Advanced Fuel Cycle Cost Basis Report: Module D1-1

Uranium-Based Ceramic LWR Fuel Fabrication

Nuclear Fuel Cycle and Supply Chain

Prepared for
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Revision 2

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
Relevant historical context from previous version of the AFC-CBR. (2008)			Version of AFC-CBR in which this module first appeared: 2004 as Module D1-1. In the 2008 AFC-CBR, the refabrication unit costs for light-water reactor (LWR) fuel made from re-enriched reprocessed uranium were added to the already existing list of fabrication unit costs for unirradiated enriched UO2 EUO2 derived from mining and milling, U3O8 to UF6 conversion, and uranium enrichment up to 4.95% U-235.
Relevant historical context from previous version of the AFC-CBR. (2012)			Latest version of module in which new technical data or new market assessments were used to establish unit cost ranges: 2012 AFC-CBR for latest market assessment. Most of the background text and literature-derived historical costs and prices in the 2012 version are carried forward with escalation to the 2017 AFC-CBR (Dixon et al. 2017).
Rev 0	2023	All	Revision 0 of this module marks the first time this module is published independent of the AFC-CBR. Rev 0 is the first to incorporate detailed life cycle cost information based on a 1978 bottom-up estimate for a Nth-of-a-kind large LWR UO2 fuel fabrication facility prepared for the Nonproliferation Alternative Systems Assessment Program (NASAP) project. The methodology for updating the 1978 ORNL/NASAP estimate to today's U.S. dollars (USD) and deriving a new levelized unit fabrication cost therefor is presented in considerable detail. The actual work on this document started in fiscal year (FY) 2018 after publication of the 2017 AFC-CBR; hence, the use of 2017 USD for which 1978 to 2017 escalation indices were used. In this document, an escalation factor of 1.052 is used to convert the 2017 USD to 2020 USD. There has been considerable progress in the area of enhanced accident-tolerant LWR fuels (ATF), including some types already inserted as lead test assemblies in commercial reactors. Most of the technical enhancements to conventional LWR fuels are in the fuel cladding; however, some modifications to the structure and chemistry of the "fuel meat" are being considered (e.g., doping UO2 with chromia and/or alumina). For this update, a Westinghouse report (Lahoda et al. 2015) with some projections for ATF manufacturing costs has been used to calculate unit fabrication costs for two types of ATFs. For small LWRs, the use of ceramic pelletized fuels enriched to > 5% U-235 but less than 20% U-235 (i.e., high-assay low-enriched uranium [HALEU]) may be required for longer core life and neutron economy reasons. For large LWRs, the use of LEU+ (5 to 9.75% U-235) may prove economically beneficial. The possible cost effects of manufacturing such HALEU are briefly discussed for the first time in this report. Module C3 of the AFC-CBR considers the implications of HALEU use on all other affected steps of the nuclear fuel cycle, such as uranium

Rev.	Date	Affected Pages	Revision Description
			enrichment and the deconversion of HALEUF6 required before fuel fabrication. New technical/cost data which may become available and will benefit next revision. As ATFs are manufactured in small lots for partial reloads, some actual data on production costs or incremental pricing above that for conventional LWR low-enriched UOX (uranium dioxide) fuel may become available. It should be noted that many ATFs will allow higher burnups and extended fuel life, thus a higher unit fabrication cost ($/kgU) may actually translate to a lower fuel cycle cost per kilowatt-hour of energy from the utilizing reactors.

ACKNOWLEDGEMENT

Revision 0 of *Module D-1-1: Ceramic Uranium-Based LWR Fuel Fabrication* is the cumulative effort (spanning from 2004 to the present) of many authors who have contributed to the overall *Advanced Fuel Cycle Cost Basis Report* and all of its fuel cycle modules. All the authors (the four primary authors, 15 contributing authors, 12 contributors acknowledged, and many other unacknowledged contributors) have contributed various amounts to developing and writing this module prior to this current revision. Unfortunately, there is no history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

Additional acknowledgement, specific to this revision, is given to the primary technical developer and lead author of this revision, Kent Williams (Oak Ridge National Laboratory, retired). Other contributing authors to this revision are Jason Hansen (Idaho National Laboratory, jason.hansen@inl.gov) and Edward Hoffman (Argonne National Laboratory, ehoffman@anl.gov) who can be contacted with any questions regarding this document.

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ACRONYMS

ACFAC	a cash flow analysis code
ADOPT	Advanced Doped Pellet Technology
ADU	ammonium diuranate
AFC-CBR	advanced fuel cycle cost basis report
AGR	advanced gas-cooled reactors (UK)
ANL	Argonne National Laboratory
ANS	American Nuclear Society
AOO	anticipated operational occurrence
ATF	accident-tolerant fuel
BDBA	beyond design basis accident
BWR	boiling-water reactors
CEA	Commeseriat Energie Atomique (France)
CFR	Code of Federal Regulations (USA)
CPI	consumer price index
CRF	Capital recovery factor
D&D	decontamination and decommissioning
DBA	design basis accident
DOE	Department of Energy
DOE-NE	U.S. Department of Energy-Nuclear Energy
DU	depleted uranium
DU3O8	depleted triuranium octoxide
DUF6	depleted uranium hexafluoride
EdF	Electricite de France
EPRI	Electric Power Research Institute
ERI	Energy Research Institute
ES&H	environmental, health, and safety
EU	enriched uranium
EUF6	enriched uranium hexafluoride
EUO2	enriched uranium dioxide (a.k.a., EUOX)
FC	fuel cycle
FCM	fully ceramic microencapsulated fuel
FCRD	Fuel Cycle Research and Development
FOAK	first-of-a-kind

FTE	full-time equivalent
G&A	General and administrative
G4-ECONS	Generation IV- EXCEL Calculation of Nuclear Systems
GE	General Electric
GNF	Global Nuclear Fuels
HALEU	high-assay, low-enriched uranium
HF	hydrofluoric acid
HF	hydrogen fluoride
HM	heavy metal
HVAC	heating and ventilation and air conditioning
IAEA	International Atomic Energy Agency
IDC	interest during construction
INL	Idaho National Laboratory
IPD	implicit price deflator
Kg	kilograms
LCC	life cycle cost
LEU	low-enriched uranium
LEUF6	low-enriched uranium hexafluoride
LEUO2	low-enriched uranium dioxide (a.k.a.,. LEUOX)
LUEC	levelized unit electricity cost
LWR	light-water reactor
MCP&A	Material Control, Protection, and Accountability
MIT	Massachusetts Institute of Technology
MPC&A	materials protection, control, and accountability
MTHM	metric tons of heavy metal
N/A	not applicable or not available
NAC	Nuclear Assurance Corporation
NASAP	Nonproliferation Alternative Systems Assessment Program
NEA	Nuclear Energy Agency (part of OECD)
NEI	Nuclear Energy Institute (USA)
NFS	Nuclear Fuel Services, Corp (BWXT subsidiary)
NNSA	National Nuclear Security Administration
NOAK	Nth-of-a-kind
NPP	nuclear power plant
NSSS	nuclear steam supply system

O&M	operations and maintenance
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PCCI	power capital cost index
PNNL	Pacific Northwest National Laboratory
PUREX	plutonium and uranium recovery by extraction (reprocessing method)
PWR	pressurized-water reactors
QA	quality assurance
QC	quality control
RBMK	reactor bolshoy moshchnosky kanalny (high-power channel reactor): Russia
REPU	reprocessed uranium directly from reprocessing plant or in some cases product from an enrichment plant that took chemically separated U as feed)
ROI	return on investment
RSICC	Radiation Safety Information Computational Center at ORNL
RU	reprocessed uranium
SA&I	Systems Analysis and Integration (part of DOE-NE-FCRD)
SiC	silicon carbide
SWU	separative work unit
TCC	total financing inclusive capital cost
TRISO	tristructural isotropic (one type of particle fuel)
TRU	transuranic
TVA	Tennessee Valley Authority (USA)
U-LEU	unirradiated LEU
UN	uranium nitride
UNH	uranyl nitrate hexahydrate
UOX	uranium dioxide (a.k.a.,. UO2)
UREX	uranium extraction (reprocessing method)
USAEC	United States Atomic Energy Commission
USNRC	U.S. Nuclear Regulatory Commission
VVER	vod-vodyanoi energitichetsky reactor (Russian version of PWR)
WEC	Westinghouse Electric Company
WIT	what-it-takes
WNA	World Nuclear Association
Zr	zirconium

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Module D1-1
Uranium-based Ceramic LWR Fuel Fabrication

SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant U.S. Dollar (USD or $) Base Year 2020 for Revision 0 in this Fiscal Year (FY) 2023 Update.**
- **Nature of this FY-23 Module Update from Previous Advanced Fuel Cycle Cost Basis Reports (AFC-CBRs):** In this update, we are adding detailed life cycle cost data and a calculated, levelized fabrication cost derived from a non-proprietary bottom-up estimate prepared in 1978 by Oak Ridge National Laboratory (ORNL) (Judkins and Olsen 1978a). In 2018, the 1978 ORNL estimate was escalated by SA&I authors to 2017 USD using factors that represent inflation, escalation above inflation typical of nuclear projects, and the effects of more stringent safety and environmental regulations. In this FY-21 document, the $/kgU results in 2017 USD from the unpublished 2018 interim study (Williams and Ganda 2018) can be escalated to 2020 USD using a factor of 1.052. The literature-based unit cost (or price) data from previous (2004–2017) AFC-CBRs are escalated to 2020 USD using factors from Chapter 8 of the main FY-21 AFC-CBR document. This data, in addition to the results of the updated bottom-up estimate, are used to define the “what-it-takes” (WIT) range for the unit fabrication costs for conventional ceramic UOX light-water reactor (LWR) fuel. This FY-23 document also includes calculated unit costs for accident-tolerant LWR fuels (ATFs) of three different types. Some of these fuels constitute a ceramic pelletized form with fuel meat uranium compounds other than UO2 (a.k.a.,. UOX), thus the change in the title of this module in which the word “UO2” is changed to “Uranium-based Ceramic.”
- **Estimating Methodologies for the Latest FY-21 Technical Updates:**
    - Literature review of pricing for this commodity service, which is a totally mature technology for zirconium-alloy clad LWR fuel. A late 2012 technical assessment noted that unit costs for pressurized-water reactor (PWR) and boiling water reactor (BWR) fuel are moving closer together, probably a result of most commercial fuel fabricators now manufacturing both types.
    - A bottom-up 1978 estimate for an ~500 MTU/yr PWR UO_2 fuel fabrication facility prepared by ORNL (Judkins and Olsen 1978) as part of the NASAP (Nonproliferation Alternative Systems Assessment Program). In 2018, this newly identified archival estimate was accessed, analyzed, and updated for technical factors and escalated to 2017 USD. The process and results were documented in a 2018 unpublished SA&I internal report (Williams and Ganda 2018) which has been fully integrated into this revision and updated with minor changes.
    - Unit costs for two types of proposed LWR ATFs estimated from analysis of a Department of Energy-Nuclear Energy (DOE-NE)-funded life cycle cost study performed by Westinghouse (Lahoda et al. 2015).

It should be noted that this module has not been updated to reflect new market supply/demand and pricing conditions. Factors related to the sale, closure, or opening of existing or new facilities are not addressed; however, a list of domestic operating LWR fuel fabrication facilities and their production capacities is included in this document.

D1-1.1. BASIC INFORMATION

Fuel Form. Low-enriched uranium (LEU) LWR fuel for both PWRs and BWRs is in the form of ceramic-enriched UO2 (EUO2) sintered pellets stacked inside long (up to 14 ft, depending on the reactor size and manufacturer and the fuel design) and sealed Zircalloy (or other zirconium-based alloys such as Zirlo, E-110, M-5, etc.) tubes. A Western fuel assembly consists of a square (n × n) array of these tubes separated by spacers and held in place via clips and springs. Most of the hardware holding the tubes is also made of Zircalloy or a similar zirconium alloy. The upward flowing water (PWR) or steam/water mixture (BWR) removes the nuclear-generated heat by contacting the outside surface of the Zircalloy tubes enclosing the sintered pellets. Before sealing, the tubes are pressurized with helium and a free space left at the top of the rod to act as a gas plenum. The tubes are also designed to handle the pressure of the fission product gases generated during fuel irradiation. Figure D1-1.1 shows both a BWR and a PWR fuel assembly.

D1-1.2. FUNCTIONAL AND OPERATIONAL DESCRIPTION OF LWR FUEL FABRICATION INDUSTRY

Production of such ceramic pellet-based LWR fuel assemblies is a highly mature industry and is fully privatized in the United States. Because of the need to specifically tailor the fuel to the reactor, many of the companies' manufacturing LWR assemblies are also affiliated with the ones that design the nuclear steam supply system (NSSS) for the reactor using the fuel. Table D1-1.1 lists the LWR fuel fabricators in the United States and the current production capacities in terms of MTU/yr for their facilities. The World Nuclear Association publishes a similar list of all world fuel fabrication facilities on their website (WNA 2020a).

Historical Background from Previous AFC-CBRs: LWR fuel fabrication is a highly competitive nuclear business, and because of two decades of worldwide oversupply (Varley 2002) and general consolidation (Kidd 2005) of the nuclear business, the number of fabrication plants in the United States has dropped to four. The LWR fuel fabrication business, however, is highly international, and there are at least 12 countries outside of the United States that have LWR fuel fabrication plants. Some of these foreign companies have significantly expanded their business (Siebert 2006; Gizitdinov 2007; Rothwell and Braun 2007). Some of these foreign companies also sell fully-fabricated fuel bundles to U.S. utility customers; however, this procurement requires that the fuel production process and the fuel itself be certified by the U.S. Nuclear Regulatory Commission (USNRC) just as it would be for a domestic fabricator. Figure D1-1.1 shows a typical BWR and a typical PWR fuel assembly manufactured by Global Nuclear Fuel Americas and AREVA NP, respectively.

Table D1-1.1. LWR fuel fabrication capacity in the United States (2020 status).

Plant Owner	Location	Capacity in MTU/yr (Conversion/Pelletizing/Rods and Assembly)	Fuel Type
AREVA NP/ Framatome (formerly Siemens)	Richland, Washington	1,200 1,200 1,200	Both BWR and PWR
AREVA NP (Energy-Business-review.com 2008)	Erwin, Tennessee	small	LEUO2 powder was produced from blended HEU/NATU nitrate solutions provided by NFS and after conversion to UO2 is sent to Richland for pelletization
Global Nuclear Fuel Americas, LLC (GE Energy, Toshiba, Hitachi)	Wilmington, North Carolina	1,200 1,000 1,000	Mainly BWR
Westinghouse Nuclear Fuel	Columbia, South Carolina	1,600 1,594 2,154	BWR, mostly PWR, some Vod-Vodyanoi Energetichesky Reaktor (VVER) for Eastern European customers

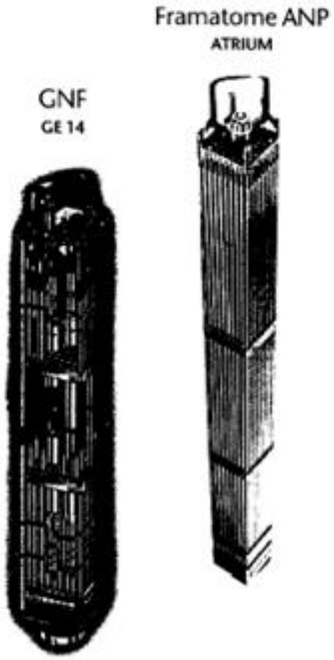


Figure D1-1.1. BWR and PWR fuel assemblies.

As mentioned above the number of fuel fabricators in the United States has decreased markedly in the 55 years since the commercial industry started. Table E-2 of a *1974 Environmental Survey of the Uranium Fuel Cycle* (USAEC 1974) lists 12 U.S. fabricators, their licensees, and geographic locations. Many of these plants had much smaller production rates than the "big three" (Richland, Columbia, and Wilmington plants) listed in the Table D1-1.1.

It is important to note that LWR fuel fabrication is a highly "campaigned" business (i.e., the production of the UO_2 powder and subsequent steps are designed to meet the utility customer's enrichment needs and the utility's fuel reload schedule). Each campaign may take several weeks, with time required between campaigns to retool for the next utility's requirements. Timely delivery of fuel is very important to a nuclear utility's profitability. The economic effects of delays are discussed in a report by Pacific Northwest National Laboratory (PNNL 2011).

D1-1.2.1 Status of the Industry in 2020

Little has changed from the 2017 AFC-CBR (Dixon et al. 2017) in the areas of the basic industrial process, its interfaces to other fuel cycle (FC) steps, and the status of LWR fuel fabrication facilities in the United States. The following should be noted, however:

- AREVA/Framatome closed its commercial reactor fuel fabrication operation at Lynchburg, VA around 2008 and moved its operations to their Richland, WA facility (February 2011). This facility uses a "dry" process to convert LEUF6 to LEUO2 for pellet production.
- Westinghouse has added the capability at its West Columbia, SC facility to produce BWR fuel. Sinterable LEUO2 powder is produced from LEUF6 via an anhydrous ammonia-free aqueous ADU process. Recent process modifications are discussed in a 2019 Environmental Assessment prepared by the USNRC (2019).
- Utilities are trying to diversify their fuel fabrication suppliers as much as possible in the hope that the pricing of this service will be more competitive. Foreign sources are considered if the fuel and production process meet USNRC-licensing regulations and standards.
- No U.S. fuel fabrication facilities are presently using feedstock uranium oxide derived from re-enriched, reprocessed uranium (REPU) derived from commercial spent LWR fuel. Unfavorable economics at today's ore and SWU prices, the lack of a U.S. reprocessing industry, and the need for additional fuel qualification have resulted in minimal interest in this route by U.S. nuclear utilities. REPU use in Europe continues and is described in a later section of this report.
- The fuel fabrication industry continues to be dominated by very high-quality assurance requirements, especially as utilities move toward the use of "zero-defect" fuel and the goal of no fuel failures.
- U.S. fuel fabrication facilities are still limited to the introduction of EUF6 (enriched UF6) feed at a U-235 assay of 4.95% or less. This is not a formal regulation but rather an industry understanding. For PWRs to exceed assembly-average fuel discharge burnups of about 55,000 MWth-days/MTHM or higher, U-235 assays may have to rise above the 5% level to what is considered "HALEU" (high-assay, LEU) (see Deutch et al. 2003, *Future of Nuclear Power*, p.119). Some LWR ATFs may also require, or benefit from, the use of HALEU; ATFs will be discussed in a later section of this module. Relicensing actions by the USNRC will almost certainly be required, which in turn might require significant modifications to the existing Security and Safeguards Category III (9.75% U-235 or less) fuel fabrication facilities for criticality safety, material accountability, and security. This is still a contentious issue in the fuel fabrication industry; however, as USNRC begins to consider rulemaking for Safeguards and Security Category II facilities (which will handle HALEU from 10 to 19.75% U-235 for customers including small modular reactors and microreactors), rules for Category III facilities handling HALEU above 5% and below 10% U-235 (also referred to as "LEU+") should evolve.

