Advanced Fuel Cycle Cost Basis Report: Module D1-4 and Module D1-5 Ceramic Pelletized Sodium-Cooled Fast Reactor Fuel Fabrication Ceramic Vibrocompacted Fuel Fabrication

Nuclear Fuel Cycle and Supply Chain

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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2017	D1-4-All	Version of AFC-CBR in which Module first appeared: 2004 as *Module D1-4*. In the *2012 AFC-CBR* costs for the fabrication of higher enrichment UO2 fast reactor fuels were added to the existing data for MOX-based FR-fuels.
			Nature of this *2017 Module* update from previous AFC-CBRs: escalation only from last time values underwent technical assessment (*2012 AFC-CBR*)
	2017	D1-5-All	Version of AFC-CBR in which Module first appeared: 2004 as *Module D1-5*
	2021	All	Latest version of module in which new technical data was used to establish unit cost ranges for *Module D1-4*: 2020 (pelletized MOX unit cost data that is informed by the NASAP study) New technical/cost data which has recently become available and will benefit next revision: • Russia continues to develop this technology to support U,Pu MOX insertion in their BN Series of SFRs. A new literature review might yield some cost information. • Vibrocompacted (VIPAC) fuel (*Module D1-5*) "what-it-Takes" (WIT) unit costs are estimated as a fixed percentage of unit costs for pelletized U,Pu MOX in *Module D1-4*. This assessment is based on technical complexity of the VIPAC manufacturing process vis-à-vis a pelletization process.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. "What-it-Takes" (WIT) unit cost estimates are in U.S. dollars ($) of year 2020.

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ACKNOWLEDGEMENT

This latest version of the *Module D1-4* and *Module D1-5, Ceramic-Pelletized Sodium-Cooled Fast Reactor (SFR) Fuel Fabrication Ceramic Vibrocompacted Fuel Fabrication* is the result of the cumulative effort of many authors that have contributed to the overall *Advanced Fuel Cycle Cost Basis Report*. It is not possible to identify and acknowledge all those contributions to the *Advanced Fuel Cycle Cost Basis Report* and this module. All the authors, including the four primary authors, 15 contributing authors, the 12 contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to the development and writing of this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

The technical update for these two modules is the result of analysis led by Kent Williams (ORNL-retired). This update reformats previous work to the current format for rerelease of the entire report as individual modules. J. Hansen (jason.hansen@inl.gov, INL) and E. Hoffman (ehoffman@anl.gov, ANL) can be contacted with any questions regarding this document.

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ACRONYMS

ACFAC	A Cash Flow Analysis Code
AEC	Atomic Energy Commission (USA)
AFC-CBR	Advanced Fuel Cycle Cost Basis Report
AFCI	Advanced Fuel Cycle Initiative
ANL	Argonne National Laboratory
ANS	American Nuclear Society
BN	Russian series of fast reactors
CDFR	China Demonstration Fast Reactor
CEA	Commerariat Energie Atomique (French Atomic Energy Commission)
CEA	French Atomic Energy Commission
CPI	Consumer Price Index
CRBRP	Clinch River Breeder Reactor Project
D&D	Decontamination and Decommissioning
DOE	U.S. Department of Energy
DOE-NE	Department of Energy-Nuclear Energy
EBR	Experiment Breeder Reactor
EMWG	Economic Modeling Working Group (Generation IV Reactor Program)
EPRI	Electric Power Research Institute
ERDA	Energy Research & Development Agency (US)
ES&H	Environmental, health, & safety
FBR	fast breeder reactor
FCM	fully ceramic microencapsulated fuel
FCRD	Fuel Cycle Research and Development (Program of DOE-NE)
FFTF	Fast Fuel Flux Facility (Hanford)
FMEF	Fuels Manufacturing and Examination Facility (Hanford)
FP	fission product
FR	fast reactor
FRFCF	Fast Reactor Fuel Cycle Facility
FY	fiscal year
HA	higher actinides
HALEU	high-assay low-enriched uranium
HALEUF6	high-assay, low enriched uranium hexafluoride

HALEUOX	high-assay, low-enriched UO2 or UOX
HEDL	Hanford Engineering Development Laboratory
HEU	highly enriched uranium
HM	heavy metal
HS&E	Health, Safety & Environmental
HTGR	high-temperature gas-cooled reactor
HTR	high-temperature reactor
HVAC	heating and ventilation, and air conditioning
IAEA	International Atomic Energy Agency
IDC	interest during construction
INFCE	International Nuclear Fuel-Cycle Evaluation
INL	Idaho National Laboratory
JAEA	Japan Atomic Energy Agency
JSFR	Japan Sodium-cooled Fast Reactor
LEU	Low-enriched uranium
LMFBR	liquid metal fast breeder reactor
LMR	liquid-metal reactor
LUEC	levelized unit electricity cost
LWR	light water reactor
MCC	mining and chemical combine
MEU	medium-enriched uranium
MIT	Massachusetts Institute of Technology
MOX	mixed oxide fuel
MTHM	metric ton of heavy metal
NASAP	Non-Proliferation Assessment Systems Analysis Program
NEA	Nuclear Energy Agency (OECD)
NECDB	Nuclear Energy Cost Data Base
NFS	Nuclear Fuel Services (Erwin TN)
NNSA	National Nuclear Security Administration
NOAK	nth-of-a-kind
NRC	Nuclear Regulatory Commission
NSSS	nuclear steam supply system
O&M	operations & maintenance

OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PFBR	Prototype Fast Breeder Reactor (India)
PHWR	Pressurized-heavy water reactor
PIE	post-irradiation material science examinations
PMDA	Plutonium Management and Disposition Agreement
PNNL	Pacific Northwest National Laboratory
Pu	plutonium
PuO2	plutonium dioxide
PUREX	Plutonium Uranium Reduction Extraction
PWR	Pressurized-water reactors
QA	Quality Assurance
RD&D	research, design, and development
REPU	reprocessing-derived separated uranium
RF-MFFF	Russian Federation-MOX Fuel Fabrication Facility
RH	remote-handling
RIAR	Russian Institute for Atomic Reactors (aka NIIAR)
RM	remote maintenance
RO	remote operations
ROI	return to investors
SA&I	Systems Analysis & Integration
SAF	Secure Automated Fabrication
SEFOR	Southwest Experimental Fast Oxide Reactor
SFR	Sodium-Cooled Fast Reactor
SNF	Spent Nuclear Fuel
SRS-MFFF	Savannah River Site-MOX Fuel Fabrication Facility
STAR-H2 reactor	Secure Transportable Autonomous Reactor for Hydrogen
SWU	separative work unit
TCC	total, financing inclusive capital cost
TRISO	tristructured isotropic (form of particle fuel)
UN	uranium nitride
UO2	uranium dioxide
UOX	uranium oxide

