuel to be re-irradiated. The penetrating radiation from these minor constituents, mostly gamma rays and spontaneous neutrons, force one to remote handling in the fuel refabrication step, transport to the reactor, and charging to the reactor. This is true for both salt-based pyroprocessing (E-chem) and gas-solid reaction-based thermochemical separation processes (Module F2/D2-2) such as DUPIC, all considered dry processes. The DUPIC process is discussed in greater detail in section F2/D2-1-2 of this module.

Since remote fuel fabrication is an integral part of the overall recycle system, it is generally envisioned to be housed in the same highly-shielded 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. The need for at least partially remote fabrication can arise also after aqueous reprocessing and extended storage of Pu-bearing fuel components such as PuO2 for MOX, however no recent cost studies were found for totally remote fabrication only, and only a few cost studies have been performed on (a) electrochemical reprocessing alone and (b) on electrochemical reprocessing with integrated remote fabrication. (Note: the relationship of aqueous fuel reprocessing and the subsequent refabrication of stored PuO2 product into MOX is discussed on Module D1-2.) 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 (aqueous reprocessing, not refabrication), 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 economies of scope 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 highly shielded and 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, as detailed studies on the cost of remote fabrication alone are produced.

Figure F2/D2-1-1. Understanding the Significant Differences between the Electrochemical Reprocessing/Re-Fabrication of LWR and Integral SFR Fuel

    Figure F2/D2-1-1 illustrates two primary considerations for the cost analyst; cost estimating E-chem processes based on an LWR fuel cycle or based on a SFR fuel cycle. The figure illustrates the technical detail, which the cost analyst can use, to form the basis of building the cost model. Factors such as fuel type, how the fuel is to be processed, and what must be done with wastes all have cost implications. The figure highlights important factors for the analyst to consider in estimation. The figure can guide the analyst on how to apply the cost estimates reported in the module. Figure F2/D2-1-2 illustrates a generic qualitative correlation between various fuel types and the qualitative impact that each has on unit cost. The vertical axis of the figure notes difference factors that will likely drive up unit cost as radiotoxicity increases.

Increasing considerations such as building physical security, material proliferation attractiveness, mat'l accountability, shielding, process complexity, criticality, HVAC req'ts, etc. **These drive unit fabrication cost!!!**

either

either

oxide metal

MOX metal

MOX metal

MOX metal

oxide metal

oxide metal

oxide metal

oxide metal

oxide metal

oxide metal

oxide metal

oxide metal

FP: fission products
R: reprocessing-derived
V: "virgin" (never in reactor) uranium or thorium
NATU: natural U
DU: depleted U
LEU: low-enriched U (< 20% U-235)
MEU: medium-enriched U (>20 and <40% U-235)
HEU: high-enriched U (>40% U-235)
FR: fast reactor
REPU: reprocessed, separated, & re-enriched U

* Np, Am, and Cm are higher actinides
* Handling of U-233 would depend on extent to which U-232 daughters are present
* Metal-casting mfg process assumed to be less complex than pellet-based process
* Handling of irradiated thorium would depend on extent to which U-232 and daughters have built in
* (Complexity of reprocessing step not considered here)

Unit Cost

Radiotoxicity ⟶

Metal-clad Cylindrical rod-type Nuclear Fuel Heavy Metal Composition for Fabrication or Refabrication

	DU only (blankets)	NATU ONLY (PHWR)	V-LEU (LWR)	V-MEU (FR start-up)	V-HEU (prod'n rx)	(U,V-Th) (LWR)	REPU-LEU (LWR)	(U,Pu) (LWR or FR)	(U,Pu,Np) (LWR or FR)	(U,Pu,V-Th) (FR)	(U,Pu,Np,Am) (FR)	(U,Th,Pu,Np, Am,Cm) (FR burner mode)	(FP targets) (FR targets)
AFC-CBR Module >>	D1-4	D1-7	D1-1	D1-4,5,6	D1-6	D1-8	D1-1	D1-2	D1-2	D1-8	D2	D2	n/a
Handling Type >> (most likely)	CH	CH	CH	CH	CH	CH	CH	CH	CH	CH	RH	RH	RH

Fuel types in green lettering generally contact-handled in hooded enclosures,
Red-lettered fuel types contact-handled in gloveboxes,
Blue-lettered fuel types generally remote-handled in hot-cells if higher actinide content is high.