- The trend of some utilities and plant operators to purchase all front-end FC materials and services (including ore, conversion, enrichment, and fabrication) into a single “bundled” price for finished and delivered fuel assemblies continues.
- Outside the United States, other types of pelletized LEU fuels are still in use for the following reactor types: CO_2-cooled advanced gas-cooled reactors in the United Kingdom and early Soviet-design, graphite-moderated light-water-cooled RMBK (reactor bolshoy moshchnosky kanalny (high-power channel reactor): Russia) reactors. These systems are briefly discussed on the World Nuclear Association’s Fuel Fabrication website (WNA 2020).

D1-1.3. PICTURES AND DIAGRAMS

D1-1.3.1 Fuel Fabrication Process

Figure D1-1.2 shows the four basic non-transportation steps in the generic LWR fuel fabrication process. Figure D1-1.3 is a somewhat more detailed flowsheet showing the inputs and outputs of each major process step. The process shown in Figure D1-1.3 is an environmentally preferable and predominant “dry” process in which there are no aqueous steps in the main process. (There may be some aqueous or “wet” steps in the scrap recycle/recovery lines for such plants, however). Two U.S. manufacturers, Framatome (Richland, WA) and Global Nuclear Fuels (Wilmington, NC), have migrated toward the dry process and have already qualified low-enriched UO2 fuel prepared in this way.

The first step in the process is a chemical one, “enriched UF_6 to enriched UO_2 conversion.” Despite the oxide stoichiometry difference, it is basically the same as the “dry” depleted UF6 to depleted U3O8 process described in Module K1; except in this case, the fuel is enriched in U-235, and the typical plant EU throughput quantities (400 to 1,500 MTU/yr) are three to four orders-of-magnitude smaller than those in the existing U.S. plants for converting enrichment plant waste or “tails” UF6 depleted in U-235.

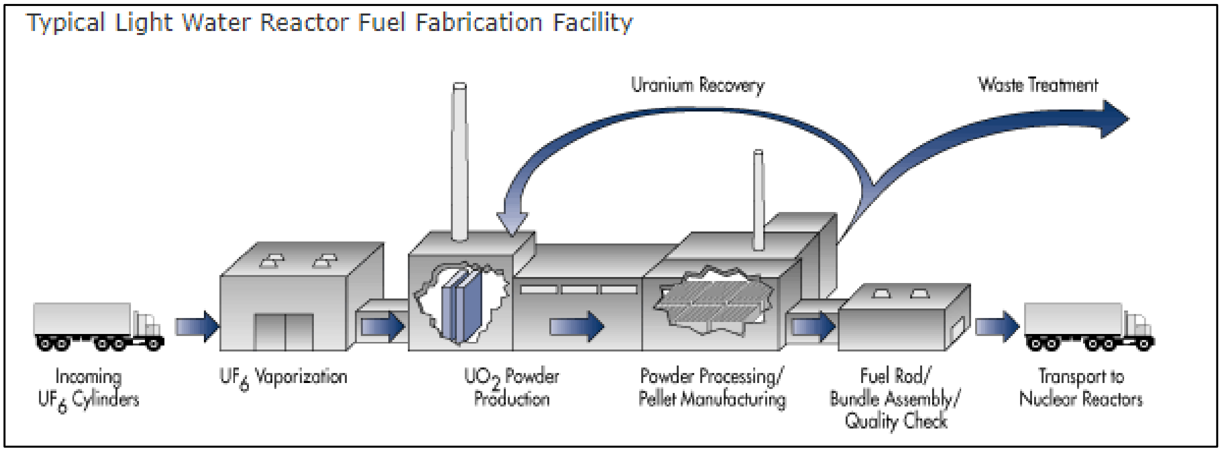


Figure D1-1.2. Major LWR fuel manufacturing steps (figure from reference USNRC 2019).

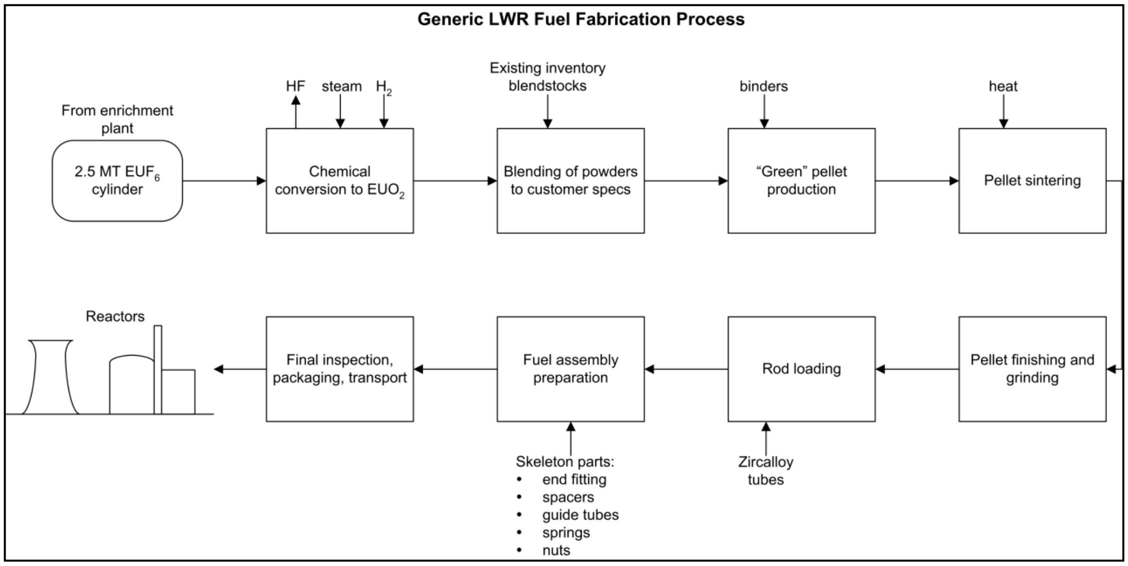


Figure D1-1.3. Generic LWR fuel fabrication process with "dry" conversion.

The chemical UF6 deconversion function is discussed in an Argonne National Laboratory report (Ranek and Monette 2001) which surveyed the deconversion capabilities of multiple U.S. commercial fuel fabricators. It should be noted that the Westinghouse (WEC) Columbia Fuel Fabrication facility (Westinghouse 2012) still uses a "wet" EUF6 deconversion process. This is accomplished via the ammonium diuranate (ADU) process which uses water and ammonium hydroxide. In 2011, WEC replaced the use of anhydrous ammonia with aqueous ammonium hydroxide. Environmental aspects of wet-type deconversion processes in fuel fabrication facilities are discussed in WASH-1284 (USAEC 1974).

Because the enrichment levels for enriched UO_2 are typically from 2 to 5% U-235, there are some criticality considerations in processing LWR fuel, and batch sizes must be limited. Quality assurance considerations are also important at every step. The enriched UO_2 powder from the first (deconversion) step must meet a very high purity and morphology specification (ASTM fuel specification) to be used in LWR fuel. The specified low impurity levels and particle size/flowability requirements ensure that the UO_2 will not attack the fuel cladding in the reactor, and the enriched UO_2 powder will sinter into a strong and stable pellet. For this reason, the cost per kgU for this first enriched UF_6 to enriched oxide deconversion step is at least an order of magnitude higher than the $5+/kgU required to deconvert depleted UF_6 as discussed in Module K1. This deconversion or "powder preparation" cost is eventually rolled into the overall unit fabrication $/kgU cost/price of the fuel assembly. The second step involves adjustment of the powder U-235 enrichment to meet the customer's requirement. This is done by blending it with small amount of preexisting enriched blendstock. A binder and flowability enhancer may also be blended with the enriched UO_2 powder to assist the pellet production steps, which are (1) pressing the "green" pellet, (2) sintering it to a homogeneous, hard ceramic structure, and (3) grinding and finishing it such that it meets dimensional specifications and loads easily into the Zircalloy tubes. Pellet inspection and loading fuel into tubes are automated processes requiring limited human interaction. Once the tubes are loaded, they are pressurized and welded shut. The washed tubes are then transported to the fuel bundle assembly room where the structural or "skeleton" hardware items, such as grids, nozzles, and spacers, are added. This operation is semi-automated and requires careful inspection and handling so that the tubes are not damaged and are inserted in the correct "n × n" tube array positions. Among the major operations costs involved in the above steps are the manufacturing and support personnel and the purchase or onsite manufacturing of Zircalloy tubes and assembly parts. As USNRC-licensed FC facilities under 10 CFR 70, LWR fuel fabrication facilities are also subject to regulatory costs such as inspections. The above recurring operations costs, however, can be partially offset by the sale of hydrogen fluoride (HF) from the UF_6 to UO_2 deconversion step if a buyer of very slightly uranium-contaminated HF can be found. Finished fuel assemblies are hung vertically for storage prior to shipping (Module O) to light-water nuclear power plants (Module R1).

D1-1.4. MODULE INTERFACES

D1-1.4.1 Front-End Interface

The enriched UF6 is received from the enrichment plant in 2.5 MTU “30B” type transportation cylinders. These criticality-safe certified cylinders must be “overpacked” during transportation from the enricher or blender in a certified outer packaging container. The chemical toxicity hazard associated with the fluorine product (gaseous HF) release in a transportation accident is far more serious than the small radioactivity level associated with any escaping uranium product UO2F2 (solid particles). (Released UF6 reacts with the moisture in the air to form HF and UO2F2.) Future use of HALEU UF6 as a fabrication plant feed will require the development and certification of a new transportation cylinder (cask) similar to the type 30B and an appropriate overpack.

D1-1.4.2 Back-End Interface

When ready for transportation, the finished fuel is loaded in special shock-absorbing packages, which are then enclosed in wooden crates. Commercial carriers usually transport these packages on flatbed trucks to the LWR plant sites. The ceramic UO_2 form in sealed tubes is a very safe non-reactive form for transportation, and the external radiation hazard is very low. For HALEU UO_2 fuel, new rules for transportation to reactors may need to be developed.

D1-1.5. SCALING CONSIDERATIONS

Additional LWR fuel fabrication capacity could be added by reopening existing shutdown production lines, constructing new additional lines, or by operating existing lines on more than one shift. New capacity would probably be added at an existing site to avoid new fixed overhead costs. A 2007 American Nuclear Society (ANS) paper by Rothwell and Braun (2007) and an earlier Stanford report (Rothwell 2007) discuss the scaling issue. Cost versus capacity scaling was also considered in a 1978 comparative study on fuel fabrication economics prepared by ORNL for the NASAP work. The results of this detailed study, including unit cost versus plant capacity scaling (Judkins and Olsen 1979), will be discussed in considerable detail in Section D1-1.8 below.

D1-1.6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

D1-1.6.1 Two Approaches to Cost Bases

Two approaches to cost bases are presented in this section. The first, used in all AFC-CBRs up to this point, involved searching for published “generic” (industry averaged) price data such as that found in nuclear economics studies prepared by other organizations such as OECD/NEA, DOE-NE, MIT, EPRI, and WNA. The second approach, to be discussed in detail below, involves the analysis by SA&I staff of an actual bottom-up LWR fuel fabrication facility cost estimate prepared 40+ years ago for basically the same fabrication technology as used today. At the end of this Section D1-1.8, the unit fabrication cost range information from these two analysis methods is then used to select the WIT unit fabrication price (or unit fabrication cost) for the uranium-based ceramic-pelletized fuel variants.

D1-1.6.2 Literature-Based

Literature-based fuel fabrication price information appears in earlier AFC-CBRs. The follow subsections discuss the information gleaned from literature searches that appear in earlier 2004–2017 AFC-CBRs in Module D1-1 of each. It is included for the sake of completeness and for the inclusion of multiple useful front-end FC price references.

D1-1.6.2.1 FY-21 AFC-CBR Cost Bases

Unlike uranium ore, natural U3O8 to UF6 conversion, and enrichment (SWU) prices, LEU fabrication prices (and costs) are unpublished and considered proprietary information. This is partly because each fuel fabrication batch, initial core or reload, is custom-designed to the utility’s core design and irradiation plan, and its price is separately negotiated. There are some nuclear consulting and fuel brokerage firms such as NAC International, UxC, NYNCO, ERI (Energy Resources International), and TradeTech that legally obtain financial data on such matters from users, which is then made available in a “sanitized” report form for subscribers to their services. An example is the “Fabrication Market Outlook” published annually by UxC. A description and table of contents for this document can be found in the following advertising reference (UxC 2020). This type of report is sold to utilities and other commercial parties at a price of several thousand U.S. dollars (USD) per copy. Quoting of such purchased numerical pricing data in a public document such as this would also be prohibited by non-disclosure agreements associated with such subscriptions. It has been possible, however, to calculate approximate LEU fabrication pricing over many initial and reloaded fuel batches from high-level data collected by regulatory agencies, universities, NGOs, and research and development institutions. Table D1-1.2 shows ranges and reference values for four data sources for LWR fuel fabrication that were cited in the 2009 AFC-CBR. Literature information sources are shown for each.

Table D1-1.2. Historical LEU fuel fabrication prices in $/kgHM (or $/kgU) cited in 2009 AFC-CBR. (Year USD assumed to be same as year of study listed on the left column.)

Study/Year	Low Value	Medium or Reference Value	High Value
ERI/20066		207 (PWR in the United States) 276 (BWR in the United States)	
Nuclear Energy Cost Data Base (Delene et al./1988)	170	200a	280
OECD NEA/1994	200	275	350
J. James and K. Williams/1999		180 (PWR)	
Harvard (Bunn et al.)/2003	150	250b	350
MIT (Deutch et al.)/2003		275	
MIT (DeRoo and Parsons)/2009		250 (PWR)	
Delene et al./2000	200	270	300

a. Higher burnup fuel would add $20/kgU to this price.

b. Bunn suggests that the cost (as opposed to price) is on the order of $200/kgU based on 1999 data of Varley and Collier (Varley and Collier 1999). Bunn also suggests low, medium, and high penalties of $5, $15, and $25 per kgU, respectively, for handling reprocessed LEU in the fabrication plant.
OECD NEA = Organization for Economic Cooperation and Development Nuclear Energy Agency
MIT = Massachusetts Institute of Technology
OECD NEA 2001, OECD NEA 2005; and Tolley and Jones 2004 present similar ranges to above (i.e., $200 to $300/kgU)

c. ERI reports European prices to be 30% higher than the United States; East Asian prices 60% higher than the United States.

The price is expressed in $/kg heavy metal or $/kgHM and normally includes the cost of converting the EUF6 to EUO2. Because the only fuel meat material is uranium, USD/kgHM is the same as $/kgU in this case. Most of the price data above are for unirradiated LEU and not LEU that arises as separated and re-enriched uranium product from LWR spent fuel reprocessing. A price penalty of 5 to 10% of the unirradiated-LEU fuel unit cost is assessed to cover the additional safety and radiation-related costs of handling reprocessed uranium and its trace fission products and trace higher actinides. This has been done mainly in Europe where reprocessing of spent LWR fuel is commonplace. The use and handling of REPU is discussed in more detail in Module K2 and at the end of this Module D1-1. The real prices for LEU fabrication have been decreasing slightly over the last 20 years. This has been due mainly to fuel fabrication overcapacity due to less than anticipated nuclear power growth, higher fuel burnup, increased automation, a highly competitive international market, and the use of now fully amortized plants. If the nuclear fuel market starts to tighten, fuel fabrication costs are likely to rise as proposed NPPs become real construction projects and other NPPs have their operating lives extended. Other factors that may drive fuel fabrication prices upward are:

1. More Robust Fuels. As longer FCs and extended burnup of LEU fuels are required for economic reasons (OECD NEA 1994), the performance requirements for cladding and fuel integrity will become more stringent. The fabricator’s research and development and other costs to allow high burnup will be passed along to the fuel buyer. Perspectives on LWR fuel development are presented in a 1998 article by Gunnar and Junkrans (1998). ATFs, which are expected to be introduced in the mid-2020s, are expected to have higher manufacturing costs but also able to achieve higher burnups. These are discussed in a later section of this document.

2. Possible Use of HALEU. Higher burnups may require LEU fuels of enrichments greater than the 5% maximum U-235 assay now used as the USNRC-licensing basis for LEU fuel fabrication facilities. Retrofitting and relicensing costs for handling HALEU will have to be passed along to utility customers. **The intent is that higher burnups will eventually result in a lower USD/kWh fuel component for the overall electricity generation cost. This reduction is because less LEU fuel will be required per kWh generated.** Gregg and Worrall (2005) discuss the effect of higher burnup on overall "front-end" UO_2 costs and nuclear design parameters. Gingold and Goldstein (2002) discuss how the choice of higher burnup fuel would affect the LWR spent fuel handling steps (Modules E, F, G, I, and L) downstream of the reactor.

3. The price of nuclear-grade zirconium metal is a major material cost to a water reactor fuel fabricator. Pure zirconium is nearly totally transparent to neutrons; thus, it is an excellent material for fuel hardware and fuel rod cladding. In nature, however, zirconium ore always contains hafnium, a metal with a high neutron absorption cross section. The need to chemically separate the hafnium from the zirconium ore concentrate drives the unit cost of the purer nuclear-grade zirconium well above that for non-nuclear zirconium metal. Like LWR fuel fabrication, the price of nuclear-grade zirconium is not published. There are consulting firms such as UxC and Intrado which sell market and pricing information (UxC 2019) on this specialty zirconium market.