USNRC	U.S. Nuclear Regulatory Commission
VIPAC	vibrocompacted
VVER	Russian Water Energy Reactor
WEC	Westinghouse Electric Company
WIT	what-it-takes
WNA	World Nuclear Association “Fuel Cycle” website

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Module D1-4
Ceramic Pelletized Sodium-Cooled Fast Reactor (SFR) Fuel Fabrication: Life Cycle Costs for SFR Ceramic HALEUOX Driver Fuels, SFR Ceramic U,Pu MOX Driver Fuels, and UOX Ceramic SFR Blanket Fuels in Large Production Quantities

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Module D1-4 Ceramic-Pelletized Sodium-Cooled Fast Reactor (SFR) Fuel Fabrication: Life Cycle Costs for SFR Ceramic HALEUOX Driver Fuels, SFR Ceramic U,Pu MOX Driver Fuels, and UOX Ceramic SFR Blanket Fuels in Large Production Quantities

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

- **Constant $ base year 2020 for this fiscal year (FY) 2021 update.**
- Nature of this module update (Rev 1) from previous advanced fuel cycle cost basis reports (AFC-CBRs): new life cycle cost data on U,Pu SFR mixed oxide (MOX) fuels is derived from the Non-proliferation Assessment Systems Analysis Program (NASAP) conducted in the late 1970s. High-assay low-enriched uranium (HALEU) ceramic fuel is also discussed in more detail compared to earlier AFC-CBRs, since some advanced SFR concepts currently under development will require this HALEU fuel type for startup.
- Estimating methodology for latest *2012 AFC-CBR* (Dixon et al. 2012) technical update (prior to this report) which escalated the last *2017 AFC-CBR* update (Dixon et al. 2017).
- Reviewing literature followed by unit cost calculations based on G4-ECONS-FC methodology. For this update (Rev 0), more useful analogues based on detailed 1979 NASAP fuel fabrication comparative studies were also utilized along with literature data.

D1-4-1. BASIC INFORMATION

D1-4-1.1 *2009 AFC-CBR* Basic Information

Fuel Form. Ceramic-fueled fast reactors (FRs) can operate on either higher enrichment (>15% U-235) uranium fuel (such as the BN-600 in Russia) or plutonium-based MOX fuels (such as the French Phenix reactors, the Russian BN-800 reactors, and the cancelled U.S. Clinch River Breeder Reactor). For electricity production "breeder" FRs, the ceramic material of choice has been either enriched UO2 or MOX (Pu, U) O2, which can be contact-handled during fabrication or refabrication if the minor actinide (neptunium, americium, and curium) content is sufficiently low. For "burner" FRs, where significant amounts of the minor actinides arising from light-water reactor (LWR) reprocessing or from the FR's own fuel cycle are to be recycled within the driver fuel, highly shielded remote-handling during fabrication will be required because of the radiation level associated with mainly americium and curium and any trace fission products carried over from FR fuel reprocessing. These fuel types will be addressed in *Modules F2/D2*, where reprocessing and remote refabrication are considered as integral fuel recycle processes. Because higher-fissile content is used, typically 15% or higher U 235 or plutonium in heavy

metal, the amount of fissile material per unit volume in the driver fuel is a factor of four or more higher than for conventional LWR fuels.[a]

For a given power level, the fuel assemblies and the reactor core are smaller in mass and volume than for an equivalent power LWR. Ceramic FR fuel assemblies are typically less than 3 m long including axial blankets and end pieces, hexagonal in shape, and with much thinner fuel rods. The cladding is stainless steel instead of Zircalloy for reasons of better chemical resistance to the liquid sodium coolant. Table D1-4-1 compares example LWR (thermal) and FR fuel assemblies:

Table D1-4-1. Comparison of fast and thermal pellet fuel (typical).

	Thermal Reactor	Fast Reactor
Fuel	UO_2	$(U,Pu)O_{1.96}$
Fuel Pellet Density (% of theoretical)	92	90
Max. fuel centerline temperature (overpower condition)°C	2450	2800
Cladding	Zircaloy-4	316 Stainless Steel
Max. cladding mid-wall temperature °C	380	660
Coolant temperature, °C	H_2O, 280-320	Na, 470-650
Maximum rod linear power, W/cm	620	550
Fuel wrapper assembly	Square, 30x30	Hexagonal, 13 cm across flats
# of pins in assembly	200	220
Fuel-rod outside diameter, mm	10.7	6.3
Cladding thickness, mm	0.6	0.4
Initial fuel-cladding radial gap, mm	0.08	0.07
Length of fueled portion, cm	365	90

Figure D1-4-1 shows a French ceramic fast reactor fuel assembly from their Superphénix fast reactor, which is typical of this type of fuel assembly.

Ceramic fuel compounds other than oxides have also been considered, with uranium or plutonium nitrides and carbides receiving the most research and development attention in the United States.

a. Fast reactors may have as many as three types of fuel rods within the core: drivers, blankets, and targets. Drivers constitute the fissile materials that account for most of the energy production and in which the fissile content falls with continuing irradiation ("burning"). Blanket fuel consists of fertile material, such as DUO_2 or ThO_2, which will be partially converted via neutron absorption to new fissile material ("breeding"), such as Pu-239 or U-233, which can be recovered by reprocessing and refabricated into new fuel. Targets contain radionuclides, such as higher actinides or fission products, which are converted by neutron irradiation to other nuclides with shorter lives; this "burning" process is sometimes called burnout, transmutation, or destruction. These spent targets can subsequently be more efficiently and safely emplaced in a geologic repository.