CH= Contact-handling (open, hood, glovebox)
RH=Remote-handling (shielded GB or hot cell)

*** Similar curve would apply to BISO ans TRISO-type particle fuels envisioned for graphite-moderated gas-cooled reactors. Unit costs would be higher because of fabrication process complexity.   (Module R1-3)
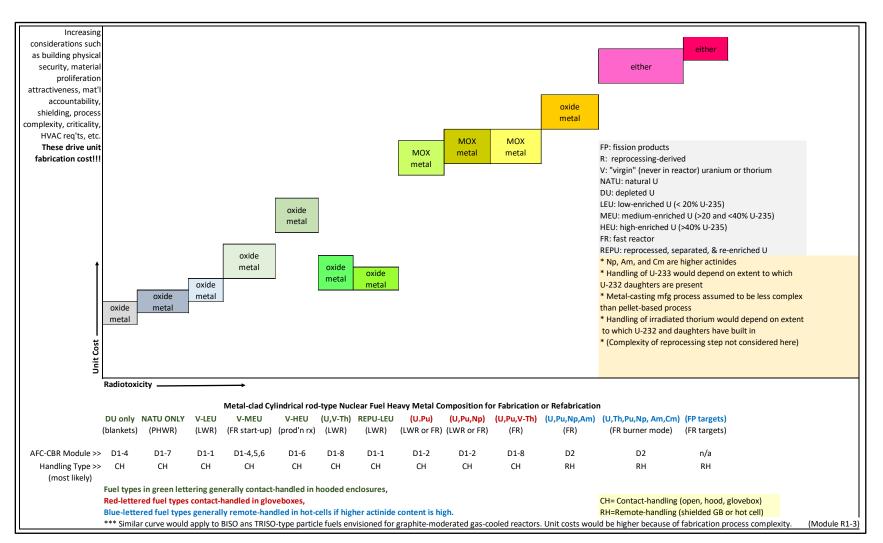
Figure F2/D2-1-2. Fuel Fabrication Complexity (Process and Overheads) Versus Heavy Metal Actinide Composition.

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

F2/D2-1-2.1. 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. Most processes of this "dry" type involve molten salt chemistry (E-chem) 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 on dry processes, 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 solid 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" or "thermochemical" 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 the Argonne National Laboratory-West (ANL-W).[1] 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) at INL 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/D2-1-3). 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 such as LWR UOX or MOX 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 uranium-handling 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)

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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 absorbed into INL and renamed the Materials and Fuels Complex (MFC).

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 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 (actinide burning). 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).

F2/D2-1-2.2. 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 "contact" glove-box handling rather than from front-end fuel cycle steps such as mining, conversion, and enrichment (Modules A, B, and C).
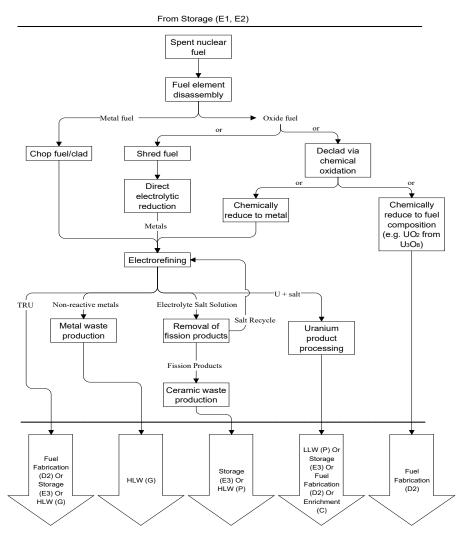

Figure F2/D2-1-3. Example of electrochemical processing flow sheet for spent nuclear fuel.

(Note: HLW metal waste might be diluted with trim metal material to form a more durable Class C low-level waste or might be re-refined. A third option of "mechanical decladding", which separates fuel meat from the cladding, could be added to the oxide fuel options in the figure above.)