In general, BWR fuel fabrication prices are somewhat higher than PWR prices because of the greater hardware complexity of BWR fuel bundles. Foreign fuel fabrication prices are generally higher than in the United States. In 1994, the Organization for Economic Cooperation and Development Nuclear Energy Agency (OECD NEA 1994) price range, which in addition to U.S. price data contains foreign price data, was higher than any of the other mostly U.S. price ranges in Table D1-1.2.

D1-1.6.2.2 FY-17 AFC-CBR Cost Bases

To prepare the 2017 AFC-CBR (Dixon et al. 2017), several additional more recent (2009–2011) data sources were accessed to provide the basis for transitioning to the 2017 WIT values from the 2009 WIT values, (i.e. the recommended low, mode [a.k.a.,. most likely], high, and mean WIT values for the $/kgU [or $/kgHM] price of fuel fabrication). There are no published year-by-year data on the actual production cost or price of the fabrication service for a particular NPP or even the industry as a whole. As in 2009, there was no "spot" market for fabrication services, since the supplied fuel assembly product is generally non-fungible and customized to the particular reactor. (Uranium ore, conversion services, and enrichment "SWUs" are "fungible" commodities that can be sold back and forth between utilities and brokers.) This means that there is no published 2012 price since most utility/fabricator contracts are proprietary.

It should be noted that six sets of literature-based price ranges (in addition to the 2009 WIT values in Table D1-1.2) are discussed below and presented in Table D1-1.3, with separate lines for PWRs and BWRs. The other differentiator for LWR fuel variants is the source of the LEUF$_6$ feed to the fabrication plant. Over 95% of the world's fabricated LEUO$_2$ fuel originates as various U-bearing ores, and the LEUF$_6$ product fed to the fabrication facility is the result of conventional mining, milling, conversion, and enrichment services. Such material has never been irradiated in a reactor and is often called "unirradiated" LEU (U-LEU). A much smaller amount of enriched LEUF$_6$ arises from the conversion and re-enrichment of near natural assay or slightly enriched uranium recovered during spent LWR LEUO$_2$ fuel reprocessing outside of the United States. This reprocessing-derived LEU (R-LEU) is slightly contaminated with very potent U-232 daughter radionuclides which require special ES&H and handling considerations in the fuel fabrication plant. A pricing penalty is added to the U-LEU price to obtain an R-LEU price which includes recovery of the additional costs. There is also a related FC penalty for the U-236 that builds in during irradiation. U-236 is a neutron absorber and requires increases in the required U-235 enrichment level slightly in R-LWR fuel, which requires more SWUs per kgU fabricated. The following Table D1-1.3 shows fabrication price data from various 2009–2011 literature sources:

Table D1-1.3. LWR fuel fabrication prices data from various literature sources presented in 2017 AFC-CBR (constant 2012 USD).

Study and Ref/Year for LWR Fuel Variant	Low Value ($/kgU)	Medium or Ref Value ($/kgU)	High Value ($/kgU)
WISE Nuclear Fuel Cost Calculator (Europe) (WISE 2009)			
PWR U-LEU	N/A	460	N/A
DEC 2009 AFC-CBR (Shropshire et al. 2009)			
PWR U-LEU	200	250	300
BWR U-LEU	250	300	350
PWR R-LEU	220	300	400
BWR R-LEU	275	350	450
EPRI Report # 1020659 (EPRI 2010)			
PWR U-LEU	150	220	250
PWR R-LEU (10% adder)	165	242	275

Study and Ref/Year for LWR Fuel Variant	**Low Value ($/kgU)**	**Medium or Ref Value ($/kgU)**	**High Value ($/kgU)**
MIT Future of Nuclear Fuel Cycle (Massachusetts Institute of Technology 2011)			
PWR U-LEU	N/A	250	N/A
PWR R-LEU (7% adder)	N/A	267	N/A
Nuclear Engineering International (2011)			
PWR U-LEU	260 (30% adder)[1]	N/A	420 (40% adder)1
BWR U-LEU	N/A	360 (20% adder)1	N/A
Private Foreign Source			
PWR U-LEU	400	N/A	500

1 To 2009 AFC-CBR value. (% added is suggested by *Nuclear Engineering International* (NEI) reference source to be added to prevailing 2009 price).

N/A No data available.

The most useful public source of new information for the 2017 AFC-CBR was the September 2011 issue of *Nuclear Engineering International* (NEI) (2011) which included a review of the entire front-end FC. The author's market analysis discussed the significant increase in fabrication prices since the 2008 period to 2011. The reasons mentioned were the following:

- Higher costs to cover the higher quality requirements for "zero-defect" fuel.
- Large increases in the cost of raw zirconium due to high demand, especially in Asia. The source material for zirconium cladding and hardware is zirconia (ZrO_2) derived from the mineral zircon found in certain sands. Historical pricing is as follows in USD per metric ton of zircon (imported ZrSiO4), which comes from the "Zirconium Industry Update" (ABSCO 2012):

Year	Price
2007	872
2008	773
2009	850
2010	1155
2011	2500
2012	2600
2014	1050 (added July 2017)
2019	1487 (added Dec 2020): equivalent to ~$3/kg elemental Zr in ore.

- Processed “nuclear grade” zirconium sponge results from zircon reduction to pure metal and hafnium removal. The unit cost for this material is from $50 to 80/kg Zr.
- Higher labor costs for qualified professionals.
- Recovery of increased capital costs for equipment and facility modifications, including facility expansion and environmental compliance.

Cost factors related to proposed ATFs such as SiC-clad UO2 and uranium nitride (UN) will be covered in a later section of this module. These ATFs would allow higher burnup and longer fuel life in addition to safety benefits.

D1-1.7. INTRODUCTION

D1-1.7.1 A Calculated Unit Cost for LWR Fuel Fabrication Based on a Bottom-Up Life Cycle Cost Estimate

D1-1.7.1.1 Basic Life Cycle Costing Methodology

Basic Life Cycle Costing Methodology Using a Bottom-up Design and Cost for a PWR Fuel Fabrication Facility. In this report, life cycle cost data (rather than market price information) will be presented and utilized because it reflects the true value-added in converting low-enriched UF6 (LEUF6) to a fuel assembly product ready for charging to a commercial reactor. If life cycle costing includes financing costs, as often represented by a “discount rate” or a return to investors (ROI), a profit is essentially covered in the calculated unit cost. In an equilibrium market free of significant oversupply or undersupply, this unit cost can be said to represent a unit price where revenues to the facility owner cover all costs including a return on investment.

As mentioned earlier fuel fabrication pricing is based on provision of a manufacturing service for what is essentially a “custom-made” UOX fuel assembly designed for a particular PWR or BWR reactor vendor’s reactor design and specific utility requirements, such as irradiation exposure time. A detailed fuel assembly design is generally highly proprietary, and pricing is generally directly negotiated between the nuclear utility and the fuel fabricator. The design details of the actual fuel fabrication plant are also proprietary as are the costs to design, construct, start up, and operate the fabrication facility. For this reason, none of the previous AFC-CBRs have been able to present a unit cost based on life cycle cost data for an actual facility design. Since UOX fuel fabrication is a mature and totally privatized FC step, there are no recent publicly available “government estimates” such as those that exist for more advanced nuclear facilities where the FOAK (first-of-a-kind) plants are government built and owned. There also have not been any recently completed “greenfield” UOX fuel fabrication plants upon which to address cost-related inquiries to vendors. Most new fabrication capacity in the United States has been added on to existing plants that were built in the 1960s to 1980s timeframe. The Westinghouse Electric Company’s

(WEC's) Columbia Fuel Fabrication Facility (Figure D1-1.4) located in South Carolina is one such facility (Westinghouse 2012). Fortunately, the LWR nuclear fuel of today is very similar in design, hardware, and heavy metal composition to that fuel made in the plants built from the 1960s through the 1980s.

Figure D1-1.4. Westinghouse Columbia Fuel Fabrication Facility.

Fortunately, there exists one "open-source" bottom-up UOX fabrication plant design and cost estimate that was prepared by the ORNL (operated by Union Carbide Nuclear Division at the time). The 1978 document ORNL/TM-6501 (Judkins and Olsen 1979) was prepared as part of NASAP, which investigated dozens of possible FCs in search of those which were inherently "proliferation-resistant." This comparative NASAP FC economics effort was described in detail in the Module D1-PR, part of this overall document. ORNL/TM-6501 was the first of a series of documents presenting comparable fabrication facility design and cost information on multiple fuel types. (These reports are summarized in detail in Module D1-PR.) It is the only fuel fabrication report in the NASAP series based on a true "bottom-up" estimate where drawings and "bills of materials" were prepared by a design engineering team, and then engineering cost estimators engaged to develop life cycle costs. The important point to be made here is that this UOX fabrication plant is the "reference plant" from which all other cylindrical fuel types ("subject plants") and their designs and life cycle costs were calculated by the transition process schematically shown in Figure D1-PR.A.3 of Module D1-PR. The subsections below will describe this reference PWR-UOX plant, the cost estimate made in 1978 for it, and how the cost estimate was modified to reflect today's financial and regulatory environment. The resulting unit cost (in 2017 constant USD) can then be compared to the literature-based WIT unit price range in the 2017 AFC-CBR (Dixon et al. 2017). Escalation to 2021 constant USD can be accomplished by using factors appearing in the main 2021 AFC-CBR report.

The treatment of the engineering economics and calculation of the unit fabrication cost in the 1978 ORNL/TM-6501 report reflects financial conditions and taxation regulations in effect at that time for a privately owned greenfield plant financed by both the issuance of stock (equity financing) and bonds (debt financing). The revenue requirements model, used to calculate the unit cost, reflected the U.S. Treasury/IRS corporate income tax rates and allowable depreciation/amortization practices used in 1978. The economic model described later in this section for today's economic conditions is a simpler, non-country specific model based on the international G4-ECONS modeling methodology used to evaluate advanced reactors and their supporting FC facilities. G4-ECONS does not consider taxation, uses only one composite discount rate, and assumes recovery of capital over the operating life of the facility. It is not specific to one country's rules or economic policy. Selection of the appropriate discount rate can simulate both private, higher-risk equity/debt financing and the lower risks associated with government financing. All of the assumptions will be explained in the sections to follow. Price and its relationship to cost, as well as cost versus capacity scaling, will also be discussed.

D1-1.7.1.2 The ORNL/TM-6501 Report

The ORNL/TM-6501 report (part of NASAP FC studies referenced as Judkins and Olsen [1979]) includes a detailed life cycle cost analysis of a PWR-LEU oxide fuel fabrication facility, performed as part of the overall NASAP program from 1978–1980. Additional reports (ORNL 1979a; ORNL 1979b) considering the fabrication cost of alternative and more complex fuels were also developed within the same program using ORNL/TM-6501 as the starting point of the analysis. The cost of fabricating different (and generally more complex in both material content and manufacturing requirements) fuels have then been developed as "modifications" or "design transitions" to the detailed bottom-up cost estimate in ORNL/TM-6501 (Judkins and Olsen 1979).

Unlike uranium mining and uranium enrichment, UOX fuel fabrication is one FC service for which the basic manufacturing technology has changed relatively less since the early days of commercial nuclear power. The basic flowsheet for UOX pelleting/rod insertion/rod bundling technology remains the same from the 1960s designs to the present. (U-ore conventional mining in the United States been largely replaced by a newer "in-situ" mining process, and worldwide, the gas centrifuge has displaced gaseous diffusion as the predominant enrichment methodology. Both transitions resulted in significantly lower unit costs.) The following fabrication process changes have been identified; however, even together they have not affected the inflation/escalation adjusted total unit fabrication cost by a significant amount compared to fuel fabrication and enrichment process changes:

- The UF6 to UO2 powder conversion process is now a "dry" (solid-vapor) process or an improved aqueous (a.k.a.,. "wet") process involving ammonia salts rather than anhydrous ammonia. These changes result in less low-level liquid radioactive waste and its associated treatment and disposal costs.
- Automation of some processing and inspection steps has reduced some staff costs; however, other factors, such as regulatory compliance, fluorine compound disposition, material accountability (MCP&A), and security and safeguards likely require increased staff.

A description of the basic process chemistry and manufacturing steps for UOX fuel fabrication is presented in Section D1-1.5 of this document. A typical low-enriched UF6 to finished UOX bundle process flowsheet is also included there as well as more detailed process flowsheets in Figures 2–4 of ORNL/TM-6501. Figure D1-1.5, extracted from ORNL/TM-6501, is a diagram of the PWR-UOX bundle (fuel assembly) end-product shipped from the reference fuel fab facility to the reactor site. Today's PWR fuel assembly appears nearly identical and weighs approximately the same at ~460 kgU.

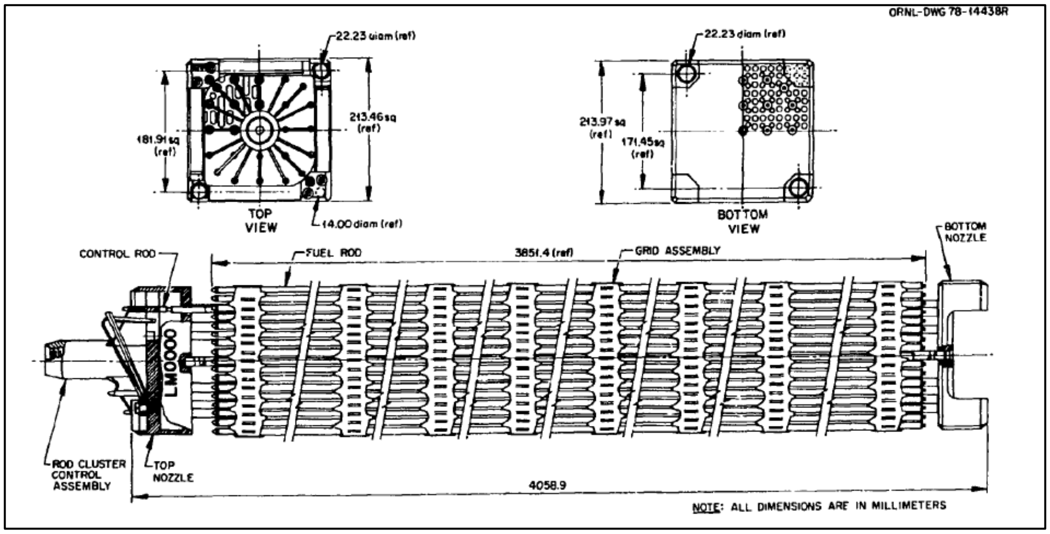


Figure D1-1.5. Diagram of a typical UO2 (UOX) PWR fuel assembly (heavy metal mass is approximately 460 kilograms of low-enriched uranium). (Figure 1 from ORNL/TM-6501).

In ORNL/TM-6501, a detailed flowsheet is first developed, and afterwards, estimates are provided for the floor space (square footage or “footprint”) necessary for each of the flowsheet functions, plus supporting functions including balance of plant. The facility total throughput was assumed at 2 MTHM/day, working 260 days/year in a 24/7 shift system. This results in a total annual average throughput of 520 MTHM/year. (This is about ¼ the average annual throughput of the Westinghouse Columbia, SC fabrication plant.)

The ORNL/TM-6501 design prepared by the engineers in the ORNL Metals and Ceramics Division and Engineering Division was based on standard design calculations for metallurgical operations, chemical and metallurgical equipment sizing, plant equipment and utility layout in a single-story building, integration of overhead functions, and preparation of “bills of materials” specification sheets for the final cost estimation. Unfortunately, none of this original late 1970s data was prepared or recorded in electronic form and subsequently archived. The author of this report has been unable to find any original design documentation, and nearly all the ORNL individuals that had been intimately involved with this late 1970s effort are retired or no longer living.

D1-1.7.1.3 Capital Costs

In the following paragraphs, a cost estimate (in 1978 USD) of the building space and equipment for each step (a.k.a.,. unit operations) in the process flowsheet is provided. The required floor space requirements appear in Table D1-1.4. Note that this facility fabricates its own zirconium hardware in the process building.

Table D1-1.4. Area requirements for a 2 MTHM/day PWR fuel fabrication facility. (Table 3 of ORNL/TM-6501 for the main process building.)

Operation	Area (ft^2)
UF_6—UO_2 conversion	5,500
UO_2 milling, blending, and storage	4,700
UO_2 powder preparation and pelleting	1,900
UO_2 pellet sintering, grinding, and inspection	5,850
Fuel rod loading and welding	2,780
Fuel rod inspection and storage	7,000

Operation	Area (ft^2)
Fuel assembly fabrication	3,000
Fuel assembly weighing, cleaning and inspection	3,400
Fuel assembly packaging and shipping	4,000
Scrap recovery and waste processing	2,000
Operational support (includes fuel assembly hardware fabrication)	20,065
Stores	2,000
Facility support	9,135
Change rooms (contaminated areas)	2,005
Quality control laboratories	7,000
Maintenance	19,665
Total facility area	100,000

Costs for the main process building construction were estimated parametrically using a USD-per-square-foot formulation for each functional space. All the functions, except quality control (QC), were estimated at $\$200/ft^2$ (in 1978 USD). The QC area was estimated at $\$400/ft^2$ (1978 USD). From this data, the total construction costs is $21.4 million (1978 USD) for a 100,000 ft^2 structure. This cost does not include process equipment but does include heating, ventilation, and air conditioning (HVAC). There are other smaller buildings and ancillary site services requirements for the overall civil construction category. These costs and those for the main process building are summarized in Table D1-1.5:

Table D1-1.5. Civil facility costs (1978$K) for a 2 MTHM/day PWR fuel fabrication plant. (Table 4 of ORNL/TM-6501; process equipment not included.)

Item	Cost ($)
Building	21,400 × 1,000
Land	500
Site preparation	500
Licensing and environmental	400
Security system	300
Office building	1,500
Subtotal	24,600
Engineering and contingency (30%)	7,380
Total	31,980

It should be noted that the civil costs were one area where parametric ($\$/ft^2$) rather than “straight-up bricks and mortar-type” bottom-up cost estimating was used. Fortunately, experience-based engineering estimating manuals with $\$/ft^2$ values for different building types have existed for years and still are used today.

Bottom-up estimation was used to estimate the process equipment requirements and costs for the major flowsheet functions and also for overhead functions, such as stores, QC labs, change rooms, etc. Table D1-1.6, extracted from Table 5 of ORNL/TM-6501, summarizes these costs in 1978$K.