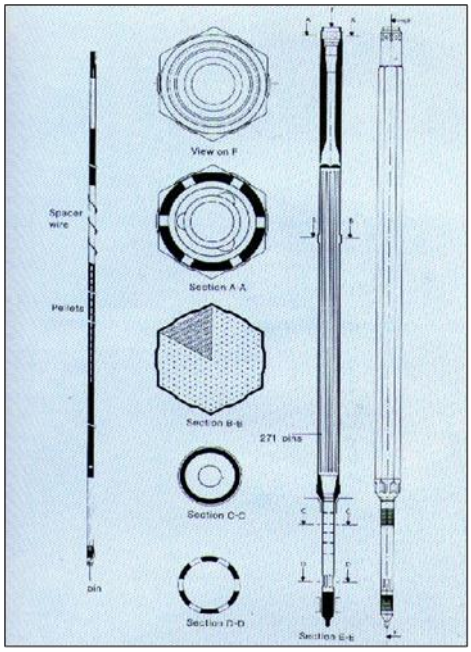


Figure D1-4-1. Superphénix fuel assembly diagram (CEA 1985).

D1-4-1.2 AFC-CBR (Rev 0) Update Basic Information.

Again, little has changed from earlier AFC-CBRs in terms of the basic industrial process for FR ceramic-pelletized fabrication and its interfaces to other fuel cycle steps. The only fabrication process that has been conducted on a near-industrial scale for FR ceramic fuel is basically the same process that is used to prepare LWR MOX fuel. However, the main differences are the following:

- FR ceramic fuel must be clad in stainless steel rather than zirconium alloys. This is a result of stainless steel having better compatibility with the hot liquid sodium coolant.
- The enrichment of the fissile material (U-235 or Pu-239) must be higher than for LWRs because of the nature of the FR neutron spectrum and the nuclear properties of not having a neutron moderator coolant.
- The pin/pellet diameter for FR fuel is generally smaller than for LWR fuel. This is to improve the heat transfer from the fuel rods to the higher-temperature molten-sodium coolant.

It is important to realize that the fuel discussed in this module can be contact-handled in gloveboxes as powder/pellets (if it contains plutonium) and outside gloveboxes in sealed pin form (for MOX or enriched UOX). If the fuel is enriched uranium (typically 13 to 25% U-235) in some ceramic form such as UO2, powder and pellets can be handled outside a glovebox environment. For this reason, the fuel must be largely free of fission products, higher Pu or Np-isotopes, or higher actinides such as curium and americium which pose radiation hazards to workers as well as posing thermal heat-generation problems from the rapid decay of these isotopes. (Such “transmutation” or “actinide burning” fuels or targets are considered in *Module D2* which deals with remote-handled fuel. “Proliferation resistant” FR fuels which carry over some fission product (FP) and higher actinides (HAs) would require totally remote refabrication.) The fuels described in this *Module D1-4* would probably be used as startup fuels for FR systems or in FR systems for which fuel recycle is not yet established. A good example of such a startup program would be the BN series of FRs in Russia. The BN-600 reactor has run mainly on medium-enriched UO2 (MEUO2) fuel with some (U,Pu) MOX assemblies undergoing lead testing. Russia is now constructing BN-800 sodium-cooled FRs (SFRs) which will use MOX fuel with Pu content (in heavy

metal with U diluent) in the 15 to 25% range. This fuel will be contact-handled in gloveboxes. A small and now shuttered glovebox pilot line "PAKET" at Mayak has been used to fabricate BN-600 test assemblies. The MOX Pu processed and burned in the first BN-800 FRs will be made with weapons-capable Pu material arising from Russian military programs. This material is now being fabricated at a small MOX plant inside a mountain at Rosatom's Mining and Chemical Combine Zheleznogorsk, Krasnoyarsk Krai, Russia. As of September 2022, the BN-800 is now operating on a full-MOX core (WNN 2022).

D1-4-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

Similarity to LWR MOX. The functions and operations in a FR fuel plant based on pellet technology are similar to those in an LWR MOX plant (*Module D1-2*). The higher-fissile content (typically >15%) of FR fuel, however, requires more stringent security and criticality avoidance measures. The previous existence of a developing FR industry in Europe, Japan, and Russia shows that such facilities are technologically viable. The following subsections summarize the status of pellet MOX fabrication in previous versions of the AFC-CBR. Some significant progress in this occurred from 2009 to 2021, especially in Russia.

D1-4-2.1 Status Update from *2009 AFC-CBR*

Slowdowns or cancellations of FR programs have put production of ceramic FR fuel worldwide at a near standstill. Belgium, the United Kingdom, France, Germany, and Japan all have fabrication plants that are now shutdown or inactive. Russia still produces mostly highly enriched uranium (HEU) and some (U,Pu) O2 MOX fuel for their BN-600 reactor located at Beloyarsk. When the United States was about to construct the Clinch River Breeder Reactor, plans were being drawn up to construct a U.S. fast fuel fabrication facility. The ceramic FR fuel production that has taken place in the United States has been on a small scale in national laboratory or reactor vendor development facilities, and most of this was in the 1960s and 1970s. Unless interest is revived in closed fuel cycles and particularly one that uses ceramic rather than metallic FR fuel (*Module F2/D2*), near-term prospects are dim for the deployment of such FR fabrication capacity in the United States. As the Generation IV and Advanced Fuel Cycle Initiative (AFCI) programs progress, however, interest may be revived. (AFCI "burner" FR concepts are more likely to require the types of remote-handled, higher actinide laden fuels discussed in *Module F2/D2*; however, the first cores are likely to be U,Pu only.)

Russia, China, India, and Japan plan to keep the FR option open, with electricity generation and "breeding" being the predominant missions rather than actinide burning. Japan is about to restart their experimental MONJU sodium-cooled reactor. India and China are constructing a 500 MWe and 25 MWe prototype FRs, respectively. The Russian Federation plans to construct an 800 MWe unit at Beloyarsk near its existing BN-600 unit and has even proposed a 1,800 MWe design. The Russian Federation has also indicated interest in using BN-type reactors to disposition surplus plutonium from their military programs. A small fuel fabrication facility at Mayak named "PAKET" could be restarted to provide early pellet-based fuel assemblies; however, the vibrocompaction process (*Module D1-5*) seems to be the presently preferred technology. The Japanese also have limited capability to produce pellet MOX fuel at their Tokai Works. Costs for production at these facilities are not known. India is constructing a FR; however, no information on the fuel source is available.