In general, the fuel refabrication step is envisioned as likely to be 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 contact-handled in hoods or glove boxes, provided that it is refabricated within a few years after reprocessing. (The issue of build in of Pu-241 and Pu-236 daughters is discussed in the 2021 Module D1-2 (LWR MOX Fuel Fabrication). Low-enriched uranium (LEU) and thermal and fast mixed oxide (Pu, U, Np mixed oxide [MOX]) fuels fall in this category and are described in the Module D1 (Contact-handled Fuels) 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 advanced aqueous spent LWR fuel reprocessing scheme, more complex than PUREX, 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. (A target is a separate rod that can be assembled to contain minor actinides (Am and Cm) and/or long-lived fission products.) Since the building radiation safety and security requirements for such a remote-handling refabrication facility are much like a reprocessing plant, economies of project scope drives one to integrate refabrication 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 for both operations and maintenance.

2. The regulatory and quality assurance requirements for such refabricated fuel are not yet available in the form of an ASTM fuel specification, such as that available for enriched UO_2 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 multi-reactor 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 U/ clean Pu driver fuel or U or Th 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 or natural-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 highly-shielded 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 in the U.S. 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 of the fuel cycle, 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 E-Chem pyro-reprocessing and pyro-refabrication. See Module D1-4 for more information about fuel fabrication of SFR ceramic pellets.)

Status of the Industry. Reprocessing and production of remote-handled metal fast reactor fuels is not yet performed 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, metal fueled fast reactors. ANL-West successfully demonstrated such technology at their Fuel Conditioning 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, South Korea 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– 4).

Figure F2/D2-1-4, Figure F2/D2-1-5, amd Figure F2/D2-1-6 provide a flowsheet and conceptual drawings for the major parts 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.
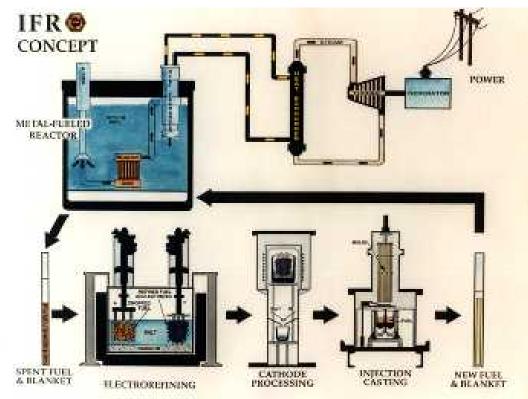

Figure F2/D2-1-4. ANL Integral Fast Reactor concept showing last three refabrication steps.
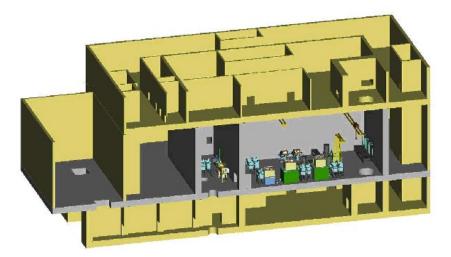
Figure F2/D2-1-5. Three-dimensional conceptual rendering of the Advanced Pyroprocess Recycle Facility (Frigo et al. 2003).
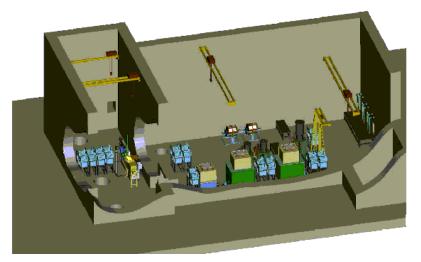

Figure F2/D2-1-6. Three-dimensional conceptual rendering of the air and process cells (Frigo et al. 2003).

F2/D2-1-4. MODULE INTERFACES

This F2/D2 module interfaces with upstream reactor R-modules (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 handling and 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. High Assay Low-Enriched Uranium (HALEU) is likely to be a component, along with "clean" separated Pu, for SFR start-up cores. (5% to 19,75% U-235 assay U is considered HALEU.)

Dirty MOX Considered. 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) 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 and actinide daughter 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 an aqueous UREX-1a reprocessing facility.

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

Table F2/D2-1-1. Summary of cost and technical parameters of studies underlying basis reported cost estimates.