Table D1-1.6. Summary of equipment costs for a 2 MTHM/day PWR fuel fabrication plant. (Table 5 from ORNL/TM-6501; costs include installation.)

Operation	Equipment Costs ($)

Operation	Equipment Costs ($)
UF_6—$U0_2$ conversion	1,434 × 1,000
UO_2 milling, blending, and storage	520
UO_2 power preparation and pelleting	320
UO_2 pellet sintering, grinding, and inspection	3,816
Fuel rod loading and welding	650
Fuel rod inspection and storage	1,010
Fuel assembly fabrication	280
Fuel assembly weighing, cleaning, and inspection	700
Fuel assembly packaging and shipping	2,500
Scrap recovery and waste processing	150
Operation support (includes fuel assembly and hardware fabrication)	4,268
Stores	60
Facility support	5,690
Change rooms (contaminated areas)	
Quality control laboratories	1,423
Maintenance	11,380
Total equipment costs	34,201

A total base plant capital cost of $66.18 million in 1978 USD results. No indirect costs other than engineering were called out. This facility is considered an Nth-of-a-kind (NOAK) facility based on mature technology.

D1-1.7.2 RECURRING OPERATIONS AND MAINTENANCE COSTS

Significant labor and material costs exist for fuel fabrication. The ORNL/TM-6501 estimators first prepared an organizational chart and staff count for the overall plant operations. The number of personnel required to staff a three-shift operation was calculated for each major process step. Figure 5 in the ORNL/TM-6501 document presents the organization chart; however, the staff count for each box is illegible since the scan made to prepare the PDF did not resolve the very small print on a large chart with many boxes. If the average “burdened” (including Social Security, benefits, workmen’s compensation tax, holidays, etcetera, for a 33% total adder) wage for a typical 1978 industrial facility was $13,000 per year, then a total staff count (FTEs) of ~1,000 employees results. Table D1-1.7 summarizes the annual staffing expenses by major organizational category indicating manufacturing floor labor is approximately three quarters of the overall staffing cost.

Table D1-1.7. Annual personnel costs for a 2 MTHM/day PWR fuel fabrication facility. (Table 6 from ORNL/TM-6501; all costs in 1978$K.)

Department	Annual Costs[a] ($)
General management	80 × 1,000
Design engineering	720
Projects	189
Finance	309
Purchasing/personnel	455
Manufacturing	9,345
Medical	237

Department	Annual Costs[a] ($)
Quality assurance	1,632
Total annual personnel costs	12,967

[a] Includes 33% burden.

Materials and consumables costs, including utilities, are also recurring costs and include specialty gases, chemicals, tools, fuels (such as natural gas for sintering furnaces), personnel safety equipment, solvents, and, most significantly of all, the mostly reactor-grade zirconium or zirconium-alloy metal required for manufacturing the hardware enclosing the UOX pellets and forming a structurally sound fuel assembly. In ORNL/TM-6501, it was assumed that all hardware was manufactured “in-house”, and that most the remaining fuel fabrication facility space consisted of sintering, rod loading, rod end cap welding, rod inspection, and loading of the rods into spacers and other structural hardware. (Some U.S. fuel fabricators such as GE-Hitachi in Wilmington, NC perform zirconium hardware manufacture on site; others such as Westinghouse purchase fabricated zirconium parts from an offsite, non-nuclear facility.) For ORNL/TM-6501, the estimators contacted hardware vendors to verify the costs for these zirconium parts. The costs of other supplies, utilities, and consumables were estimated from requirements dictated by the number of personnel, the equipment throughputs and energy requirements for the various operations, and the desired production rate. A summary of these recurring costs for materials other than utilities appears in Table D1-1.8.

Table D1-1.8. Material costs for a 2 MTHM/day PWR fuel fabrication facility. (Table 7 from ORNL/TM-6501; all costs in 1978$K.)

Item	Annual Costs ($)
Direct and indirect materials	1,014 × 1,000
Supplies	1,128
Hardware	20,899
Total annual material costs	23,041

To complete the O&M cost category, general and administrative (G&A) and utilities must be added to the labor and material costs. Table D1-1.9 adds these costs and summarizes the total recurring costs. It also lists the content of the G&A cost category.

Table D1-1.9. Summary of annual operating costs at a 2 MTHM/day PWR fuel fabrication facility. (Table 8 from ORNL/TM-6501; all costs in 1978$K.)

Operating Cost Component	Annual Costs[a] ($)
Labor and supervision	10,164 × 1,000
Overhead and general and administrative (G&A)	2,980
Materials	23,041
Utilities	239
Total annual operating costs	36,424

[a] Includes management personnel cots, travel, telephone, office supplies, postage, professional and legal fees, and miscellaneous fees, contributions, memberships, and subscriptions.

D1-1.8. ECONOMIC ANALYSIS UTILIZED IN 1978 BY ORNL TO DETERMINE UNIT PRICE OF PWR-UOX FUEL

The above life cycle cost data was used in a computerized business model assuming a private, non-government facility with a return on investment to debt and equity investors typical of a high-risk nuclear enterprise at that time. The FORTRAN code called ACFAC (A Cash Flow Analysis Code) was run assuming a 15% nominal rate of return to obtain a unit price applicable over the assumed plant life of 20 years. Table D1-1.10 shows the factors and assumptions required for this discounted cash flow analysis type code. Other life cycle cost categories, in addition to capital and O&M, such as taxes, insurance, preoperational costs, depreciation, capital replacements, working capital, and decommissioning were factored into the 1978 analysis. The author of this update (Rev 0) attempted to reproduce the unit cost calculated in ORNL/TM-6501 based on his own knowledge of process economics, which is mentioned below. (The 1978 ORNL ACFAC FORTRAN CODE was not archived. This observation is based on inquiries to the ORNL RSICC computer code repository; hence, this author was unable to obtain the algorithms and reproduce the 1978 results in an EXCEL spreadsheet.)

Table D1-1.11 shows the breakdown of the $137.87/kgHM unit price calculated by the ACFAC code. Over $20/kgHM of this unit price is attributable to taxes; if these are ignored, the price would be just over $117/kgHM. Note that unit price and unit cost are the same here, since a perfect market is assumed in which the unit cost includes all returns to investors hence the price covers all costs without losses or excess profit. A discounted cash flow analysis by this Module D1-1 SA&I author obtained $101/kgHM for a tax-free unit price. The authors of ORNL/TM-6501 were able to find one actual fuel fabrication transaction price, including the taxes, of $131/KgHM in 1978 USD from the proceedings of a late 1970s lawsuit.

Table D1-1.10. Economic assumptions for determining PWR fuel assembly unit price. (Table 9 from ORNL/TM-6501; economic conditions of 1978.)

Analysis Methodology	Discounted Cash Flow
Financing, % of equity	100
Economic factors	
Rate of return	15
Income tax rate (effective), %	50
Property tax, % of initial capital	2.5
Property insurance, % of initial capital	0.5
Expendable equipment charge, % of initial equipment cost	1.0
Depreciation method for tax purposes	Sum of years digits
Capital life, years	
Facility	20
Equipment	10
Plant operating factors, %	
First year	33
Second year	67
Subsequent years	100
Preoperational expenses (% of operating costs)	
Three years before start-up	10
Two years before start-up	25
One year before start-up	50
Cash flow during construction	
Years -8 to -1	0.045, 0.072, 0.115, 0.172, 0.208, 0.162, 0.144, 0.082
Replacement equipment	Year 11
Working capital	3 months receivables on operating costs

Analysis Methodology	Discounted Cash Flow
Decommissioning fund, % of sales	1
Investment tax credit, %	
Facility	5
Equipment	10

Table D1-1.11. Summary of costs for determining the unit price of a PWR fuel assembly. (Table 10 of ORNL/TM-6501; all costs in 1978$/kgHM for a plant with 20-year life.)

Component	Cost ($/kg HM)
Capital recovery	40.44
Material	44.31
Operating[a]	26.64
Property tax	3.66
Property insurance	0.73
Replacement capital	0.66
Working capital	3.04
Income tax	17.03
Decommissioning	1.38
Total	137.89

[a] Excluding materials.

D1-1.8.1.1 Transitioning from the 1978 ORNL/TM-6501 Unit Cost Estimate to Regulatory and Economic Conditions in 2017

To transition from the 1978 ORNL life cycle cost estimate to 2017 conditions, the following factors must be considered:

- General inflation and escalation incremental to the inflation rate
- Other economic factors such as interest rates and taxation
- Regulatory changes affecting project life cycle costs
- Process technology and design changes affecting life cycle costs.

Each of these four items is discussed below:

1. General inflation. Inflation in the United States as measured by the implicit price deflator (IPD) and "cost-of-living" (a.k.a.,. consumer price index [CPI]) has caused the average "market basket" price (weighted average of prices for various commodities and services as defined for each measure) to increase from 1978 to 2017 by factors of 2.95 and 3.75, respectively. Incremental escalation would be the additional average annual increase in prices pertinent to the industry of interest above this general inflation. Unfortunately, for nuclear reactor construction in the United States, this escalation above inflation has been above 3%/year for those years in which significant nuclear construction was underway. The question is whether this reactor-based "nuclear project" escalation above general inflation is also partially or fully applicable to FC facilities such as fuel fabrication plants.
2. Other economic factors. The ORNL/TM-6501 discounted cash flow analysis used to calculate the levelized unit cost assumed the economic conditions present at the time (1978). The 1970s were a time of high inflation, hence very high interest rates for companies and individuals borrowing money. (They were also a time of higher borrowing rates for the U.S. government, as measured by the discount rate.) Corporate federal income tax brackets were also much higher than today's and were around 46% in 1978. Local property taxes were also likely higher in 1978 since many of the local tax incentives to locate higher-wage type industries, such as nuclear ones, in a particular location did not exist back then.
3. Regulatory factors. Since the early 1970s, the USNRC has promulgated many new safety and security rules and requirements for the construction of reactors (10CFR50) and FC facilities (10CFR70). Many of these are due to tighter seismic standards and more facility physical protection against weather events, material diversion, and terrorist attacks. Chemical safety and criticality safety rules have also become more stringent, and new rules for MCP&A (Material Control, Protection, and Accountability) have been promulgated. These new regulations have greatly affected the design and cost of new structures housing nuclear material and processes. The fact that toxic uranium hexafluoride and HF and flammable hydrogen are involved in the "dry" conversion steps for fuel fabrication also mandate inclusion of much stricter chemical safety considerations in both building design and the operations within. "Wet" processes such as low-enriched UOX scrap recovery and liquid waste disposal also create the possibility of leaks and ground water contamination.
4. Process technology. Process changes from 1978 are mostly related to the switch from "wet" to "dry" chemistry for the front-end low-enriched UF_6 to low-enriched UOX powder conversion step. This switch results in less aqueous low-level waste and fewer criticality concerns that would normally arise in handling of low-enriched 2 to 5% U-235 in an aqueous environment. Hydrofluoric acid (HF) generated by the conversion reactions must be stored on site until a buyer, such as a fluorine producer or a yellowcake (ore derived natural U_3O_8) to UF_6 converter, elects to recycle the slightly uranium-contaminated HF product for a fluorination step.

The question is now how to consider these four factors into the calculation of a levelized 2017 unit cost for PWR fuel assemblies from a new NOAK "greenfield" LWR fuel fabrication plant.

D1-1.8.1.2 Inflation/Escalation

It was recognized that the 3% escalation (above inflation) experienced by U.S.-built nuclear reactor construction costs during the late 1970s and most of the 1980s does not necessarily apply to nuclear FC facilities such as fuel fabrication plants. There is, however, a very real cost risk factor associated with all nuclear projects as a result of changing regulation, ES&H litigation, shortages of nuclear-qualified craft workers, supply chain issues, and the tendency of managers to be optimistic on project cost and schedule estimates made at project inception. This is not to say that non-nuclear projects do not encounter such risks. A literature search on “megaproject costs” will generate many useful references. The problem is that nuclear projects are much more susceptible to impacts of these risks. It was decided that for fuel fabrication capital costs a “nuclear risk”-informed, combined inflation plus incremental escalation factor (year 2017 USD cost divided by year 1978 USD cost) based on recognized industry and government indices was required. Chapter 8 of the 2017 AFC-CBR includes a discussion of such a calculated factor, its data sources, and a table (Table 8.3) listing the factor (a multiplier) for years 1978 through 2017. Other life cycle costs, such as recurring annual personnel and utility costs, involve less risk, and the application of a government-published, CPI-only based factor can be used. Table D1-1.12 shows the composite factors, (i.e., “multipliers”) used to convert the 1978 USD life cycle costs by category in the ORNL/TM-6501 reference plant (Table D1-1.4 through Table D1-1.9) from 1978 USD to 2017 USD. The table also includes the multiplier definitions and rationale for use.

Table D1-1.12. Multiplication factor used to convert 1978 USD to 2017 USD for various life cycle categories for the reference LWR fuel fabrication facility.

Composite inflation-escalation factor (2017 cost divided by 1978 cost), (i.e., a multiplier)	**Indices utilized for multiplication factor calculation and rationale for use**	**Life cycle cost categories for which it is applied**
7.58	Ratio of algorithm-developed capital cost (in 2017 USD) for a reinforced concrete NQA-1 “robust” process building (include HVAC) to the 1978 USD less-robust process building cost in ORNL/TM-6501. (Algorithm input assumptions discussed below.)	Main Process Building Capital cost including HVAC, environmental support, and security systems capital costs
5.95	1978 to 2017 Nuclear Market Basket: Table 8.3 of 2017 AFC-CBR (Dixon et al. 2017). Table is developed from multiple nuclear project-related indices such as Handy-Whitman (WRA 2020), DOE Nuclear Construction, PCCI, and IPD.	Capital cost of auxiliary buildings, process equipment, preoperational costs, and replacement equipment
3.75	CPI from 1978 to 2017. Since this factor is applied to mostly personnel-related, recurring costs, it was felt that the consumer item “market basket” essentially covered by worker salaries would be more appropriate than the more generic IPD. Recurring costs are also much less subject to nuclear-related cost-risks than capital costs.	Recurring costs such as fully loaded labor and general/administrative (G&A) costs, purchased material costs, utility costs

D1-1.8.1.3 Process Changes and Regulatory-Mandated Design Changes

The conventional, non-ATF UOX fuel fabrication process itself has changed little from 1978 and involves mostly standard chemical and metallurgical equipment, much of which can be ordered “off-the-shelf” without serious supply chain issues. (Note, however, in most cases, the fuel fabrication process must be qualified by a national regulator, such as the USNRC, and QA for all equipment items and operations is essential.) The one major change identified for today’s regulatory environment includes the cost of a considerably more robust building than that required by nuclear FC regulations in 1978. Fire protection, chemical safety, natural phenomena, and physical protection (for fissile materials) requirements today would likely require a reinforced concrete building for the process area. The HVAC system would have to accommodate current requirements for airborne radionuclide particles (UOX dust), normal industrial dusts, halogens (including HF), and radon. It would be considered part of the main process building civil cost. Fortunately, there are cost estimating relationships (algorithms) which can calculate an approximate, nuclear-grade (NQA-1) building structural cost in today’s (2017) USD. One of the co-authors of this report, Francesco Ganda, found an algorithm for reinforced concrete reactor containments of various thicknesses for which the steel liner is omitted. The following paragraph explains how this algorithm is applied.

It is observed from ORNL/TM-6501 that the total required floor area for the main process building is estimated at 100,000 ft^2 or slightly below twice that of an American football field. The length, width, and height dimensions of the rectangular building were not provided, so the footprint was arbitrarily assumed at 400 × 250 ft to reach 100,000 ft^2 on a single floor, with a building height of 40 ft (to accommodate using a large crane for equipment installation and removal). For an extremely conservative design, the structural requirements for this building should be similar to those of reactor containments, considering that the required physical protection required for such a facility is likely to be high. No liner is specified for the interior surfaces of the building, since it is not expected that overpressure from an explosion would be experienced, or extensive decontamination should be required.

The exterior walls are assumed made of reinforced concrete with a thickness of 1 ft and the roof at 1 ft (i.e., similar in appearance to a standard rectangular reactor containment building but with much lower thickness walls due to the fact that significant overpressure cannot occur in an accident scenario).

Using the cost estimating relationship mentioned above for this main process building without equipment yields a total cost of $162 million in 2017 USD. This includes the HVAC system equipment.

The total ORNL/TM-6501 base equipment cost was $34.2 million in 1978 USD, or $203.5 million in 2017 USD using the nuclear risk-adjusted multiplication factor in the second row of the above Table D1-1.12 (the base cost was calculated to increase by a factor of 5.95 between 1978 and 2017).

Applying to both the building and the equipment costs a contingency of 10%, and indirect costs of 20% of total direct costs as typical for chemical plants (Peters 2003), would yield a total construction cost of $687 million in 2017 USD. Table D1-1.13 shows a breakdown for the various components of the capital cost and the escalation rationale for the change in values from 1978 to 2017.

Table D1-1.13. Process building floor areas by unit operation and comparison of 1978 and the 2017 base capital cost components for all buildings and equipment.