D1-4-2.2 Status Update from *2012 AFC-CBR* Update

It is of historical interest to review the 2012 status of the world's existing or planned fabrication facilities as follows:

- United Kingdom: The United Kingdom is still considering burning MOX fuel in new Generation III+ LWRs and/or in sodium-cooled fast reactor (SFRs) as a method of dispositioning its large stockpile of

over 110 MT of separated Pu from its commercial and military reactor programs (Nature News and Comment 2011). A new MOX plant would be required that might be able to produce MOX fuel for FRs in addition to LWRs. The United Kingdom is considering the FR as part of its future Pu disposition strategy and is evaluating the GE-Hitachi PRISM FR design, which can be customized for ceramic or metal FR fuels. The hypothetical UK MOX plant is discussed from a cost standpoint in *Module D1-2*.

- Japan: Japan's Tokai Works has the capacity to produce 20 metric ton of heavy metal (MTHM) of FR MOX fuel per year. The capacity is in two 10 MT/yr lines, and the facility has made fuel for test reactors. (WNO 2012).
- Russia: As part of the 2000 Joint U.S-Russia PMDA (Plutonium Management and Disposition Agreement, both the United States and Russia had agreed to burn excess weapons Pu in their LWRs. Russia has now decided to burn their Pu in SFRs of the BN-800 variety rather than in Russian Water Energy Reactor (VVER). The type of fuel is likely to be pelletized MOX (*Module D1-4*) or VIPAC fuel (*Module D1-5*) or both. The PMDA was modified in 2010 to reflect this new reality. At Mayak, there is a small, now shut down, FR MOX pilot line called PAKET which has manufactured pellet fuel for lead test assemblies for irradiation in BN-600. The United States formerly was slated to give technical and financial assistance to Russia for the eventual construction of a larger FR MOX plant to supply military-derived Pu fuel for the BN-800 reactors. The Pu in the MOX will have the high Pu-239 content typical of weapons Pu. No credible cost estimates are yet available for this proposed facility, which is to be located at Zheleznogorsk.
- United States: An industrial scale ceramic fuel fabrication line for Pu-containing FR fuel has never been operated in the United States, although such a line was constructed at Hanford (the secure automated fabrication [SAF] line) to support the cancelled Clinch River Breeder Reactor Project. The >$100M SAF line was never operated. There is a B&W plant in Lynchburg, VA that has the capability to produce enriched U fuels above 5% U-235 (HALEU), and it does this for mainly government customers (naval fuel, research reactors, etc.) The Category I site security and safety envelope for this site would very likely be adaptable to the production of medium- to high-enriched uranium oxide ceramic fuel (>20% U-235) or Category II HALEU fuel (15 to 19.95% U-235) that might be used for the startup of a SFR. A smaller plant operated by Nuclear Fuel Services (NFS) at Erwin, Tennessee can also handle enriched uranium forms greater than 5% U-235. From 1969 through 1972, NFS had prepared several tons of SFR U,Pu MOX for the Southwest Experimental Fast Oxide Reactor (SEFOR) in northwest Arkansas. NFS Building 234 in which this process was operated was decommissioned after the SEFOR campaign ended in 1973.
- China: To support their 1,000 MWe China Demonstration FR (CDFR), which will start up in 2017 and will ultimately burn ceramic (U,Pu) MOX fuel, a 40 MTHM/yr FR ceramic MOX plant is planned at Sanming. No cost information is available on this facility. SFR MOX fuel is available from Russia until this plant is complete.
- India: India's nearly complete 500 MWe Prototype Fast Breeder Reactor (PFBR) will ultimately use (U,Pu) MOX fuel produced in a proposed FR Fuel Cycle Facility (FRFCF) located adjacent to the PFBR at Kalpakkam. Fuel rods will be 21 and 28% fissile Pu (SME Times 2010). The FRFCF will also reprocess oxide fuel and handle waste management. Its cost has been estimated at 5,000 crore (US$[2012]898M).

D1-4-2.3 Status Update from *2017 AFC-CBR* and Subsequent

The *Module D1-4* in the *2017 AFC-CBR* (most recent online-published) (Dixon et al. 2017) had SFR MOX fabrication life cycle cost information from multiple sources, none of which presented detailed life cycle data. Much of it was estimated unit cost projections from various large domestic and international

reports on the economics of multiple fuel cycles and reported in $/kgHM in various years dollars. The capacity, technologies, and constituent costs behind these generic estimated unit costs were not available or were not well-developed.

In 2018, an old but very detailed study comparing multiple fuel cycles, including fuel fabrication technologies, was located and studied (i.e., the 1977–1980 NASAP). This multi-volume study, described later in this Rev 0 report, presented side-by-side design and cost comparisons of many fuel types, including LWR UOX, LWR and SFR U,Pu MOX, SFR metal fuel, pressurized-heavy water reactor (PHWR) UOX, and high-temperature gas-cooled reactor (HTGR) tristructured isotropic (TRISO) fuels. Many thorium-containing cylindrical and TRISO fuels were also considered. By consistently updating the life cycle cost data to today's dollars and economic/regulatory conditions, it was possible to obtain comparable 2017$ unit fabrication costs for most of the fuel types covered in the AFC-CBR (i.e., LWR UOX in *Module D1-1*, LWR MOX in *Module D1-2*, SFR MOX in *Module D1-4*, and SFR Metal Fuel in *Modules D1-6A* and *D1-6B*). In FY 2018 and FY 2019, this NASAP data was recast into present day economics (2017$) and integrated into unpublished draft supplementary reports for *Modules D1-1*, *D1-2*, and *D1-6*. This FY Rev 0 report adds *Module D1-4* to this list. Unit costs for HALEU all UOX startup SFR fuel were also developed in this report. ***The reader should keep in mind that the unit fabrication costs presented in this report are for large Nth-of-kind plants serving a fleet of SFRs, mature process technologies, and reliable plant operations. R&D costs are not included.***

The NASAP reports also assumed that "first pass" SFR MOX fuel, assumed prepared from the aqueous reprocessing of LWR spent nuclear fuel (SNF) would itself be aqueously reprocessed to recover enough Pu to refabricate "second pass" U,Pu SFR MOX fuel. These "refabrication" costs are also presented. (It should be noted that Japan is still planning to recycle their spent LWR MOX fuel and will need to establish the reprocessing and fabrication capacity to do so [NHK World News-Japan 2021]).