Chracteristic	IFR	ALMR	So Korea Pyro	So Korea PRIDE
Study Authors	Lineberry et al.	Delene et al.	Kim et al.	Kim et al.
Vintage of Report	1985	1993	2013	2015
Originating Organization	ANL (USA)	ORNL (USA)	KAERI (S. Korea)	KAERI (S. Korea)
Average Plant throughput in kgHM/yr	20,000	200,000	32,900	10,000
Reactor Capacity Serviced (Mwe)	1,400	1,488	3,600	n/a
Reactor Fuel Type	U-Pu-Zr metal alloy	generic metal or MOX	metal alloy	DU + surrogate HAs and FPs
Annual Reload Fuel amount required per GW of reactor capacity supported (MTHM/Gwe)	13.6	15.4	9.1	n/a
Unit Cost in then-yr $ with no interest per report authors' data ($/kgHM)	685	2,521	5,128	993
Escalation index from then-yr $ to 2017$	3.51	2.74	1.066	1.04
Escalation table source	Nuclear Market Basket from ch 9 of 2017 ARC-CBR Main report	Nuclear Market Basket from ch 9 of 2017 ARC-CBR Main report	US Implicit Price Deflator	US Implicit Price Deflator
Unit Cost in 2017 $ with no interest using author's cost data ($/kgHM)	2,405	6,906	5,467	1,033
Unit cost in 2017$ with IDC, capital recovery, and D&D sinking fund ($/kgHM)	2,668	7,377	6,755	1,220

F2/D2-1-5.1. ANL-GE Estimates from 1985-1993

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 regular reactor refueling. Recycled fuel is also fabricated in this facility. In this study, of the annual recycled fuel, 60% is blanket and 40% is driver. 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 (indicated as "IFR" in Table F2/D2-1-1) (Lineberry et al. 1985). While the estimate was performed by a government-sponsored laboratory, and based on government experience, no assumption was made on whether government or private funding/operation of the proposed facility is assumed. Table F2/D2-1-1 shows that for the IFR, after escalation to 2017 dollars, the unit costs from this study are $2,668/kgHM.

Based on the same ANL technology of the (Lineberry et al. 1985) reference discussed above, GE's ALMR program a few years later prepared a conceptual design and conducted a cost study for a more advanced electrochemical processing facility (Taylor et al. 1991; ORNL 1992; Delene et al. 1993). 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. In Delene et al. the modeled technology for ALMR relies on unit fuel fabrication cost from a source not provided in the documentation. As shown in Table F2/D2-1-1, escalating the cost estimates to 2017 dollars yields a unit cost of $7,377/kgHM, which reflect the cost of separations and fuel fabrication. The reader should note that this estimate is "generic" in that the study did not specify a fuel type (whether oxide, carbide, nitride,

or metal) and thus the relatively high cost estimate likely accounts for a range of fuel types. 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).

F2/D2-1-5.2. KAERI Estimates from 2013-2015

Based on recent publications, electrochemical reprocessing and remote fuel fabrication are under investigation at the Korea Atomic Energy Research Institute (KAERI) (Kim et al. 2013; Kim et al. 2015; Gao et al. 2016; Kim et al. 2017a,b). A theme noted in these studies is the interest on the part of researchers at KAERI to solve the problem of spent nuclear fuel, particularly as Asian counties expand nuclear power generation. While several aspects of technology and economic uncertainty with respect to electrochemical reprocessing and fuel fabrication are examined in these studies, two of them (Kim et al. 2013 and Kim et al. 2015), are germane to the discussion of this module.