DIRECT CAPITAL COSTS	Main Process Building Civil							Equipment				Total Civil + Equipment	
PROCESS BUILDING LAYOUT AND COSTS BY UNIT OPERATIONS FOR 520 MTU FABRICATION PLANT	Area (ft^2) per ORNL/TM-6501	Yr 1978 USD cost per ft^2 per ORNL/TM-6501	Yr 1978$M from ORNL/TM-6501	Combined inflation & incremental escalation multiplier for conversion to 2017 USD (for robust nuclear-grade building structure)	Yr 2017 USD cost per ft^2	Yr 2017$M		Yr 1978$M from ORNL/TM-6501	Combined inflation & incremental escalation multiplier for conversion to 2017 USD (for capital costs with some “nuclear risk”)	Yr 2017$M		Yr 1978$M from ORNL/TM-6501	Yr 2017$M
Yr													
UF6 to UO2 Conversion (aqueous process)	5,500	200	1.100	7.58	1,516	8.338		1.434	5.95	8.532		2.534	16.870
UO2 powder milling, blending, and storage	4,700	200	0.940	7.58	1,516	7.125		0.520	5.95	3.094		1.460	10.219
Subtotal: conversion to pelleting ready packaged powder	10,200		2.040			15.463		1.954		11.626		3.994	27.090
UO2 powder loading and pelleting	1,900	200	0.380	7.58	1,516	2.880		0.320	5.95	1.904		0.700	4.784
UO2 pellet sintering, grinding and inspection	5,850	200	1.170	7.58	1,516	8.869		3.816	5.95	22.705		4.986	31.574
Subtotal: pellet production operations	7,750		1.550			11.749		4.136		24.609		5.686	36.358
Fuel rod loading and welding	2,780	200	0.556	7.58	1,516	4.214		0.650	5.95	3.868		1.206	8.082
Fuel rod inspection and storage	7,000	200	1.400	7.58	1,516	10.612		1.010	5.95	6.010		2.410	16.622
Subtotal: rod loading operations	9,780		1.956			14.826		1.660		9.877		3.616	24.703
Fuel assembly fabrication	3,000	200	0.600	7.58	1,516	4.548		0.280	5.95	1.666		0.880	6.214
Fuel assembly weighing, cleaning, and inspection	3,400	200	0.680	7.58	1,516	5.154		0.700	5.95	4.165		1.380	9.319
Fuel assembly packaging and shipping	4,000	200	0.800	7.58	1,516	6.064		2.500	5.95	14.875		3.300	20.939
Subtotal: fuel assembly operations	10,400		2.080			15.766		3.480		20.706		5.560	36.472
Scrap recovery and aqueous waste	2,000	200	0.400	7.58	1,516	3.032		0.150	5.95	0.893		0.550	3.925

Module D1-1 Uranium-Based Ceramic LWR Fuel Fabrication

DIRECT CAPITAL COSTS	Main Process Building Civil							Equipment				Total Civil + Equipment	
PROCESS BUILDING LAYOUT AND COSTS BY UNIT OPERATIONS FOR 520 MTU FABRICATION PLANT	Area (ft^2) per ORNL/TM-6501	Yr 1978 USD cost per ft^2 per ORNL/TM-6501	Yr 1978$M from ORNL/TM-6501	Combined inflation & incremental escalation multiplier for conversion to 2017 USD (for robust nuclear-grade building structure)	Yr 2017 USD cost per ft^2	Yr 2017$M		Yr 1978$M from ORNL/TM-6501	Combined inflation & incremental escalation multiplier for conversion to 2017 USD (for capital costs with some “nuclear risk”)	Yr 2017$M		Yr 1978$M from ORNL/TM-6501	Yr 2017$M
Yr													
processing													
Operational support area including fuel assembly hardware fabrication	20,065	200	4.013	7.58	1,516	30.419		4.268	5.95	25.395		8.281	55.813
(Most zirconium parts such as tubes are fabricated from nuclear-grade zirconium metal. Metal costs are in recurring costs appearing in a later table)													
Stores	2,000	200	0.400	7.58	1,516	3.032		0.060	5.95	0.357		0.460	3.389
Facility support area	9,135	200	1.827	7.58	1,516	13.849		5.690	5.95	33.856		7.517	47.704
Change rooms for contaminated areas	2,005	200	0.401	7.58	1,516	3.040		0.000	5.95	0.000		0.401	3.040
Quality control laboratories	7,000	400	2.800	7.58	3,032	21.224		1.423	5.95	8.467		4.223	29.691
Maintenance area	19,665	200	3.933	7.58	1,516	29.812		11.380	5.95	67.711		15.313	97.523
Subtotal ancillary floor space	39,805		9.361			70.956		18.553		110.390		27.914	181.347
Total in ft^2 (col C) or USD (cols F, H, J)	100,000	$M tot>>>	21,400			162.212		34.201		203.496		55.601	365.708
										0			
										0			
DIRECT CAPITAL COST FOR ALL STRUCTIONS AND EQUIPMENT			1978 USD CIVIL	MULTI		2017 USD CIVIL		1978 USD EQT	MULTI	2017 USD EQT		1978 USD TOTAL	2017 USD TOTAL

Module D1-1 Uranium-Based Ceramic LWR Fuel Fabrication

DIRECT CAPITAL COSTS	Main Process Building Civil							Equipment				Total Civil + Equipment	
PROCESS BUILDING LAYOUT AND COSTS BY UNIT OPERATIONS FOR 520 MTU FABRICATION PLANT	Area (ft^2) per ORNL/TM-6501	Yr 1978 USD cost per ft^2 per ORNL/TM-6501	Yr 1978$M from ORNL/TM-6501	Combined inflation & incremental escalation multiplier for conversion to 2017 USD (for robust nuclear-grade building structure)	Yr 2017 USD cost per ft^2	Yr 2017$M		Yr 1978$M from ORNL/TM-6501	Combined inflation & incremental escalation multiplier for conversion to 2017 USD (for capital costs with some "nuclear risk")	Yr 2017$M		Yr 1978$M from ORNL/TM-6501	Yr 2017$M
Yr													
Process building (from above)			21,400	7.58		162.212		34.201	5.95	203.496		55.601	365.708
Land purchase			0.500	5.95		2.975		0.000	5.95	0		0.500	2.975
Site preparation			0.500	5.95		2.975		0.000	5.95	0		0.500	2.975
Licensing and environmental			0.400	5.95		2.38		0.000	5.95	0		0.400	2.380
Security system			0.300	5.95		1.785		0.000	5.95	0		0.300	1.785
Office building			1.500	5.95		8.925		0.000	5.95	0		1.500	8.925
Subtotal			24,600			181.252		34.201		203.496		58.801	384.748
Effective multiplier for all direct costs is calculated as	6.54												

It should be noted that the capital costs above are for a USNRC Category III contact-handling facility with hoods and fans being the predominant methods of personnel protection from airborne radionuclides. No gloveboxes or hot cells are required. Areas where hydrofluoric acid (HF from the UF6 deconversion step) is handled have their own special containment and ventilation requirements.

The recurring, annualized O&M costs from the 1978 ORNL/TM-6501 are assumed to only undergo general inflation from 1978 to 2017. It is likely that more security personnel would now be required than in the late 1970s; however, any increase in this personnel area would be offset by automation in the process are and the need for fewer chemical and metallurgical operators. The conversion from “wet” to “dry” UF_6 to UOX powder technology is assumed to have minimal effects on staffing and consumables. Any credits for the sale of conversion process-generated hydrofluoric acid (HF) are ignored since these credits are not guaranteed due to the volatility of the HF market. Table D1-1.14 shows a breakdown and comparison of the 1978 and 2017 annual costs in $M per year. Note that capital equipment replacements are averaged over the plant life for purposes of cost levelization (a.k.a.,. annualization). It is assumed that on the average all $34 million worth of equipment is replaced every 20 years.

Table D1-1.14. Comparison of 1978 and 2017 annual recurring O&M costs.

Recurring Life Cycle Cost Category	**1978 USD Annual Cost in $M/yr From ORNL/TM-6501**	**Composite Inflation & Incremental Escalation Multiplier Used**	**2017 USD Annual Cost in $M/yr**
PERSONNEL (All costs include 33% burden)			
Direct manufacturing & maintenance labor	9.35	3.75	35.04
Non-manufacturing personnel including labor supervision, management, and general & administrative costs	3.80	3.75	14.25
Subtotal personnel-related costs	13.14	3.75	49.29
CONSUMABLES			
Direct & indirect materials, supplies	2.14	3.75	8.03
Hardware feedstock (mostly nuclear-grade zirconium metal feedstock forms)	20.90	3.75	78.37
Utilities (water, sewer, natural gas, electricity)	0.24	3.75	0.90
Subtotal consumables	23.28		87.30
Total recurring annual O&M costs	36.42		136.59
Annualization of process equipment capital replacement costs (All process equipment assumed to be replaced every 20 years; hence $34.2M/20 year in 1978 USD)	1.71	5.95	10.17
TOTAL RECURRING COSTS IN $M/yr	38.18	3.85 Effective avg	146.76

The facility annual O&M costs, including personnel, administration and overhead, materials (including all of the zirconium metal for fuel assembly hardware but excluding the LEU hexafluoride [EUF6] feed itself), plus all the chemicals used in the fabrication process, and the utilities, are $36.4 million in 1978 USD or $142 million in 2017 USD. (Important note the cost of the EUF6 feed material has uranium ore [U3O8], conversion, and enrichment components which are separate front-end FC costs and covered in Modules A, B, and C of the AFC-CBR, respectively.)

The remainder of this section deals with conversion of the 2017 USD base life cycle costs to a levelized unit cost (price) for the PWR fuel fabrication service. It was decided to use a less country specific, more universal, and simpler levelized unit cost calculation technique than the business model approach used in ORNL/TM-6501 (Judkins and Olsen 1979) and ORNL/TM-6522 (Olsen, Judkins, Carter, and Delene 1979). Fortunately, a well-documental methodology exists in the G4-ECONS methodology (Williams and Miller 2007) developed for calculating the levelized unit electricity cost from life cycle cost data for nuclear power plants. When this tool was developed from 2004 to 2007, an adjunct program called G4-ECONS-FC was also developed specifically for converting life cycle cost data on FC facilities into a levelized unit cost of a product or service over the entire operating life of the plant. In order to make this LWR fuel fabrication analysis more comparable to other SA&I life cycle cost studies, the following changes and assumptions have been made:

- **Plant Lifetime.** The lifetime of the fuel fabrication facility has been extended from 20 years (per ORNL/TM-6501) to 50 years. Uniform O&M costs will be assumed for 50 years and a uniform annualized capital recovery will be calculated over the same 50 years (i.e., the operating lifetime of the plant). It should be noted that the ORNL 1978 “20-year plant” might actually be operated for more than 20 years with only recurring costs incurred from year 21 onward. Using a short amortization or “write-off” period for “up-front” capital costs is common in Western economies but does not allow the calculation of a levelized cost over the life of the facility. The levelized unit cost over the entire production lifetime is a much better way of comparing technology alternatives.
- **Allowances.** Good cost estimating practice requires the adjustment of direct capital costs with the addition of indirect costs and contingency. The plant described in ORNL/TM-6501 either did not explicitly include these or they were buried on other cost categories. A subsequent NASAP report, ORNL/TM-6522, suggested adding 10% of the direct civil construction costs to cover contingency and 20% of the resulting sum to cover indirect costs. Based on the *Generation IV Reactor Cost Estimating Guidelines* (Williams and Miller 2007), it was decided that these allowances should also apply to equipment costs, especially since installation and pre-installation testing often has associated schedule and manpower cost uncertainties. Table D1-1.15 shows the addition of contingency and indirect cost allowances. The table also shows the addition of a preoperational cost allowance, also used in most of the 1978 ORNL/NASAP reports such as ORNL/TM-6522. It is calculated by taking 152% of a typical operating year’s projected non-material recurring O&M costs. It essentially is an “owner’s cost” covering plant start-up activities and is included as part of the capital cost.

Table D1-1.15. Capital costs with allowances (in 2017 $M for 520 MTU/yr PWR fuel fabrication facility).

Life Cycle Cost Category	Civil 2017 $M Costs	Eqt. 2017 $M Costs	Total 2017 $M Cost
Direct Capital Costs Without Allowances	181.4	203.5	384.9
10% contingency on direct costs	18.1	20.3	38.5
20% indirect cost allowance on (Direct costs+ contingency)	39.9	44.8	84.7
Subtotal Overnight Cost for Civil Plus Equipment	**239.4**	**268.6**	**508.1**

Life Cycle Cost Category	Civil 2017 $M Costs	Eqt. 2017 $M Costs	Total 2017 $M Cost
Other Capital Capitalization Costs			
Preoperational Costs: (152% of 1 year of 1978 USD non-material recurring O&M costs) × (inflation & increase escalation multiplier of 5.95 for a higher-risk life-cycle activity)			121.0
(Essentially an Owner's Cost to cover start-up activities)			
Total Overnight Capital Cost in 2017 USD			**629.1**

- **Construction Financing Costs.** It is assumed that the funds required to construct the plant will need to be borrowed, and an interest during construction (IDC) amount needs to be calculated for the 5 years of design and construction assumed. Continuous discounting at a real discount rate of 3% is used for the IDC calculation, and an S-curve shaped spending pattern is assumed for the cumulative design/construction cost. Table D1-1.16 shows the inputs and results of the IDC calculation. The lump sum IDC calculated is added to the overnight capital cost to obtain the total, financing inclusive capital cost. (Note if this IDC [a.k.a., construction financing cost] is not included, this capital cost total is called the "overnight costs" [i.e., the cost if the facility could be constructed "overnight" with no interest or financing costs incurred].)

Table D1-1.16. Total capital cost for 520 MTU/yr PWR fuel fabrication facility including financing costs.

Interest During Construction Calculation (Construction Financing Costs)	
Years required to design, procure equipment, construct, and start up fabrication facility	5
Real discount rate for construction financing	3%
Calculated lump sum IDC (interest during construction) as %age of overnight cost	7.73%
(Cumulative up-front spending is in the shape of an S-curve)	
Overnight capital cost ($M)	629.1
Calculated interest during construction ($M)	48.6
Total capitalized cost to be recovered ($M)	677.7

- **Recovery of Capital Costs.** The UOX fabrication facility is assumed to be a NOAK plant since the process technology is mature. The 5% real discount rate used for calculation of the IDC is also used for amortization (capital recovery) of the financing inclusive over the assumed 50-year plant life. This "real" discount rate free of general inflation reflects the lower risk associated with a NOAK facility and the fact that LWR fuel fabrication is a relatively non-hazardous activity compared to other FC steps, such as reprocessing, and the nuclear reactors themselves. At the time of plant commissioning (commercial operations), the sum of the overnight capital cost plus the IDC (financing) is "rolled-over" into a 50 year "mortgage" of equal annual payments in much the same way as a conventional real estate entity would be amortized via a mortgage in the United States. The annual payment (divided by the average annual production) represents the capital recovery component of the levelized unit cost. The Generation IV Reactor Cost Estimating Guidelines (Williams and Miller 2007) and the G4-ECONS User's Manual (Williams 2007) present the formula used for the amortization calculation. Table D1-1.17 shows the inputs and outputs to the capital recovery algorithms. The following is the formula for the capital recovery factor:

$$\mathrm{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{1}$$

where:

i = the real discount rate

N = the number of years over which the capital is recovered.

This capital recovery factor (CRF) (a.k.a.,. “fixed charge rate”) when multiplied by the financing inclusive TEC, gives the amount which must be paid over every year of the facility’s operating life to recover the front-end costs including the construction loan interest. Essentially, this is the “annual mortgage payment” which amortizes these front-end costs (TCCC).

- **Average Annualized Production.** Production of PWR fuel assemblies at a “reference” uniform rate of 520 MTHM/yr (or 520 MTU/yr) is assumed over all 50 years of plant operations. The capacity factor of ~70% is already rolled into this average annual production rate. Over its life, the plant will process 26,000 MTU, which represents over 55,000 PWR fuel assemblies of ~460kgU each. In 1978, this production rate would have provided fuel reloads for 17–20 1,000 MWe PWR NPPs; today’s number would be higher at 21–24 due to higher average fuel burnups and longer irradiation cycles. These reload values are not adjusted for increasing average reactor capacity factors from 1978 to 2017.

End-of-Life Costs. After 50 years of operations, the plant is assumed to be decommissioned to the point where all radioactively contaminated material and equipment has been removed and dispositioned and a clean building and site can be made available for other purposes. A lump decommissioning sum is calculated using a decontamination and decommissioning (D&D) rule-of-thumb for chemical plants that estimates approximately 10% of the direct capital costs will cover D&D. A decommissioning fund or escrow account is created to collect a set amount annually over all 50 years of operations so that the lump sum D&D amount is available at end-of-life. It is assumed that the D&D fund earns 1.5% per annum, since a long-term sinking fund or escrow fund generally earns less than a “mortgage type” interest rate. The formula used for calculating the annual fund contribution is also discussed in the G4-ECONS documentation and the Gen IV Cost Estimating Guidelines.

- Table D1-1.18 shows the inputs and outputs to the algorithm calculating the annual contribution to the D&D fund. The following is the sinking fund factor formula used in the algorithm which calculates the factor in the second to last line of Table D1-1.17:

$$\mathrm{SFF}(i, N) = \frac{i}{(1+i)^N - 1} \tag{2}$$

where:

“i” = (in this case) is the interest rate assumed available for the D&D escrow fund

N = the number of years over which it is collected.

Table D1-1.17. Inputs and outputs to the annualized capital recovery calculation.

Capital Recovery Factor for Levelization (Amortization) of Financing Inclusive Capital Costs	
Real (inflation free) interest date for recovery of capital	3.0%
Years to accumulate fund = operating life of facility (yrs.)	50
Payments per year into fund	1
Fabrication plant total capital cost total (including all allowances and financing) ($M)	677.7
Capital recovery factor (CRF or "fixed charge rate")	0.03887
Annual payment required for capital recovery ($M/yr)	26.34

Table D1-1.18. Inputs and outputs to decontamination and decommissioning calculation.

Decontamination & Decommissioning (D&D) Fund Calculation in 2017 USD	
Real (inflation free) interest rate for D&D sinking (a.k.a.,. "escrow") fund	1.5%
Years to accumulate fund = operating life of facility (yrs.)	50
Payments per year into fund	1
Fabrication plant capital cost total (not incl contingency and indirect costs) ($M)	384.9
Percent of direct capital cost total used to approximate lump sum D&D cost	10%
Lump sum D&D cost needed at end of life ($M)	38.5
Sinking fund factor	0.01357
Annual payment required for D&D sinking fund ($M/yr)	0.522

Unit Cost Summary. The three levelized and annualized cost amounts (capital recovery, recurring costs, and D&D) can now be converted to unit costs in $/kgHM or $/kgU by dividing each by the annual baseline production rate of 520,000 kgU/yr. Note that in FC calculations, it is customary to deal with elemental heavy metal for material balance calculations, hence the need for $/kg U rather than $/kg UO2 figure-of-merit. Table D1-1.19 shows the breakdown of the annualized and unit costs by major aggregated life cycle cost (LCC) category and the percent contribution of each.

Table D1-1.19. Summary of levelized costs in 2017 $M/year and 2017 $/kgU.