D1-4-3. PICTURES AND DIAGRAMS

For FR MOX pellet fuel, the schematic would be very similar to the process diagram shown in Subsection D1-4.2 on LWR MOX fuels, except there would be one less blending step. Figure D1-4-2 shows the fabrication process for the mixed ceramic nitride fuel being examined by the AFCI Fuels Working Group for Generation IV FR applications. Most of the steps for this alternate ceramic fuel compound are similar to those for MOX fuel.

Fast Reactor Pellet Fuel Fabrication Process. For Safeguards and Security Category II high-assay low-enriched uranium (>10% U-235 or <19.75% U-235 [aka HALEU] or Category I HEU [>20% U-235]) ceramic fuel, the basic manufacturing flowsheet would be much the same as for low-enriched uranium (LEU) fuel production. Because of the security and criticality concerns, however, batch sizes would be very limited in size. For MOX ceramic FR fuel, the process is much the same as for thermal LWR MOX (*Module D1-2*). Again, the batch sizes handled would have to be much smaller. Both type plants (MOX and U-only) would likely have to purchase or fabricate their own stainless-steel fuel assembly hardware such as grids and spacers.

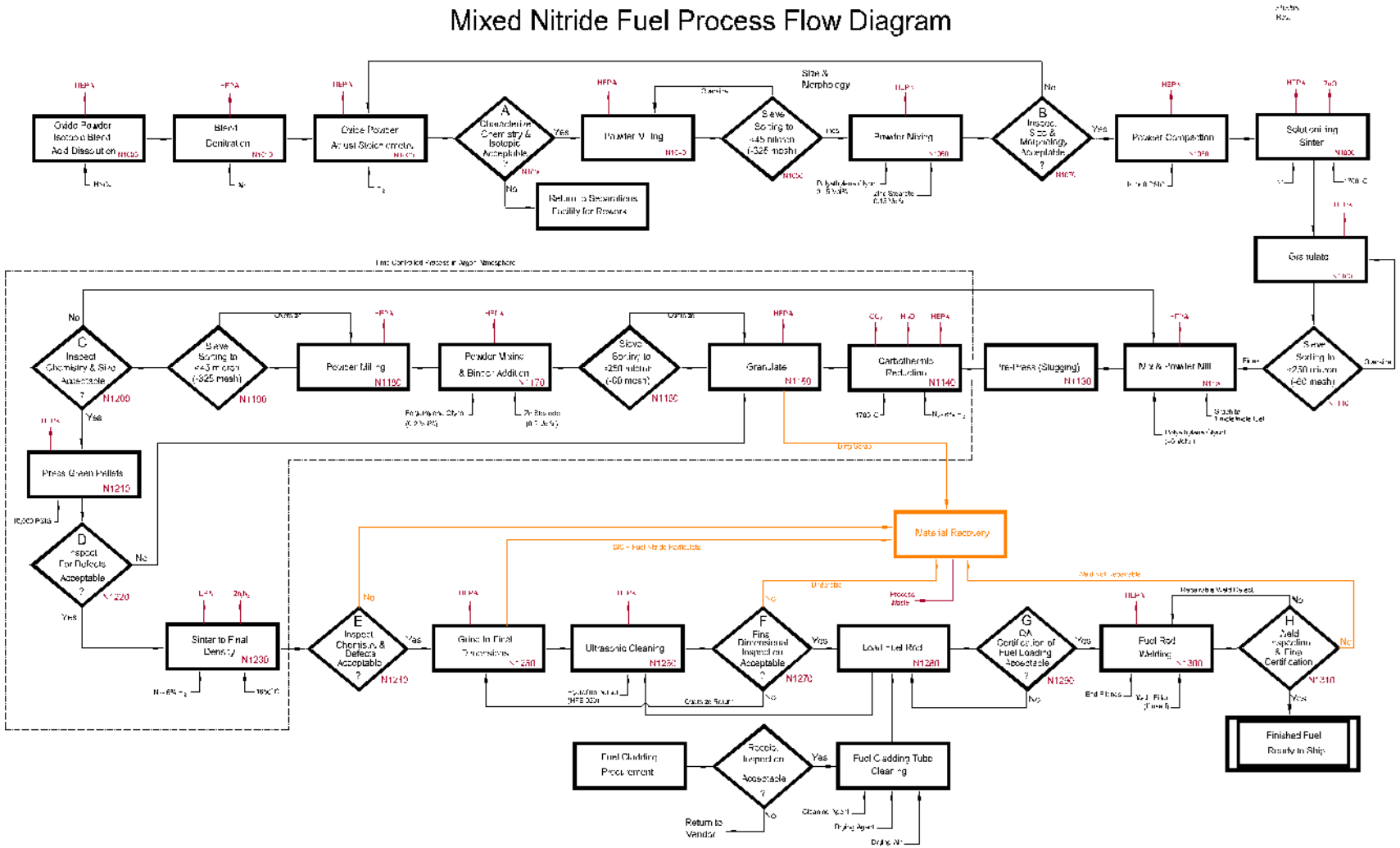


Figure D1-4-2. Fabrication process for mixed nitride fuels (Shaber 2004).

D1-4-4. MODULE INTERFACES

For the FR MOX plant the starting material for ceramic U,Pu driver fuel would likely be clean, reactor-grade PuO2 powder from the reprocessing plant or an existing PuO2 storage facility. (For contact-handling, some neptunium and/or very small amounts of americium can be present with the plutonium.) For the EUO2 driver fabrication plant, the starting material is likely to be EUF6 from a CAT-II HALEU enrichment facility or UO2 from a surplus HEU CAT-I blend-down facility with metal to oxide conversion capability. Blanket UO2 fuel could be produced in a conventional Category III industrial facility with minimal security and radiation protection requirements (i.e., no gloveboxes or criticality alarms). Transportation of finished FR MOX driver fuel will, of course, need special certified casks for added security and radiochemical safety reasons. Other interfaces are similar to those for LWR MOX.

MOX driver fuel and DUO2 blanket fuel are best matched to aqueous reprocessing at the back end of the FR closed fuel cycle. The Japanese have already begun planning such a plant to reprocess spent fuel and blankets from their proposed Japanese SFR (1,500 Mwe; JSFR) concept. Note that SFR fuel (SFR-SNF) is likely to require development of a new type of storage/shipping cask.