Recognizing that electrochemical reprocessing of spent nuclear fuel can reduce the need for fuel disposal and disposition, Kim et al. 2013 conducts a break-even analysis of electrochemical reprocessing technology against direct disposal of spent nuclear fuel. The justification is that electrochemical reprocessing must at least be cost competitive with disposal costs in order for electrochemical reprocessing to be an economically viable option in the nuclear fuel cycle. These authors generate a cost estimate for electrochemical reprocessing using cost estimating by analogy, parametric and engineering cost estimating. The analogy method that the authors apply selects a cost object, which is a process in the separations technology. Then the authors estimate the cost of the object under consideration based on the degree of similarity in the object forming the basis and the object to be cost estimated. The parametric method is a form of regression analysis. It includes as the dependent variable the total cost then includes in the regression independent variables such as facility scale and production quantity of nuclear fuel. The engineering cost estimating method begins at what the authors call the "low phase" then the cost estimate is accumulated to the highest phase. The authors note that the availability of a conceptual design is required for this approach. These cost estimating methods are discussed in greater detail in AFC-CBR Ch. 3. Additionally, the authors utilize expert elicitation and earned value management system. However, they do not report which methodologies pertain to each component of their presented analysis. Their analysis finds a levelized unit cost (LUC) of $5,311/kgHM ($5,630 in 2017 dollars). Underlying assumptions to this estimate include a facility that processes about 33 MTHM/yr, operating 200 days per year for a 50% load factor, and the output irradiated fuel is uranium at wt 20.6% and transuranics at wt 10%. A couple years later Kim et al. estimated another aspect of electrochemical reprocessing unit cost (Kim et al. 2015).

Kim et al. 2015 utilized the process costing approach to estimate the unit cost of electrochemical reprocessing based on a small, pilot scale facility in South Korea called PRIDE (PyRoprocess Integrated inactive DEmonstration). The authors note a weakness in the engineering approach to estimate unit cost because the cost of each unit operation cannot be estimated separately, hence the advantage in the process costing approach. Unlike the engineering approach to cost estimation, where inputs used are individually costed out, the process costing method allocates cost based on levels of throughput. Specifically, instead of assigning costs by inputs used, costs are assigned by process costs. The PRIDE facility can process up to 10 MTHM/yr. In the study, the simulated fuel, containing depleted uranium and "surrogate" rare earth elements as stand-ins for HAs, are the materials underlying the basis of the study. This study estimates the cost of electrochemical reprocessing at $951/kgU-TRU ($980 in 2017 dollars).

These two studies inform on an important point. Researchers at KAERI are actively investigating the economics of electrochemical reprocessing. The difference in the cost estimates from each study suggests there is much yet to learn about the costs of electrochemical reprocessing systems. As additional economic information is available, this module will incorporate it in future updates.

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 INL-FCF (Fuel Conditioning

Facility) 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 $212,440/kgHM ($637M to process 3,000 kgHM). Blanket fuel processing will cost $29,380/kgHM ($588M 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.

F2/D2-1-5.3. 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 (e.g. see Module D1-5 on vibrocompaction) for fast reactor fuel fabrication to electrochemical fuel reprocessing.

F2/D2-1-5.4. 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 of SFR metal fuel.

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 studies 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 at least a request for a life extension to 80 years have been submitted to the NRC as of 2018. 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 become 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.

F2/D2-1-5.5. The (WSRC 2008) Cost Study

This study on pyroprocessing cost was performed as part of a GNEP "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 differences in technology and equipment to those of aqueous separation. In particular, an "engineering analysis" was performed for pyroprocessing to adjust the estimates based only on a $/ft^2 basisalthough 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 Module F1 (Aqueous Reprocessing). 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 for LWR UNF without refabrication, of between $12.4B and $18B, was adjusted as discussed above to between $6.5B and $9.5B. For a facility lifetime of 50 years and a 3% discount rate, the levelized unit capital cost would therefore be between 839 $/kgHM and 1221 $/kgHM. O&M was reported in (WSRC 2008) as between $294.3M and $447M annually, resulting therefore in a unit O&M cost of 981 $/kgHM to 1493 $/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 (Ganda 2016). 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 1820 $/kgHM (assuming the low of capital and the low of O&M costs) and 2703 $/kgHM (assuming the high capital and the high O&M costs), approximated as 1853-2725 $/kgHM.

F2/D2-1-5.6. The (Carter 2010) Cost Study

The (Carter 2010) study is for an integrated facility (serving SFRs) performing both electrochemical separation and remote fabrication of the separated actinide material. As with the WSRC 2008 cost study, the cost estimates for the (Carter 2010) facility are 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 Module) 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 $3.0B and $4.3B (low and high estimates) for a 21.7 MTHM/year facility. After the capital cost adjustment discussed above, the expected construction cost was reduced to between $1.6B and $2.3B. 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 levelized unit capital cost would be between 855 $/kgHM and 1254 $/kgHM. These values are very close to those obtained in (WSRC 2008), at 855 $/kgHM and 1277 $/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 levelized unit cost because of (1) larger size, with possible economies of scale; and (2) removal of 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 separations 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 equipment and 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 $61.6M (assuming 4% of the low range of capital cost) and $159.6M (assuming 7% of the high range of capital cost), resulting in levelized unit O&M costs of between 878 $/kgHM and 2280 $/kgHM.