PWR-UOX FUEL FABRICATION (50 yr PLANT)	2017 Constant USD for Production Rate of 520 MTU/yr		
SUMMARY OF ANNUAL AND UNIT COSTS @CapRec AND IDC DISC RATE OF			
3.00%	$M/yr	$/kgHM	__%
Capital Recovery	26.34	50.65	15.2%
Recurring Costs Include O&M	146.76	282.24	84.5%
D&D Sinking Fund @ 1.5% Interest Rate	.052	1.00	0.3%
Totals>>	173.63	333.9	100.0%

This total unit cost “reference case” value of 334 $/kgHM compares well with the range values derived in the cost basis report (CBR 2017) for the fabrication of LEU oxide fuel, with a low, mode (most likely), high, and mean of respectively 230 $/kgHM, 400 $/kgHM, 575 $/kgHM, and 402 $/kgHM. This unit cost can be interpreted as a unit “price” in the sense that if all production could be sold at this value as revenue, all LCCs including returns to investors would be covered. It can also be seen on a percent contribution to the unit cost basis that recurring O&M costs greatly exceed capital amortization of the facility. This is not surprising, since fuel fabrication is a “value-added” service with considerable labor-hours and additional costly materials such as zirconium and burnable absorbers added to the LEUOX and OX pellets introduced into the rod-filling and bundle assembly parts of the plant.

It is of interest to consider what unit costs for this 50-year facility would result if the 1978 base capital and base recurring costs from ORNL/TM-6501 were inserted into the SA&I G4-ECONS based model with 2017 financing assumptions. A unit cost of $81/kgU was the result and is low compared to the $100 to 150/kgU unit cost values obtained by the ORNL authors. This result makes sense, however, considering 1978 discount rates would have been much higher, and a 20-year life was assumed. Operating a plant for only 20 years instead of 50 means that more front-end fixed capital costs are distributed into the total unit cost, thus requiring a much higher annual capital recovery contribution.

The ratio of the 2017 USD unit cost to the 1978 USD unit cost for a 50-year plant is 4.1 (i.e., 334/81). This increase is due mainly to general inflation and nuclear risk-related incremental escalation.

D1-1.8.1.4 Unit Cost/Plant Capacity Scaling

It is useful to consider how the unit cost might scale with the plant production capacity, especially since today’s LWR fuel fabrication facilities are tending toward larger plants more in the 1,000 to 2,000 MTU range as opposed to the NASAP/ORNL reference size of 520 MTU/yr (nominally 2 MTU/day). ORNL/TM-6522 did consider cost scaling using cost scaling exponents derived for equations of the form:

$$C/Cref = (P/P_{ref})^{x} \qquad (3)$$

where:

C = a cost of a “non-reference capacity” LCC

Cref = the cost of that item for the “reference capacity” plant

P = the “non-reference” production rate or capacity

Pref = the reference plant production rate or capacity

X = the scaling exponent for the LCC category of interest (i.e., O&M, capital equipment, civil capital).

Table D1-1.20 shows the values that the 1978 ORNL/NASAP authors assigned the scaling exponent “x” for various LCC categories applicable to different types of fuel fabrication plants and their radionuclide containment characteristics. A few categories, such as D&D, did not appear in the NASAP reports, therefore the SA&I author of this report selected them. Classic chemical engineering economics textbooks such as *Plant Design and Economics for Chemical Engineers* (Peters and Timmerhaus 1958) were used by ORNL and SA&I for the selection of appropriate scaling factors. Multiple cost/scaling equations and exponents are tabulated in this text for dozens of equipment and process plant types.

Table D1-1.20. Exponential scaling factors used fuel fabrication facility economic studies.

Scaling Factor Used in NASAP Reports Except Where Noted Under “Source”	Exponential Scaling Factor (x)	Source
All categories for reprocessing plants	0.35	NASAP
All capital categories for all contact-handling (“C”) fab plants	0.60	NASAP
Base Facility category for RO/CM and RO/RM plants	0.80	NASAP
Base Equipment category for RO/CM and RO/RM plants	0.70	NASAP
Preoperational category for capital	0.70	SA&I authors
Expendable materials and hardware for all type plants	1.00	NASAP
Recurring operating costs including personnel	0.80	NASAP
Capital Replacements	0.70	SA&I authors
Annual D&D Cost	0.80	SA&I authors
Module D1-1 LWR fuel fab facility is a type “C”, CAT-III facility; values in red text. “C” = contact-handled fuel facilities “RO/CM” = remote operations/contact maintenance” fuel facilities “RO/RM” = remote operations/remote maintenance” fuel facilities		

For each non-reference production rate, a new set of base FC costs was calculated using the cost scaling equation and above factors. Using the same G4-ECONS based model as that for the reference baseline throughput, a new table of annualized cost results. Each of these costs are divided by the non-reference production rate to obtain the capital recovery, recurring cost, and D&D components of the non-reference overall levelized unit cost in $/kgU. These unit cost components are merely added to obtain the total unit cost which appears in Figure D1-1.6 for a throughput range of 50 to 2,000 MTU/yr. Figure D1-1.6 also shows a plot of this data.

	Capacity in MTU/yr	2017 $/kgU
	50	485
	100	429
	200	383
	300	361
	400	346
ref>>	520	334
	750	318
	1000	307
	2000	284

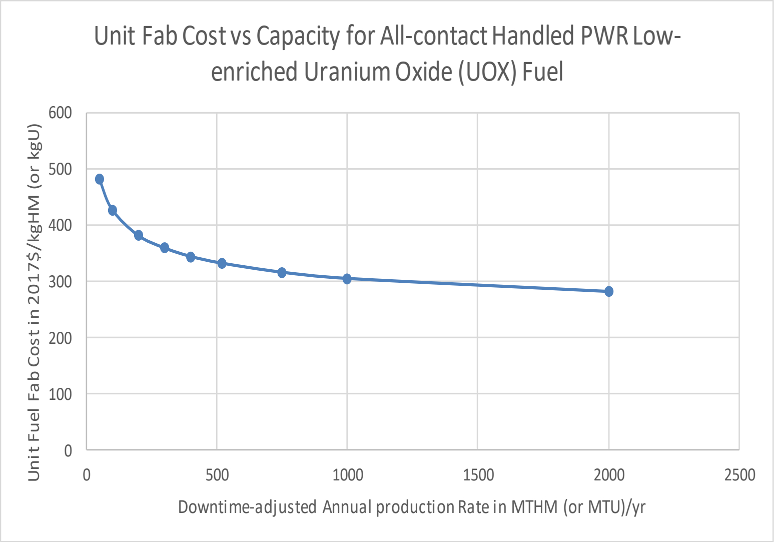


Figure D1-1.6. Levelized unit cost in $/kgU versus PWR fuel fabrication plant production size (e.g., adjusted capacity or throughput).

The unit cost versus throughput curve would not be so smooth, since fuel fabrication plants are usually designed for an integer number of production lines each with an optimized size. The general curvature of the plot would have more of a stairstep appearance. Neither the 1978 analysts for the NASAP reports nor the author of this report had enough design data to develop a more accurate unit cost versus throughput sensitivity study.

This analysis was for PWR fuel; however, the plant design and final fuel assembly product configuration for BWR fuel is quite similar. BWR fuel assemblies have somewhat more complex hardware supporting the fuel rods. It is expected that at most the unit cost will be a few tens of $/kgU higher.

The use of reprocessed uranium (RU or "REPU") in UOX would also incur some additional O&M costs for personnel radiation protection from the strong gamma rays emitted by U-232 daughters. The facility itself would be basically the same as described above. The use of REPU is also discussed in this report.

D1-1.9. DATA LIMITATIONS

D1-1.9.1 Identification of Gaps in Cost Information

The data above are for today's LWR fuel market. Some changes are envisioned for the future, however. It is likely that use of HALEU fuel enrichments over 5% associated with higher burnups will eventually become commonplace. In order to understand how the LEU fabrication price will be affected, the following cost studies should be made:

1. The determinable costs of advanced higher burnup fuel research and development should be calculated and amortized over some number of reloads. This includes the ongoing ATF research and development on new alloys, improved cladding, better process automation, etc.
2. The cost of modifying and relicensing existing fuel fabrication plants to handle HALEU enrichments must be determined. These costs must also be recovered in the new, higher price. New enrichment plants will be needed in the United States to produce these higher LEU U-235 assays for feedstock to these fabrication plants. At least two gas-centrifuge-based enrichment plant concepts are being developed in the United States, and both are intended for producing U-235 assays greater than 5% to meet the U.S. government's need for EU for national security needs that is not restricted or encumbered by international nonproliferation agreements.
3. As stated earlier, no information was available on the costs of constructing or operating new, "greenfield" LEU fabrication plants. Such historical information would be proprietary in a highly competitive industry. It is likely that if new U.S. production capacity is needed, it will be added by reopening existing lines, constructing additional process lines, or utilizing additional shift operations at existing facilities. An educated guess is that a new fabrication line of 200 to 300 MTHM/yr capacity would cost over $100 million (2004 USD) in an existing building. This value is based on analysis of data in reports that consider the use of LEU fabrication plants for producing thorium oxide (ThO2) fuel (Hermes et al. 2001a; Hermes et al. 2001b; Lahoda 2004).

D1-1.9.2 Technical Readiness

LWR pelletized UOX fuel fabrication falls in the technical readiness category of "viable and fully commercial." Some ATF concepts, which will be discussed in Section D1-1.13, are nearing readiness for commercial production. Some have already undergone or are now undergoing lead test rod irradiation in commercial power plants.

D1-1.10. COST SUMMARIES

D1-1.10.1 Literature-Based “Pricing” Data

Very little new price data for the period 2012 to 2017 have been collected to inform entirely new values for Module D1-1 of the 2017 AFC-CBR. For the 2017 Module D1-1 Report, the 2012 values were escalated by ~9% to generate 2017 USD WIT unit cost values. Table D1-1.21 summarizes the data.

Table D1-1.21. Module D1-1 what-it-takes unit cost data from the 2017 AFC-CBR and recent updates (all in 2017 $/kgU).

Fuel type	Reference cost if available	Low	Mode	High	Distribution type	Calculated mean
Std PWR UOX	240 (lit survey)	230	400	575	Triangular	402
Std BWR UOX	400 (lit survey)	285	400	575	Triangular	420
REPUEPU PWR UOX	N/A	250	435	635	Triangular	442
REPUEPU BWR UOX	N/A	315	435	635	Triangular	462

Note that this table includes WIT unit costs for UOX LWR fuel fabricated from REPU. Discussions with a European fuel fabricator indicated that an approximately 10% adder to the price of standard (a.k.a.,. unirradiated) LWR-UOX unit price would cover the additional radiation safety steps and equipment involved in its manufacture.

No new LWR-UOX published pricing data have been identified since 2017, so the 2017 USD values above still stand as the “literature-based” WIT values.

D1-1.10.2 Inclusion of NASAP-Based Data

Now that we have the NASAP and G4-ECONs LCC models developed by ORNL in 1978 and SA&I in 2018, we can add that information to produce a new, updated WIT table. It has already been determined that the 520 MTU/yr reference case with the calculated, levelized unit cost value of 334 $/kgU fits well within the range of the data above. For larger plants of 1,000 to 2,000 MTU/yr, which are more likely for new greenfield facilities, the Figure D1-1.6 graph above indicates that lower unit costs of 284 to 307 $/kgU are possible. It should also be noted that all the NASAP-based unit costs (ranging from 285 to 484 $/kgU) in Figure D1-1.6 fall within the 2017 AFC-CBR “literature-based” cost range in the Table D1-1.21. Table D1-1.22 shows the updated WIT unit cost values for this Module D1-1.

Table D1-1.22. FY-21 Module D1-1 revised what-it-takes levelized unit fabrication costs for conventional non-ATF LWR-UOX ceramic fuel in 2020 USD.

Fuel type	Reference cost if available	Low	Mode	High	Distribution type	Calculated mean
Std PWR UOX (D1-1a)	334 (NASAP-informed)	242	421	605	Triangular	423
Std BWR UOX (D1-1c)	334 (NASAP-informed)	300	421	605	Triangular	442
Rep PWR UOX (D1-1b)	N/A	263	458	668	Triangular	463
Rep BWR UOX (D1-1d)	N/A	332	486	668	Triangular	495

For this update, a mode (most likely) value of $334/kgU for standard PWR UOX was selected, since it represented a credible base case derived from the bottom-up NASAP study. It is lower than the 2017 AFC-CBR value of $400/kgU which was literature-survey and opinion derived. The NASAP-informed low and high ranges (284 and 485, respectively) for PWR-UOX were derived from cost/capacity scaling relationships and fall entirely within the old 2017 AFC-CBR WIT range of 230–575 $/kgU. It was decided to keep this wider range for the 2020 update to cover other possible uncertainties outside of cost/capacity scaling, such as labor and regulatory costs and zirconium costs.

The triangular distributions based on the costs in the above WIT table are shown in Figure D1-1.7 through Figure D1-1.10. Both relative and cumulative probability distributions are shown. These probabilistic data are very useful for FC economic models where cost uncertainty is a major consideration.

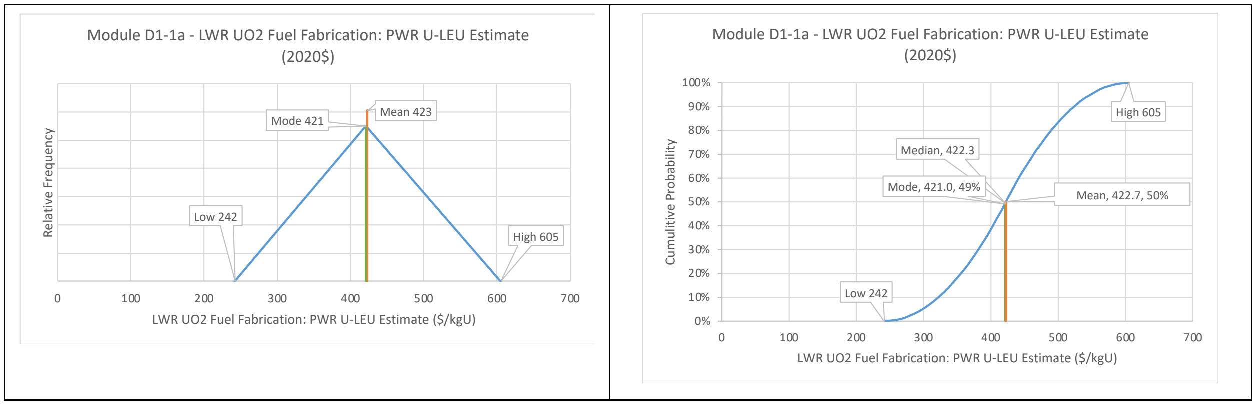


Figure D1-1.7. Reference LWR UO2 fuel fab (PWR: Standard LEU) estimate (2020 USD).

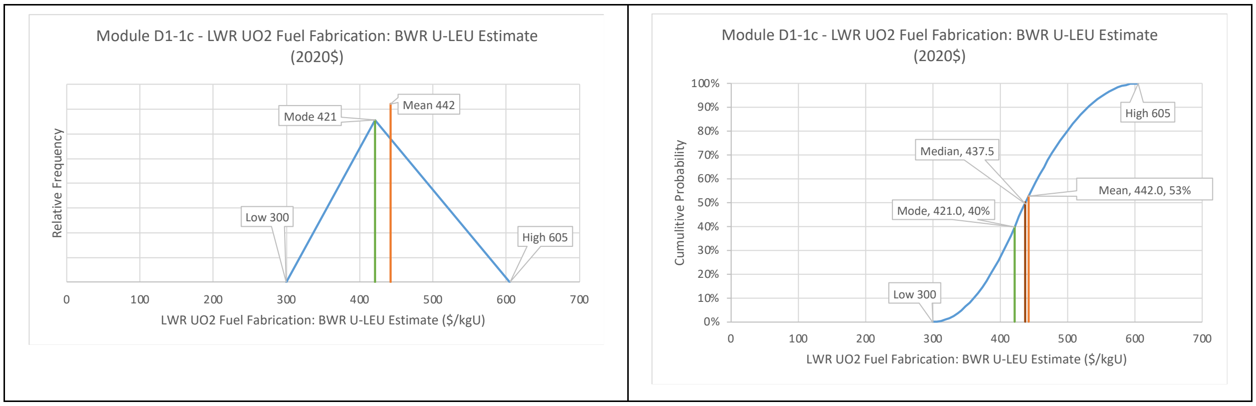


Figure D1-1.8. Reference LWR UO2 fuel fab (BWR: Standard LEU) estimate (2020 USD).

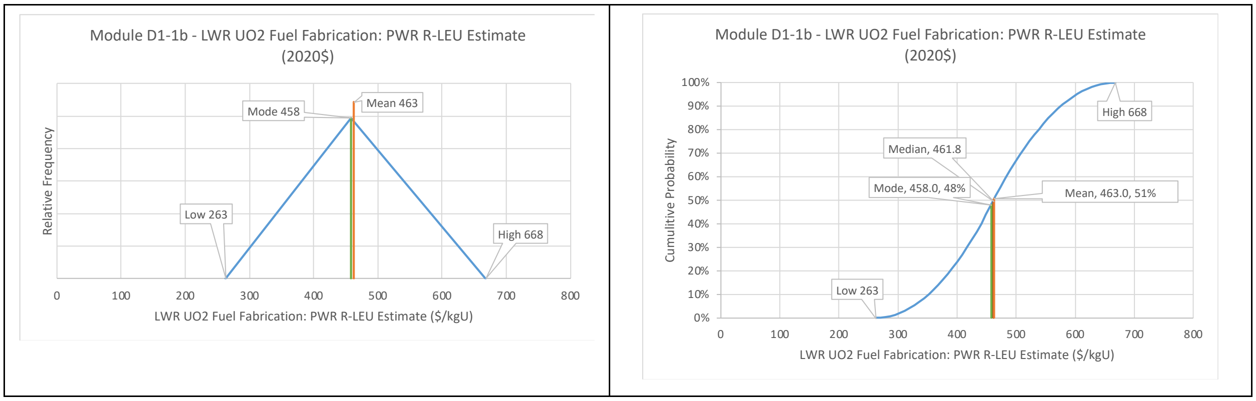


Figure D1-1.9. Reference LWR UO_2 fuel fab (PWR: reprocessed and re-enriched LEU) estimate (2020 USD).