D1-4-5. SCALING CONSIDERATIONS

The same considerations apply in this area as for LWR MOX fuel (see Subsection D1-2.4). In terms of heavy metal throughput, the reference FR MOX plant will be much smaller for the same amount of fissile nuclide (plutonium) processed. A NASAP summary report (Olsen et al. 1979) discussed how life cycle costs scale with MTHM/yr production capacity. These scaling results and methodology are discussed in a later section of this report and in detail in *Module D1-PR*.

D1-4-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

In the first two subsections below the cost information from the 2009 and 2012 versions of the AFC-CBR are summarized. This provides some historical context as to how SFR fuel fabrication life cycle cost data has been developed over the last two decades.

***2009 AFC-CBR* Cost and Pricing of Fast Reactor Fuel Fabrication.** Fixed costs for a FR ceramic MOX fuel fabrication plant are likely to be similar to those for an LWR MOX fabrication facility. These costs are distributed over a smaller heavy metal throughput; however, because less of the heavy metal is non-fissile diluent, and more is fissile U-235, one would expect that the cost per kgHM for ceramic FR fuel would be higher than for LWR MOX, and the plant heavy metal throughputs would be smaller. Table D1-4-2 shows projected unit costs for FR (sodium-cooled LMR) ceramic MOX ([U,Pu] O2) fuel from various literature sources. Some of the cases below have fabrication costs for MOX fuel that contain minor actinides such as neptunium, americium, and curium, which make the radioactivity hazard associated with fabricating fuel somewhat more serious. Remote-handling facilities of the type discussed in *Module F2/D2* would be required for these facilities. “Heterogeneous” FRs have two types of fuel in their cores: the fissile “driver” core with high fissile content and the fertile blanket with natural or depleted uranium oxide or other ceramic forms. Fabricating blanket fuel should cost no more than fabricating LEU fuel because criticality and radiotoxicity are minor or nonexistent concerns. “Homogeneous” FRs do not have a separate blanket or separate set of targets.

The sizing of ceramic FR fuel fabrication plants is uncertain because it is not known how many FRs utilizing pellet fuel might eventually be used. The only scaling data found were from the 1988 Oak Ridge National Laboratory’s Nuclear Energy Cost Data Base (NECDB) (1988) which references data from the late 1970s NASAP (see *Module D1-PR* for discussion of this extensive life cycle cost study) that looked at many fuel cycles. A table from the NECDB (1988) is reproduced here (Table D1-4-3) to show some plant capacity and capital cost data. All costs are in 1987 dollars. A multiplication factor of 1.9 would bring them to 2009 dollars.

Table D1-4-2. Unit fabrication costs for various fast reactor fuels in "then year" U.S. dollars.

Reference/Date	Fuel (Contact-handled Unless Otherwise Noted)	Fab Cost in $/kgHM ("then year $")*
DOE/2002	MOX with minor actinides (ceramic pellet)	Core (driver) (M) 2,600
Bunn et al. 2003	MOX (ceramic pellet)	Core (L/M/H) 700/1,500/2,300 Blanket 150/250/350
OECD 1994	MOX with minor actinides (ceramic pellet) (Reference did not specify whether facility was totally remote-handling.)	Core (L/M/H) 1,400/2,600/5,000
NECDB 1988	MOX (ceramic pellet)	Core (L/H) 1,900/2,250 Blanket (M) 430
Delene et al. 2000	ALMR metal fuel (for comparison, remote-handling assumed)	Core (L/M/H) 4,600/5,150/7,700
G4-EMWG 2005	MOX from equilibrium breeding cycle (JSFR data)	Core (M) 1537 revised in 2006 to 1,675
OECD 2005	FR MOX	Core (L/M/H) 1,000/1,500/2,000
OECD 2006	FR MOX	Core (L/M/H) 1,100/1,650/2,200
MIT 2009	FR MOX	Core (M) 2400
Red Impact 2006	FR MOX	Core (M) 2832

- Where a range is given, "L" is low, "M" is mid, "H" is high.

Table D1-4-3. Fast reactor (LMR) recycle costs from 1988 Oak Ridge National Laboratory's Nuclear Energy Cost Data Base 1988 study (NECDB 1988).

Table [illegible]. Recycle facility costs
(1987 dollars)

Capitalization, fraction	
Debt	0.3
Equity	0.7
Interest on debt, %/year	9.7
Return on equity, %/year	17
Tax depreciation life, years	15
Decommissioning cost,[a] % initial investment	10
Plant life, years	30
Design and construction lead time, years	8

Process	Fuel	Plant size (10^3 kg/yr)	Capital cost[b] ($10^6)	Capitalized cost[c] ($10^6)	Operating cost[d] ($10^6/yr)	Unit cost ($/kg HM)
Fabrication	LWR-MOX	100	365	530	40	1200
		480	960	1390	140	730
	LMR core	100[e]	615	890	90	2250
		270[e]	1335	1930	220	1900
	LMR blanket[f]	100	55	80	30	430
Reprocessing	LWR	400	1030	1490	60	710
		1500	1850	2680	100	340
	LMR[g]	750	1850	2680	100	680
Integral[h]	LMR metal	20	135	175	30	2800
	LMR oxide	20	260	330	25	3700[i]

[a] 10% of capital investment (including AFUDC) in constant 1987 dollars (escalates with inflation in nominal dollars) accumulated in an annuity at 7.0%/year nominal interest rate.

[b] 1987 overnight cost. Includes all preoperational costs except AFUDC.

[c] Total capitalized cost in 1987 dollars including AFUDC.

[d] Includes equipment replacement.

[e] Throughput of active core material only. Unit cost applied to active core throughput only and includes axial blanket costs.

[f] Radial and internal blanket fuel.

[g] Core and blanket fuel throughput combined.

[h] Five-year design and construction time.

[i] Estimated unit cost for 35 × 10^3 kg/year oxide fuel facility = $2700/kg HM.

The Japan Atomic Energy Agency (JAEA) (G4-EMWG 2006) has projected a capital cost of approximately $750 million for a 200-MTHM/yr pellet MOX fabrication facility needed to support JSFRs. The updated unit cost of $1,675/kgHM in G4-EMWG 2005 data of Table D1-4-2 is calculated based on amortization of this capital cost and the addition of operations and maintenance (O&M) and decommissioning levelized costs.