The total adjusted combined pyroprocessing and refabrication levelized unit costs of (Carter 2010) can therefore be estimated at between 1739 $/kgHM (with the low range of capital investment and the low fraction of O&M costs of 4%) and 3515 $/kgHM (with the high range of capital investment and the high fraction of O&M costs of 7%), approximated as 1710-3534 $/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.

F2/D2-1-5.7. The (Landmark 2015) Cost Study

This is a 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 for LWR UNF without refabrication, but with oxide reduction to metal before the processing (separation) steps. 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. This study reflects a plant that reprocesses LWR fuel coming in as oxide and consisting of > 90% U.

The estimated total construction cost was found to be between $388.5M and $472.5M 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 $756M. For a facility lifetime of 50 years and a 3% discount rate, the levelized unit capital cost would therefore be 397 $/kgHM. O&M was reported in (Landmark 2015) as $53.6M annually, resulting therefore in a levelized unit O&M cost of 536 $/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 827 $/kgHM, approximated as 840 $/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.

- The need for an oxide to metal reduction step for LWR SNF prior to pyroprocessing is in itself a significant cost, since reduction to metal is generally a batch process limited by criticality considerations even for spent fuel. The reduction process would need to take place in the same highly shielded process building as the separations step. Incremental O&M costs could be in the hundreds of dollars per kg of initial LWR HM.

- 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 912 $/kgHM (1739 $/kgHM (Carter 2010) minus 827 $/kgHM (Landmark 2015)) and 2675 $/kgHM (3515 $/kgHM minus 840 $/kgHM), approximated as 900 $/kgHM to 2700 $/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/D2-1-1 shows the unit cost for a 20 MT/y (Lineberry et al. 1985) and a 200 MT/y (Delene et al. 1993) 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 0.44, 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 (Lineberry et al. 1985), and the 200 MT/y in the period 1991-1993 was performed by ORNL (Delene et al. 1993), 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. Nevertheless, since this scaling exponent is the only one that could be derived thus far based on available studies, it is recommended to use it until further studies may provide further data on scaling considerations.

F2/D2-1-7. DATA LIMITATIONS

No commercial-scale pyroprocessing and remote fabrication facility for nuclear fuel has been built so far. One engineering-scale facility has operated: the FCF at MFC at INL processed and fabricated metal fuel for the EBR-II and demonstrated electrochemical reprocessing. One pilot scale facility has been operated by KAERI. In practice, virtually all the cost data that were found and collected here are from studies based on the same IFR 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… To overcome this limitation, the cost estimates reported in Table F2/D2-1-2 have been vetted for consistency. The studies discussed in section F2/D2-1-5 have been reviewed in detail. Cost estimates reported therein have been escalated to $2017 based on the escalation methodologies discussed in Chapter 8 of the CBR. Then estimates have had interest during construction (IDC), the capital recovery factor, and payment into the D&D fund applied equally. This forms a basis of comparison and also the cost range reported in Table F2/D2-1-2. The study documenting the costs of the ALMR technology, found in Delene et al. (1993), are not part of the cost basis for the following reason: The study does not provide sufficient detail about the type of fuel assumed for fuel fabrication. This is likely because the focus of the study was not on estimating the fuel fabrication costs; rather these costs were part of a larger SFR fleet analysis and thus detail on fuel fabrication is not included. However, the lack of detail implies that it does not provide a sufficient basis to be part of the range recommended in Table F2/D2-1-2.

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/D2-1-5.