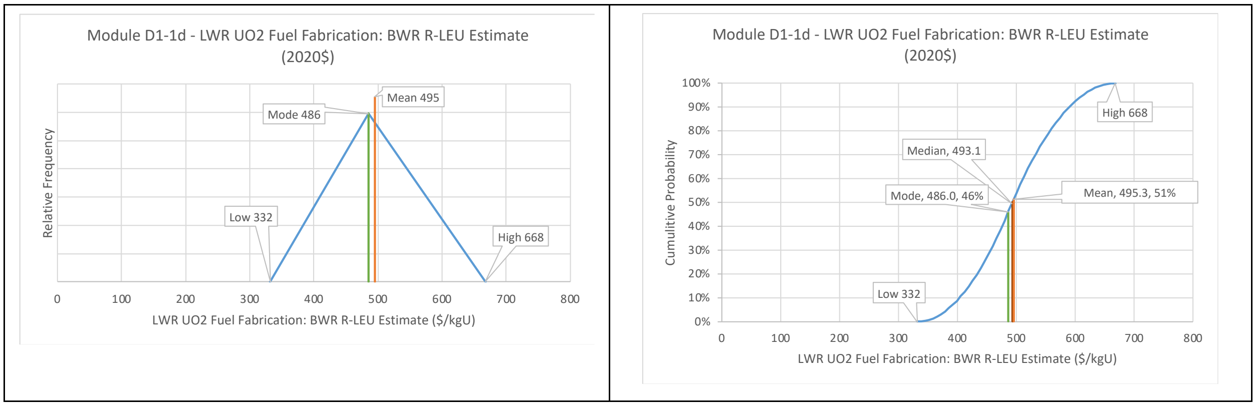


Figure D1-1.10. Reference LWR UO2 fuel fab (BWR: reprocessed and re-enriched LEU) estimate (2020 USD).

D1-1.11. SENSITIVITY AND UNCERTAINTY ANALYSES

Because of the high readiness level of this fuel fabrication technology, no studies other than plant life cycle costs versus production capacity were performed. Fuel fabricators have likely done additional studies on fuel design changes for ATFs; however, these are likely to be proprietary. ATFs are discussed in Section D1-1.12.

D1-1.12. SPECIAL TOPIC: LEUO2 REFABRICATED FROM REPROCESSED URANIUM

Note although this special topic section was originally written for the 2009 AFC-CBR, it is still mostly applicable today. LEU in the form of uranyl nitrate hexahydrate (UNH) solution or crystals is one of the separated by-products of existing PUREX or proposed UREX reprocessing of LWR fuels (Module F1 of AFC-CBR) in addition to high-level waste, TRU waste, low-level waste, and separated higher actinides such as plutonium. (It is also possible that by adding an extra post-separation process step at the reprocessing plant, solid UO3 or U3O8 product could be produced from UNH into a physical form more amenable to safe storage.) Like separated plutonium, the separated uranium has some value if it can be re-enriched and reused as REPU fuel. Over 94% of the mass of spent LWR fuel is still in the form of uranium, for which the U-235 isotopic content is significantly reduced from that prior to irradiation. Over 80,000 MTU of uranium already exists (2020) in U.S. legacy spent fuel. If this separated U is not re-enriched and refabricated, it must be safely stored and dispositioned. Storage and disposition options for reprocessing-derived U forms are covered in AFC-CBR Modules K2 and K3, depending on whether aqueous or electrochemical technology is used in the reprocessing step. Also, like the plutonium solution to solid mixed oxide (MOX) fuel preparation, there are cost-incurring process steps that must be taken on the route from reprocessing plant uranium byproduct (UNH solution or crystals) to LWR reprocessed/re-enriched/refabricated UO2 fuel. The costs of these steps must be assessed against any monetary “credits” for the unirradiated low-enriched UO2 assemblies displaced by REPU assembles, just as MOX preparation costs are assessed against “credits” for the unirradiated low-enriched UO2 assemblies displaced by plutonium-derived (U,Pu) MOX.

The uranium is essentially what is left when the 2–4.9595% U-235 unirradiated LEUO$_2$ pellet fuel has burned down to unfissioned uranium enrichment levels of 0.5–1.2 % U-235. This unburned uranium constitutes about 94+% of the heavy metal mass of a spent LWR fuel assembly. The remaining HM-derived masses are fission products and transuranic actinides such as plutonium, neptunium, americium, and curium. Unfortunately, undesirable uranium isotopes, such as U-236 (a neutron absorber) and U-232 (an isotope with a very strong gamma-emitting daughter), have been generated in the unburned uranium by irradiation, and their percentages increase with reactor fuel burnup. U-232 has the undesirable nucleonic aspect of producing radioactivity that for a few decades increases with time. Its decay chain includes the radioisotopes lead-212, bismuth-212, and thallium-208; the latter is especially notable for its 2.615 MeV hard gamma emission. Gamma activity of the freshly separated RU increases for about a decade due to the accumulation of these decay products and then slowly decreases. The associated radiation increases the ES&H risks of (and costs of) handling reprocessing-derived uranium vis-à-vis “unirradiated” uranium in the conversion, re-enrichment, and refabrication steps. The natural nonfissile isotope U-234 is also enhanced in REPU above its level in unirradiated-LEU fuel by the fact that it does not fission, whereas its adjacent U-235 isotopic species does. U-234 has a short enough half-life (245,000 years) that it becomes a problem for long-term waste disposal somewhat like other actinides. These and other issues are treated in greater detail in Michaels and Welch’s ORNL 1993 report (Michaels and Welch 1993) and in a more recent ORNL report (Del Cul 2009).

PUREX-derived REPU has been successfully used in commercial reactors; however, steps are needed to prepare it for reactor use. First, the UNH or other stored product form, such as U_3O_8 or UO_3, must be converted to UF_6. This is usually done at the reprocessing or enrichment plant site and is anticipated to cost significantly more than the \$5–8/kgU (per Module B) for natural U_3O_8 to UF_6 conversion. The presence of radiotoxic minor isotopes and criticality issues associated with possible higher than natural enrichments probably results in conversion costing more on the order of \$11 to 20/kgU. The second step is re-enrichment to a U-235 assay capable of use in the same reactor that burns the “unirradiated” $LEUO_2$. Because of the U-236 and U-234 content, a higher U-235 level than for unirradiated LEU is needed to compensate for the U-236 “poisoning” effect. Because handling the more radioactive reprocessed UF_6 is difficult, the enrichment cost is anticipated to be higher than for unirradiated EUF_6 enrichment plant feed. A 20–30% penalty on the price per SWU is probably warranted. The last step is fuel fabrication from the $LEUF_6$ enrichment plant product. If not blended with other $LEUF_6$ or passed through an additional enrichment cascade, the U-232 and U-236 content of this enrichment plant product material will be even higher than for the UF_6 feed to the enrichment plant. This is because the gaseous diffusion and centrifuge enrichment processes tend to push these undesirable “lighter” uranium isotopes into the product stream. The refabrication plant must now minimize personnel radiation exposures and utilize more automated handling of the process steps. Additional shielding may be required. For these reasons, the cost of reprocessed UO_2 fuel fabrication is expected to be at least several percent higher than for unirradiated $LEUO_2$ fuel. In Bunn’s report (2003), penalties of up to \$20/kgU are suggested. Michaels and Welch (1993) indicate that as reactor burnups for LWR fuel increase, the REPU derived from reprocessing thereof will have increasingly undesirable isotopic content, thus refabrication costs could go even higher. This will limit the number of irradiation passes for which all REPU material can be used. (This multi-pass limitation is also true of reprocessed MOX fuel.)

Michaels and Welch (1993) also consider storage and disposal options for the REPU. UNH or any oxides produced may not qualify as low-level waste under USNRC regulations because of the minor isotopes and any residual fission products therein. Costs for uranium storage are also covered in Michaels and Welch (1993) and Spencer et al. (2005) and are discussed in Modules K2 and K3.

REPU reconversion, re-enrichment, and refabrication for the production of reprocessed UO_2 fuel have been under way in Europe, and with the low price of U_3O_8 today, expansion of this REPU capability has been slowed down from earlier estimates (Platts 2007c and 2007d). Figure D1-1.11 shows the scheme used in Russia at the Siberian Chemical Combine (Seversk/Tomsk) to take stored French REPU (produced at LaHague and stored at Pierrelatte), remove the undesirable daughter products (a.k.a., aqueous polishing), convert the resulting oxides to UF_6, and re-enrich this clean material to low U-232, U-235 enhanced product in two centrifuge cascades for ultimate refabrication. The processes and economics are described in a report from the International Business Relations Corporation (IBR 2006). Russian cost estimates in this reference indicate that this scheme should produce finished reprocessed UO_2 fuel at prices competitive with unirradiated $LEUO_2$ fuel, especially if uranium ore (U_3O_8) prices rise.

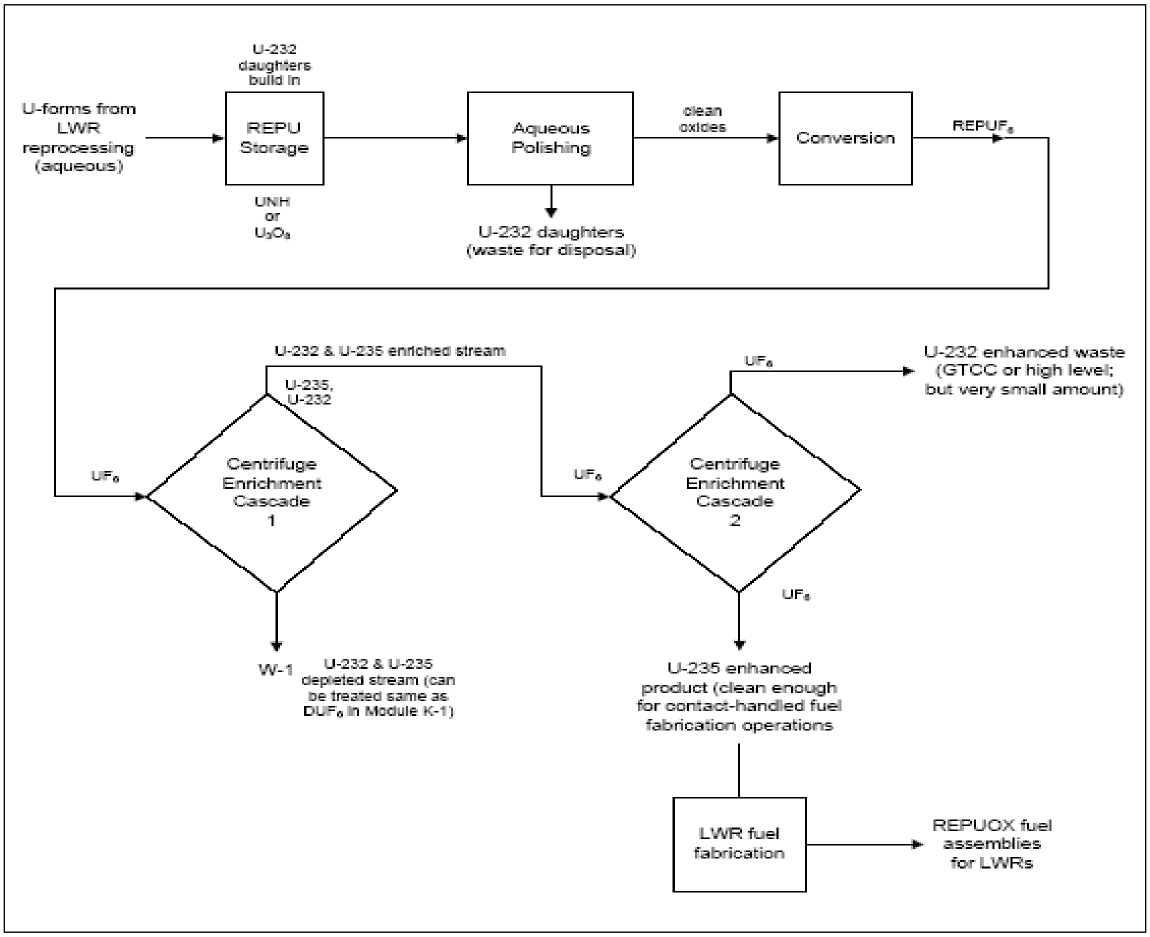


Figure D1-1.11. French-Russian scheme for reprocessed uranium recycle.

In 2006, AREVA (now ORANO) announced plans (Platts 2006) to build their own 1,000-MTU/yr RU oxide to reprocessed UF6 conversion plant next to their proposed centrifuge enrichment plant at Pierrelatte. At the time, this announcement seemed to indicate that rising uranium ore costs and large quantities of stored reprocessed U3O8 are making deployment of this scheme in France economically attractive. As they were in 2007 (Platts 2007a), these plans may be on hold due to recent low U3O8 and SWU prices.

The United States has recently gained some experience in using reprocessed-material fuels via Project BLEU (Tousley 2005). In this program, the Tennessee Valley Authority, a government-owned U.S. utility, is burning LWR fuels produced by blending reprocessed military production reactor highly enriched uranium with lower U-235 assay blendstocks. A Nuclear Fuel Services Inc. press release on May 30, 2006 (Nuclear Fuel Services 2006) and a later trade press item (Nuclear Street 2009) described this U.S. DOE-National Nuclear Security Administration (NNSA)-supported program in more detail. This REPU-derived fuel is still being irradiated in TVA’s Brown’s Ferry NPP in Alabama.

D1-1.12.1 Special Topic: Accident-Tolerant Fuels for LWRs

D1-1.12.1.1 ATF Technology

Nearly all the LWR fuel fabricators are now considering the development and manufacture of ATFs as a means of reducing the possibility of accidental fuel melting and the regulatory concerns that result from this possibility. Such ceramic fuels will still involve a cylindrical fuel form enclosed by a cylindrical clad of some type; however, the pellets and cladding could involve entirely new ceramic uranium compounds (or even metal) and new types of cladding or cladding treatments instead of the traditional zirconium-alloy types. It should be noted that Lightbridge Corp is proposing a metal ATF with a cruciform cross section. This is discussed in Module D1-6 on metal fuel fabrication. In a recent presentation to the USNRC, it was stated that such fuels may be ready for use as early as 2023 (NEI 2018). Some are now being tested in commercial reactors in reload test assemblies**. These fuels could involve higher unit fabrication costs; however, the resulting improved safety performance and possible longer fuel life and higher burnup could reduce costs elsewhere in the reactor life cycle. This is a result of the fact that the amount of fissile material required in a reload could also be reduced**.

According to a recent survey article by the ANS (Holtzman 2021), the types of fuel and cladding concepts being considered are in the following table.

Table D1-1.23. ATF technology concepts.

FUEL CONCEPTS	
Enhanced UO2 Fuel Pellets	Addition of small amounts of dopants, such as aluminum oxide and/or chromium oxide.
High-density Fuel	More U-235 atoms within the same volume of space and a higher thermal conductivity than conventional UO2 pellets. Examples are uranium silicide and UN.
Metallic Fuel	U/Zr alloys which are metallurgically bonded (non-pellet/cladding concept). To be discussed in AFC-CBR Module D1-6A (Uranium metal Fuel Fabrication).
CLADDING CONCEPTS	
Coated Cladding	Addition of a thin metallic or ceramic coating to the current Zr or Zr-alloy cladding.
Advanced Steel Cladding	Cladding made from variants of iron-based alloys, including Fe/Cr/Al.
Silicon Carbide Cladding	Monolithic or composite SiC cladding—a leading non-metallic cladding variant.

Other advanced fuel concepts such as Fully Ceramic Microencapsulated (FCM) fuel utilizing TRISO particles embedded in right-circular cylindrical matrix form, similar to an LWR fuel pellet. are under development for micro and modular reactors using HALEU fuel enrichments. For some microreactors, the pressed fuel shape could be different than a circular cylinder. (Note these small reactors are mainly intended for military uses, or for use in remote locations, and will be considered in a future AFC-CBR reactor module.) The Ultra-Safe Nuclear Corporation recently described their development effort in a recent World Nuclear News Update (WNA 2020). Such fuel might be used in conventional LWRs to replace typical UOX pellets of < 5% enrichment; however, the TRISO kernels embedded in the pellet matrix, probably silicon carbide, would have to have an enrichment well above 5% U-235 (HALEU) and still below 19.75% U-235 to qualify as LEU and provide the needed spatial fissile density. A recent Idaho National Laboratory (INL) report (INL 2020) is an initial evaluation of some of the LEU fuel-reactor concepts that could make use of this FCM fuel. A more detailed consideration of the economic implication of fabricating the TRISO particles for this fuel type will appear in future Module D1-3 (Particle Fuel Fabrication).

D1-1.12.1.2 Potential ATF Fuel Fabricators

Lead use rods have been irradiated in commercial reactors for some ATF concepts starting in 2018. The first types loaded were using: (1) the Global Nuclear Fuel's "IronClad" Fe-based cladding concept and (2) GNF's "ARMOR" coating on zirconium; both irradiated in Hatch Unit 1 in Georgia (WNN 2018). Shortly thereafter, in 2019, full ATF assemblies were inserted into the Vogtle 2 reactor in Georgia (NN 2018). ATF concepts are expected to improve reactor performance during normal operations as well as the full spectrum of transients/accidents (AOOs, DBAs, BDBAs). Unit costs (or prices) have not yet been determined and are likely to be proprietary information, even when sales of the initial batch reloads begin. In the future, the only "actual" price information will be the result of public disclosures from legal or contractual proceedings dealing with utility fuel procurements, especially for utilities regulated by public utility commissions. No published "market price" will likely be available, unlike the market for enrichment (SWUs), U3O8 to UF6 conversion, and uranium ore (U3O8). Westinghouse and DOE did, however, undertake a "business case" study (Lahoda et al. 2015) that showed lower overall FC costs ($/kwh attributable to fuel) due to longer fuel irradiation life (and the consumption of less fuel), even if the unit fabrication cost per kgU of fuel is higher.