***2012 AFC-CBR* Cost Bases and Data Sources.** A few recent data sources have been accessed to provide the basis for changing the recommended low, nominal, and high values for the $/kgHM cost of ceramic MOX and MEUO2/HEUO2 FR fuel fabrication. (Note that as with UO2 pelletized LWR fuel, there is no published data on the actual production cost or pricing of material from an operating fabrication facility.) Most fuels of this type are produced (or have been produced) in quantities very small compared to LWR MOX fabrication. The following Table D1-4-4 shows some ceramic-pelletized FR fabrication cost data from various sources. Some of the numbers required escalation to bring them to 2012 dollars. Most of the data are for (U,Pu) type MOX FR fuels; however, the cost numbers might be comparable for large-scale production of nitride- or carbide-pelletized FR fuels. **Note that enriched U FR fuel has been added since the *2009 AFC-CBR*, since this material would likely be used to startup FRs until enough Pu-based fuel became available.** The fissile content (Pu or U-235) for all of these fuels would be in the 13 to 25% range. The costs of uranium ore, conversion, and enrichment are not included in the unit fab cost for MEU (some of which is now called HALEU if less than 20% U-235) or HEU FR fuel.

Table D1-4-4. Reactor fuel unit costs from various sources (constant 2012$ unless otherwise indicated).

Study or Ref/Year	Low Value ($/kgHM)	Medium or Ref Value ($/kgHM)	High Value ($/kgHM)
DRIVER FUEL (U,Pu)			
DEC *2009 AFC-CBR* (Shropshire et al. 2009b) (2009$) Pelletized (U,Pu) O_2 Ceramic	3,200	4,000	6,000
(EPRI 2010) (2010$) FR MOX (U,Pu) O_2	750	1,500	2,100
MIT Economics of Nuclear Fuel Cycle (MIT 2009) (2010$) FR MOX (U,Pu) O_2	N/A	2,400	N/A
Escalated unit cost from ORNL/TM-6522 (Olsen et al. 1979) (U,Pu) MOX FR fuel (Complexity factor=8.45 against $LEUO_2$ fuel)	N/A	2,950	N/A
BLANKET FUEL (NATU or Depleted U)			
Escalated from 2003$ (in parentheses) to 2012$ (Bunn et al. 2003)	175 (150)	300 (250)	425 (350)
ORNL/TM- 6522 (Olsen et al. 1979) using complexity ratio	N/A	450	N/A
MEU/HEU DRIVER FUEL (15% < U-235 < 40%)			
ORNL/TM- 6522 (Olsen et al. 1979) using complexity factor	N/A	825	N/A

The most recent reports up to 2012 which included unit costs for the FR fuels category were the EPRI "Multi-recycling" economic study (EPRI 2010) and the MIT "Economics of the Nuclear Fuel Cycle" (MIT 2009) reports. The unit costs provided are for a hypothetical, mature fuel fabrication industry supporting multiple FRs. These values fall in the lower range of the LWR MOX (*2009 Module D1-2*) range, which leads the author of this module to believe that more credible unit costs will be significantly higher, especially since the higher-fissile enrichment FR ceramic fuel will encounter the same manufacturing difficulties, plus some additional challenges, as LWR MOX fuel. As with HTR fuel in *Module D1-3*, one can look at old estimates for multiple fuel types prepared by the ORNL NASAP staff in 1979 (Olsen et al. 1979) to gauge the level of technical complexity of FR ceramic fuel (driver [U,Pu] MOX in this case) fabrication vis-à-vis for LWR UO2 fuel. If escalation and normal private industry financing risk is considered, a unit cost of $2,950/kgHM is obtained for a nominal case. The same "complexity factor" approach can also be used to assign a unit cost to the UO2 "blanket" fuel required by some FR designs. A nominal value of $450/kgU is obtained for this material, which would be natural or depleted UO2 that can be contact-handled without criticality or security concerns and with minimal HS&E difficulties associated with CAT-III facilities. (Author's note: these ORNL "NASAP" studies would be considered in much greater detail from 2018–2021 and their use reported in most of the Rev 0 updates to the AFC-CBR which are presented in later sections of this report.)

Two cost reports on the fuel cycle (Bunn et al. 2003; EPRI 2010) suggested blanket fabrication unit cost values that were the same as for LWR UO2 fuel. No actual cost data was found on enriched U (15 to 25% U-235 range) ceramic FR driver fuels. The "complexity factor" approach using the 1979 ORNL NASAP cost studies was again used to obtain a nominal unit fabrication cost of ~$825/kgU. This fuel would not need glovebox handling; however, Category I or Category II building design, criticality and security concerns could be much beyond those for Category III LEUO2 fuel. The higher projected unit cost is therefore appropriate. (Author's note: U.S. Nuclear Regulatory Commission-mandated regulations on facilities for handling nuclear materials of varying "attractiveness levels" to proliferators have resulted in three "classes" of facilities, with Category I being the most stringent for fissile materials capable of use in nuclear weapons. Category III is the least stringent and would apply to blanket U and U less than 10% U-235. In the AFC-CBR update (Rev 0), the cost effects of these "category" requirements are frequently mentioned.)

D1-4-7. SFR FUEL CYCLES AND FUEL TYPES CONSIDERED IN THIS MODULE

For civilian RD&D (research, development and demonstration) programs on FR systems, which have been underway since just after the Manhattan Project, there is considerable, publicly available 1950s through early 1990s "vintage" design and cost information available. Much of this is in older U.S. national laboratory technical reports, of which many have been archived, scanned, and made available on the internet. Of these older reports from the late 1970s to the early 1990s, one specific report (Olsen et al. 1979) is most useful for this *Module Dl-4*, since the objective of FR technology development at that time was Pu "breeding" via the irradiation (by higher-fissile content U,Pu MOX SFR "drivers") of depleted uranium oxide axial blanket pellets at the ends of the driver rods and the irradiation of full radial blanket DUO2 fuel assemblies surrounding the inner SFR core. This type of equilibrium (conversion factor~ 1.0) breeding fuel cycle along with a complete annualized equilibrium material balance is shown on page 150 of *Nuclear Chemical Engineering* by Benedict, Pigford, and Levi (1980). A diagram of an SFR driver fuel assembly of that vintage and its associated fuel design data are shown on Figure D1-4-3. (Today's FR fuel cycle concepts are more oriented toward lower conversion ratio actinide burning in metal-fueled, pool-type SFRs and the destruction of the HAs that would otherwise present long-term waste package integrity problems in a geologic repository). A 2009 report (Shropshire et al. 2009a) describes two such equilibrium fuel cycles along with complete material balances. Today's U.S. SFR design concepts also

prescribe the use of on-site integrated SFR metal fuel recycle through "dry" pyrochemical/electrochemical reprocessing (*Module F2/D2* of *AFC-CBR*) instead of aqueous reprocessing of ceramic MOX FR SNF. *Module D1-6* discusses the costs associated with contact-handled metal fuels of all types.