In Section F2/D2-1-8, unit costs ranges, including probability distributions to represent 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 levelized unit cost in terms of dollars per kg heavy metal ($/kgHM). Therefore, in order to arrive at a uniform unit cost so that costs are comparable, assumptions on facility lifetimes and discount rates are necessary. Those assumptions add to the uncertainty in the data. 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 additional 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 Nth-of-a-kind (NOAK) 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/D2-1-2 (integrated pyroprocessing separation and remote refabrication) and F2/D2-1-3 (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/D2-1-2, 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 reprocessing only, as discussed in Section F2/D2-1-5.

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

Figure F2/D2– 7 and Figure F2/D2– 8 show the probability distributions for summary the unit costs described in Tables F2/D2-1-2 and Table F2/D2-1-3.

Table F2/D2-1-2. WIT cost summary table for integrated pyroprocessing separation and remote refabrication (2020$).

Reference Cost(s) Based on Reference Capacity	Low	Mode (=Mean)	High
Integrated pyroprocessing separation and remote refabrication	$2700/kgHM	$4750/kgHM	$6800/kgHM
Justification	Approximated from $2668/kgHM found in Lineberry et al. (1985). Includes IDC, capital recovery at 5%, and D&D payment.	Simple average between the two extreme values.	Approximated from $6755/kgHM found in Kim et al. (2013). Includes IDC, capital recovery at 5%, and annual D&D escrow fund payments.
Escalated to $2020 at 5.2% then rounded to nearest 50	$2850/kgHM	$5000/kgHM	$7100/kgHM

Table F2/D2-1-3. WIT cost summary table for remote refabrication only (2020$).

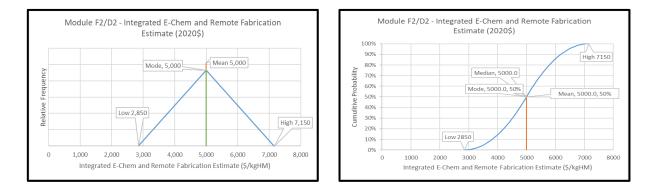| Reference Cost(s) Based on Reference Capacity	Low	Mode (=Mean)	High
Remote refabrication only	$1000/kgHM	$1850/kgHM	$2700/kgHM
Justification	Difference from integrated and UREX+1a, using low values for both.	Simple average between the two extreme values.	Difference from integrated and UREX+1a, using high values for both.
Escalated to $2020 at 5.2% then rounded to nearest 50	$1052/kgHM	$1950/kgHM	$2850/kgHM

Figure F2/D2-1-7. Module F2/D2 distribution of combined unit cost for electrochemical reprocessing and remote fabrication of fast reactor metal fuel.
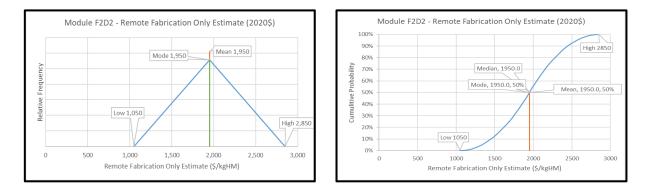

Figure F2/D2-1-8. Module F2/D2 distribution of unit cost for remote fabrication only.

F2/D2-1-9. REFERENCES

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F2/D2-2 Gas-Solid Phase Thermochemistry

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F2/D2-2 Gas-Solid Phase Thermochemistry

F2/D2-2 SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**

- **Nature of this 2017 Module update from previous AFC-CBRs**: This represents a new section that is under development by authors of the AFC-CBR. New data and cost bases to be provided in the future subject to newly available information.