Before further discussion of the 2015 DOE/Westinghouse ATF study (Lahoda et al. 2015), the following information, gathered in 2019, is included to provide the reader a short synopsis of the various innovations being pursued by the world's largest fuel fabricators. Many of these fabricators are working jointly with government-owned laboratories within their nations. In 2022, a more comprehensive ORNL/TM report (Hall et al. 2021) on ATF R&D was discovered and supplements the less detailed fabricator information below:

- **Global Nuclear Fuels (GNF)/GE-Hitachi** in cooperation with ORNL (USA) and other national laboratories (WNN 2018).
    - GNF's advanced fuel products are as follows: "Iron Clad" brand (iron, chromium, aluminum alloy cladding) and "ARMOR" brand (Zirconium cladding with proprietary coating). Both are currently being tested at Southern Company's Hatch Unit-1 in Georgia (USA) following initial irradiation in INL's ATR.
- **Framatome/AREVA** (France and USA) (WNN 2019c).
    - Near term development fuels: chromium-coated Zr-alloy cladding for improved wear resistance and lower reaction rate with water and Cr_2O_3 (chromia)—doped UO_2 in pellet for improved fuel performance (heat transfer) and reduced fission product loss. Irradiation tests are underway or planned at INL's ATR, the Gosgen NPP (Switzerland), Arkansas Unit 1, and Vogtle Unit 2 (Georgia). There is significant experience on the performance of chromium-coated cladding and

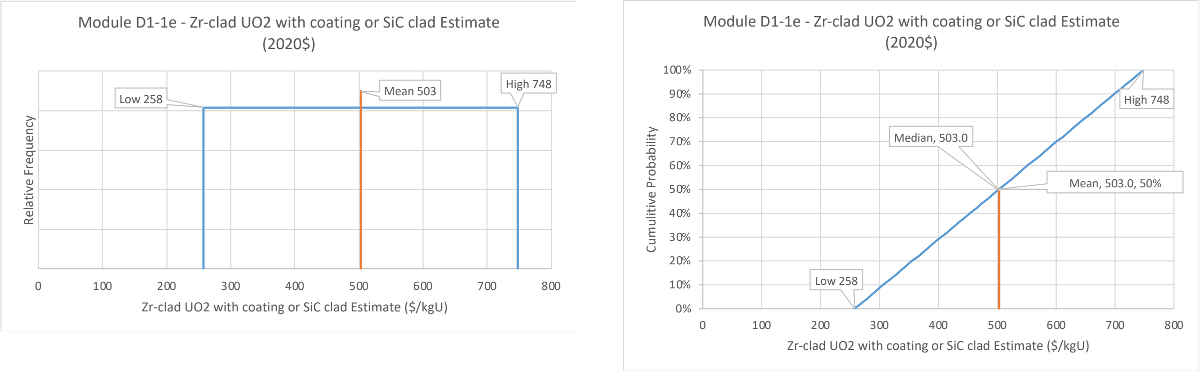
  - chromium-doped UO_2 by French organizations CEA and EdF (Commesariat Energie Atomique and Electricite de France).
  - Longer term development ATF concepts: silicon carbide coatings or possible silicon carbide composite as the overall cladding.
- **Westinghouse** in cooperation with INL and Los Alamos National Laboratory (LANL) USA (NN 2019b; NN 2019c).
  - The Westinghouse ATF development program is called "EnCore." Uranium silicide pellets (U_3Si_2) with higher U-density and higher thermal conductivity than UO_2 are undergoing process development. The zirconium cladding is coated with chromium to reduce oxidation by hot water. After further development, the silicon carbide cladding will be introduced. INL has fabricated uranium silicide from uranium metal powder and has pressed sample pellets. (Note high throughput EUF_6 to U-metal powder conversion process and U-Si alloying process will need further development.) Lead item testing is planned for Byron Unit 2 in Illinois using coated zirconium tubes. Higher U-density from U_3Si_2 pellets can enable higher burnup or reduced enrichment Westinghouse recently announced a re-focus of their ATF fuel from silicide to UN with fully enriched nitrogen-15, which has a low neutron absorption cross section. Westinghouse is also developing ADOPT (Advanced Doped Pellet Technology) fuel pellets, which are modified UO2 pellets doped with chromia and alumina. These ADOPT pellets are already in commercial use in Europe.
- **TVEL/ROSATOM** (Russia) (WNN 2019b).
  - ROSATOM is testing some ATF concepts in the MIR Test Reactor at Dimitrovgrad. Concepts under development are chromium-nickel alloys for cladding and uranium-molybdenum alloys for higher U-density and higher thermal conductivity pellets. These technological choices are based on similar objectives to the Westinghouse options discussed above.
- **CGN** (China General Nuclear) (WNN 2019a).
  - CGN is considering coated Zr-alloy cladding, iron-chromium-aluminum alloy cladding, and eventually silicon carbide cladding. Research on higher density UO_2 pellets is underway.
- **Lightbridge/EnFission** (HLNN 2018).
  - Lightbridge is proposing extruded U-metal/zirconium alloy ATF for LWRs based on Russian ice breaker fuel. The fuel has a four-lobe cruciform transverse cross section and high thermal conductivity. This concept is discussed in further detail in AFC-CBR Module D1-6A (Uranium Metal Fuels).

D1-1.12.2 Cost Data from a 2014 DOE/Westinghouse Study

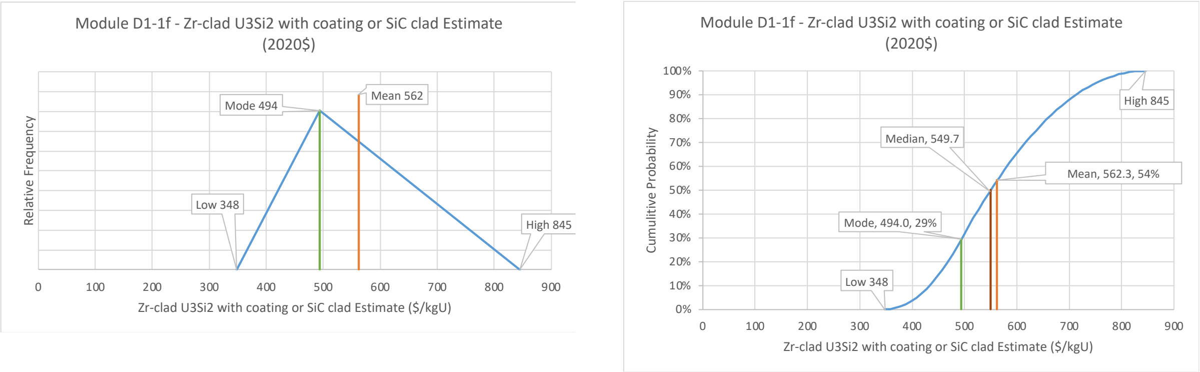
In 2015, the economic implications of using ATFs in LWRs began to be examined, since it appears that the safety and licensing advantages for this fuel type are considerable. Because of possible higher burnup, the average annual amount of reloaded LEU required per reactor-year can decrease considerably, thus lowering the FC cost component of the levelized cost of electricity. This may be true even if the unit cost of fabricating ATF-LWR fuel is higher than that for conventional zirconium-alloy-clad UOX. Unfortunately, no more recent estimates for the cost of ATF production have been found, and it is likely that any prospective ATF vendors would consider such to be proprietary information. In 2019, a 2014 DOE/Westinghouse report (Lahoda et al. 2014) was found which included an LCC analysis and business plan for introducing ATFs into widespread use as LWR reloads. This Westinghouse-led study was funded by DOE-NE and had team members from the following institutions in addition to Westinghouse: General Atomics, Southern Nuclear Co., INL, LANL, MIT, Texas A&M, University of Wisconsin, and the Edison Welding Institute. The report included mainly the incremental manufacturing costs (over UOX) of utilizing UN and triuranium silicide (U3Si2) as the fuel meat instead of UO2. The pellets made from these compounds have higher thermal conductivity and higher uranium density than UO2, thus allowing expedited heat removal (a safety-related factor) in addition to higher energy production per unit mass. Using this incremental cost data on fuel meat preparation, Zr tube coating application, and silicon carbide cladding preparation, it was possible for the SA&I author of this report to calculate the percent increase in unit fabrication cost above that of UOX for three types of ATFs: (1) zirconium-alloy-clad UO2 with special coatings to inhibit oxidation at elevated temperatures, (2) U3Si2 pellets clad with coated zirconium-alloy or silicon carbide (SiC), and (3) UN pellets clad with coated zirconium-alloy or silicon carbide. To generate WIT unit cost data for each fuel meat type, the lower cost ATF variant (coated zirconium) was considered the low case. Silicon cladding was the more expensive (high) case. The following table lists the results.

Table D1-1.24. What-it-takes unit fabrication costs for three types of ATFs containing different ceramic uranium compounds.

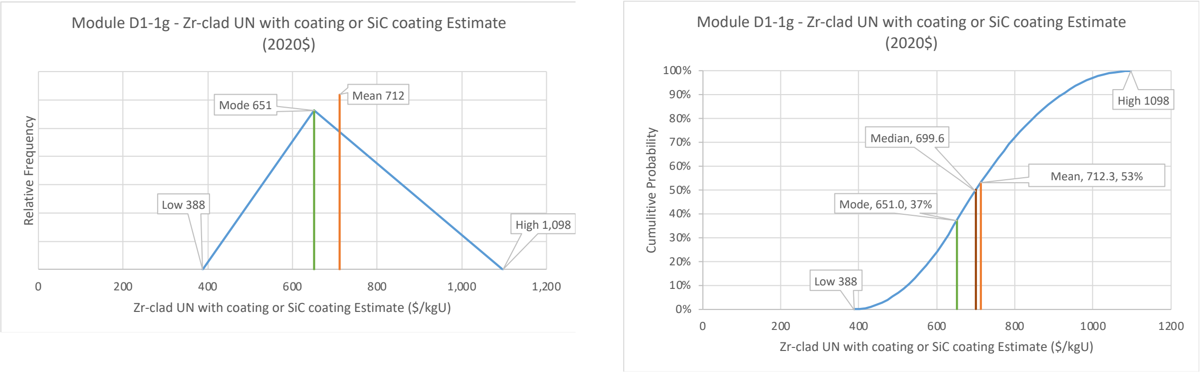
ATF Fuel Type	Low	Mode	High	Distribution	Calculated Mean
Zr-alloy-clad UO2 with coating or SiC clad (D1-1e)	258	N/A	748	Uniform	503
Zr-alloy-clad U3Si2 with coating or SiC clad (D1-1f)	348	494	845	Triangular	562
Zr-alloy-clad UN with coating or SiC coating (D1-1g)	388	651	1098	Triangular	712



Zr-alloy-clad UO2 with coating or SiC clad



Zr-alloy-clad U3Si2 with coating or SiC clad



Zr-alloy-clad UN with coating or SiC coating

Figure D1-1.12. Above shows the relative and cumulative probability distributions corresponding to the ATF unit cost data in Table D1-1.24.

Higher unit fabrication costs for ATFs can be attributed to several causes as follows:

- Most process steps for ATFs are in addition to or replacing the steps required to produce conventional Zr-alloy clad UOX fuel.
- Use of fuel meat ceramic uranium compounds other than UO_2 requires different front-end EUF_6 to ceramic-grade powder conversion and powder preparation processes than for the conventional EUF_6 to UO_2 “dry” and “wet” conversion routes.
  - U_3Si_2 requires a special batch “spark” U-Si co-melting pyrochemical technique requiring LEU metal feed and is pyrophoric. The EUF_6 to EU-metal process itself is a batch pyrochemical reduction process which is more expensive to build and operate than a continuous UF_6 to UO_2 process. (Module C3 on HALEU economics discusses this UF6 to U-metal deconversion step in detail.)
  - The nitrogen in UN must be enriched in the less abundant natural isotope N-15. N-15 has a very low neutron absorption cross section. The more abundant N-14’s much higher cross section would allow the (n,p) (neutron-proton) reaction that would form large amounts of carbon-14, which would constitute a long-lived, biologically active waste radioisotope in the spent fuel. The large-scale isotopic separation of natural N_2 into high-assay N-15 enriched nitrogen would be an expensive isotope separation process which has not been tested on a large scale. UN powder is also highly pyrophoric, which requires that all powder-handling processes be conducted in an inert atmosphere.
- Use of coated zirconium or silicon carbide cladding requires new or additional steps needing cold spraying or other non-3D additive manufacturing techniques to apply the coatings or to produce the SiC tube structure. A recent article in the *Journal of Nuclear Materials* (Koyanagi et.al. 2020) discusses this possibility.
- Some ATF concepts might require HALEU and its higher anticipated handling costs during fabrication (Adams 2017). As noted above, HALEU is the subject of Module C3 of the AFC-CBR.)

D1-1.12.3 SPECIAL TOPIC: NASAP-derived PWR-UOX Fab Plant Life Cycle Cost Model

How the NASAP-derived PWR-UOX Fab Plant LCC model will provide the reference basis for cost estimation of more complex fuel fab facilities involving multi-actinide fuel content and glovebox or remote-handling requirements.

As explained in more detail in Module D-PR of this document, the 1978 ORNL-NASAP team that prepared the ORNL/TM-6501 report was also commissioned to evaluate the economics of nuclear fuels used in other FCs than the “once-through” LWR-UOX cycle already in use at the time. The intent was to see if any other FCs, some involving partial or total recycle of separated fissile material, would have nonproliferation or economic advantages over the existing UOX cycle and the MOX FCs (both thermal and fast) under development at the time. For some proposed FCs, fuel fabrication was correctly perceived to be a major economic contributor to the overall levelized FC cost since many of these cycles involved thorium/U-233 or recycled transuranic fuel components with radiotoxicity and health physics considerations much more serious than those for UOX. Each fuel type was examined by starting with the PWR-UOX plant “floor plan” and equipment list as the starting “baseline.” The 1978 ORNL team then assessed the additional floor space, process equipment, building modifications, personnel protection, and recurring cost modifications needed to manufacture these more complex and radiotoxic fuels. This team’s analysis included the generation of “complexity factors” used to modify the costs of the major LCC elements of the advanced fuel fabrication plant types. Algorithms of the type described in an earlier *Nuclear Technology* paper (Lotts and Washburn 1968) and other papers (Lotts et al. 1972; Lotts, Washburn, and Homan 1968) were utilized in this process. For non-UOX fabrication facilities, a bottom-up design and cost estimate were not performed at the same detail level that it was for UOX; however, the PWR-UOX estimate generated by the ORNL/TM-6501 team served as a high-quality starting point or “reference plant” for estimating new and modified “subject” fuel fabrication plants of higher complexity.

It was the intent of the 2018 SA&I analysts to investigate whether this “complexity factor” type transitional analysis can be used to check the validity of unit cost estimates for other types of fuel appearing in Modules D1-2, D1-3, D1-4, D1-5, D1-6, D1-7, D1-8, and D2/F2 of the 2017 AFC-CBR. An attempt to duplicate some of the 1978 ORNL results (ORNL/TM-6522) for MOX and metal fuel fabrication has already been performed or to duplicate the type of calculations originally made by hand or using mid-1970s FORTRAN programs on punched cards. As explained in Module D-PR, these LCC results will be reported in future D-Module updates. In addition to Module D1-PR, a 2019 TOPFUEL paper (Ganda 2019) describes the methodology used by the SA&I Economic Analysis Team.

The X-axis of Figure D1-1.13 lists fuels of increasing complexity and radiotoxicity as one moves to the right. The unnumbered Y-axis is a quasi-qualitative measure of the magnitude of the factors which influence (and increase) manufacturing cost. There are no numerical units for the X or Y axes. The point is that as we move toward fuel recycling, these complicating factors will need to be considered in any additional calculations or unit cost ($/kgHM) estimates done for the remaining D-Module unit costs.

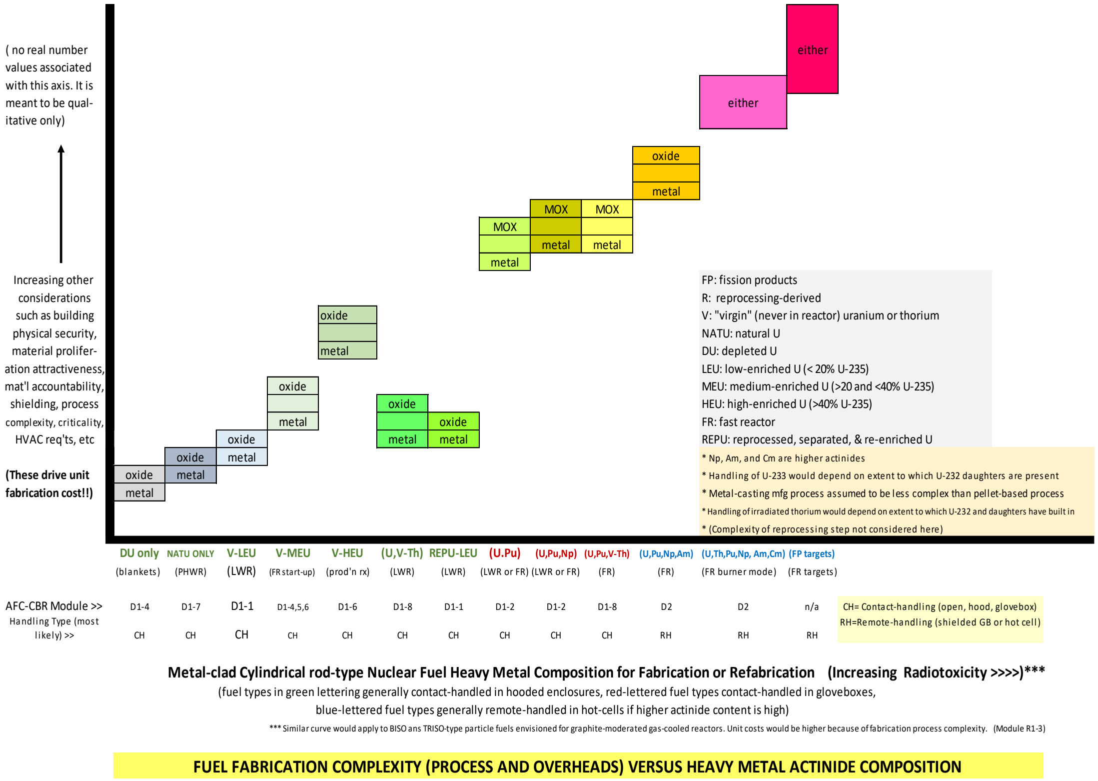


Figure D1-1.13. Qualitative plot of fuel fabrication complexity versus HM radionuclide composition of various nuclear fuels.

Once all the D-Modules (Fuel Fabrication) are complete, it should be possible to produce a more quantitative plot similar to the figure above, except that the Y-axis will then have numerical unit cost uncertainty bars.

D1-1.13. REFERENCES

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