F2/D2-2-1. BASIC INFORMATION

Electrochemical reprocessing (a.k.a. pyroprocessing) and refabrication falls into a major class of nuclear fuel cycle processes known as "Dry" Processes, all of which do not involve the use of aqueous solutions such as the more familiar PUREX, UREX, and COEX processes. The other major category of dry processes might be called "Gas-Solid Phase Thermochemistry" processes which involve changing the physical form of the UNF by heating and the removal (separation) of particular fission products and actinides by reaction of the UNF with a reactive gas and/or further heating and component volatilization. An example would be the AIROX process where addition of air at high temperature causes the spent UO_2 pellets to form U_3O_8 and thereby crumble to a powder capable of further gas-solid phase reactions. The heat itself also drives off volatile fission products such as tritium, iodine, and technicium. In fluoride-volatility-type dry processes, fluorine is used to convert uranium to the volatile gas UF_6 which can be collected and easily purified. In most of these dry processes a powder product freed of many of the most volatile fission products remains and can be formed (refabricated) into still-very-"hot" fuel which can be re-irradiated in a reactor. The post-volatilization remaining fission products and actinides, however, require that the refabrication and refueling steps be remote rather than contact handled. AIROX and CARBOX were two such processes investigated from the 1960s through the 1990s. DUPIC is still being considered by the Canadian and South Korean nuclear industry as a way of converting LWR spent fuel into a form suitable for use in Canadian CANDU pressurized heavy water reactors. Life cycle cost estimates have been made for CARBOX, AIROX, and DUPIC and have been normalized by the AFC-CBR authors into year 2017 $ unit costs using a consistent set of economic parameters and escalation factors. This Table appears in Module Section D2/R2-2 separate from the Tables for E-chem in D2/R2-1.

F2/D2-2-2. COST BASES, ASSUMPTIONS, AND DATA SOURCES

The Atomics International Reduction OXidation (AIROX) process was developed for the treatment of UO_2 fuel. Heat is applied in an oxidizing atmosphere to create U_3O_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 UO_2. Most fission products are removed during a series of these oxidation-reduction reactions, and the final impure UO_2 product can be remotely reformed into fuel pellets for recycle. Thomas (1993) describes the AIROX process for a facility with capacity of 200 MTHM/yr, and includes remote fuel refabrication. The modeled facility processes LWR UO_2 ceramic fuel. Escalating the reported costs in that study to $2017 results in an estimate of AIROX at $3,777/kgHM, which represents the cost of reprocessing and fuel refabrication in hot UO_2 assemblies. 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). Escalating the reported costs from those two studies to $2017 dollars, yields the unit cost of the CARBOX process at $2,374/kgHM. This unit cost represents the cost of reprocessing fuel, and refabricating fuel. More recently, researchers at KAERI applied bottom-up estimating to the cost of fuel fabrication based on DUPIC technology (Choi et al. 2001). The assumed

facility in the KAERI study, centrally located and in support of seven 1000 MWe CANDU reactors, has a capacity of 400 MTHM/yr. This facility is based on four processing lines using AIROX, dry processing technology. After escalating the reported cost estimates in the study to 2017 dollars, the estimate results at $978/kgHM.

F2/D2-2-3. COST SUMMARIES

The module cost information is summarized in the What-It-Takes (WIT) cost summaries in Table F2/D2-2-1 and Figure F2/D2-2-1. 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/D2-2-2, the unit costs are derived primarily from studies documented in Choi et al. (2001), Thomas (1993), and in Colby et al. (1965; 1963). For a full explanation of the derivation of the cost summaries, as well as the limitation and uncertainty of the data, the reader is advised to read the relevant sections of this module.

Table F2/D2-2-1.WIT cost summary table for gas-solid phase chemistry separations and fuel fabrication (2020$).

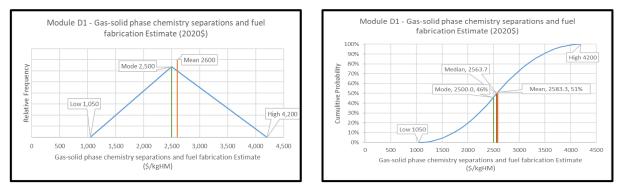| Reference Cost(s) Based on Reference Capacity	Low	Mode (=Mean)	High
Gas-solid phase chemistry separations	$1,000/kgHM	$2,376/kgHM	$4,000/kgHM
Justification	Approximated from $978/kgHM found in Choi et al. (2001).	Simple average over the estimates of three studies reviewed. Also, the escalated CARBOX (Colby, et al. 1963, 1965) cost of $2,374/kgHM come very close to this value, providing further support.	Approximated from $3,777/kgHM found in Thomas (1993).
Escalated to $2020 at 5.2% then rounded to nearest 50	$1050/kgHM	$2500/kgHM	$4200/kgHM

Figure F2/D2-2-1. Module F2/D2 distribution of unit cost for gas-solid phase chemistry separations.

F2/D2-2-4. REFERENCES

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