In the late 1970s, the Clinch River Breeder Reactor (CRBRP) was envisioned to be the prototype for a large fleet of fast breeder reactor (FBRs) (at that time called LMFBRs, a subset of loop-design SFRs) for which either an oxide or metal-based fuel cycle was possible. (The oxide-based fuel cycle was eventually chosen for the loop-type FBR which was to be constructed in Oak Ridge, TN.) Initial HALEU-based driver fuel (15 to 20% U-235) startup cores would be quickly transitioned to U,Pu MOX-based cores, for which the U-235 plus Pu-239 fissile content would be in the 15 to 19% range. Essentially "zero-source material cost" blanket DUO2 fuel could have been chemically deconverted and fabricated from the huge U.S. government DUF6 "tails" stockpile resulting from decades of uranium enrichment operations, and zero-cost plutonium feed made available from surplus weapons-grade-Pu or Pu recovered in government production reactors.

A prototype MOX fuel fabrication plant, the SAF line in the Hanford Fuels Manufacturing and Examination Facility (Williams and Rice 1980; Gerber, Benson, and Dahl 1986), was actually constructed (but never "hot" operated) for initial CRBRP fuel fabrication, and an liquid-metal fast breeder reactor (LMFBR) spent fuel reprocessing plant was "on the drawing board" for recycling the plutonium recovered from CRBRP driver and target spent fuels.(The presence of only traces of trans-plutonium HAs, minimal higher Pu isotopes, and traces-only of fission products in the refabricated "second-pass" MOX fuel feed would allow glovebox contact-handling in this new "refabrication" plant.) In the early 1970s optimism for the continued growth of nuclear power was high, and over one-thousand operating 1000 MWe-class reactors, including mostly LWRs, some HTGRs, and a few LMFBRs, were predicted for the United States by the year 2000. The SFR fuel fabrication and refabrication plants that were predicted to support the growing LMFBR enterprise were seen to require a deployment level on the order of hundreds of MTHM of fuel production per year per fabrication plant, with the ~500 MTHM/yr fuel fabrication plants selected as the NASAP fabrication plant design baselines for MOX fabricated from LWR-SNF and SFR-SNF, respectively. Such a FR MOX fabrication or refabrication plant would support approximately 50 1,000 MWe-class LMFBRs. The "breeder" fuel cycle was seen as the solution to an at-that-time perceived future shortage of uranium ore. Pu-239 in all reactor types would substitute for increasingly less available U-235 as natural uranium resources were exhausted.

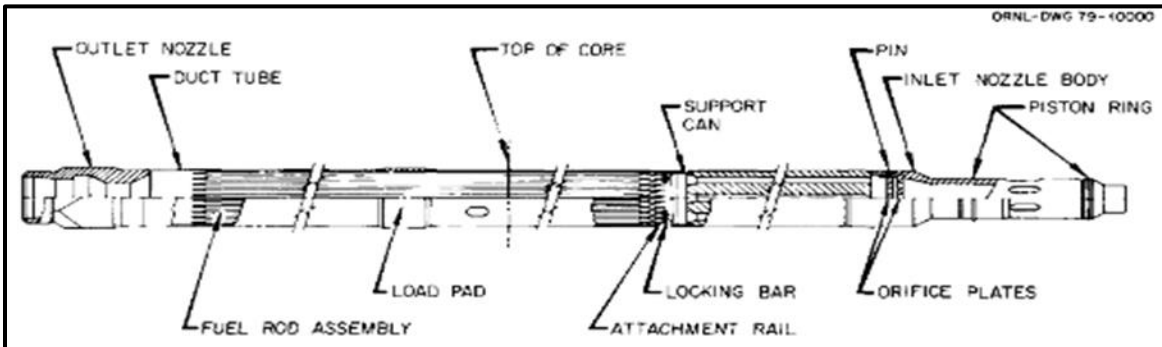


Fig. 4. LMFBR fuel assembly.

Table 3. Design characteristics of fuel used for cost estimations, liquid-metal cooled fast breeder reactors — core and axial blanket ANL NASAP data[a]

Characteristics	Oxides	Carbides	Metals
Reactor output, MW(e)	1000[b]	1000[b]	1000[b]
Fuel assemblies/core	357	258	303
Fuel assemblies/reload	178	129	151
Bonding	He	Na	Na
Fuel rods/assembly	271	169	169
Smear density, % TD	88	86	75 (U) 85 (Th)
Cladding material	316 SS	316 SS	316 SS
Cladding outside diameter, mm (in.)	7.37 (0.290)	8.89 (0.350)	8.89 (0.350)
Cladding inside diameter, mm (in.)	6.60 (0.260)	8.13 (0.320)	8.13 (0.320)
Pellet diameter, mm (in.)	6.35 (0.250)	7.75 (0.305)	7.04 (U) (0.277) (U) 7.49 (Th) (0.295) (Th)
Pellet length, mm (in.)	6.35 (0.250)	7.75 (0.305)	7.04 (U) (0.277) (U) 7.49 (Th) (0.295) (Th)
Pellet stack height, total, mm (in.)	1778 (70)	1778 (70)	1778 (70)
core, mm (in.)	1016 (40)	1016 (40)	1016 (40)

Fuel	Density[b] (% TD)	Heavy-metal content (kg)	
		Rod	Assembly
$(^{233}U,Th)O_2/ThO_2$	95	0.48[b]	128.9[b]
$(Pu,U)O_2/UO_2$	95	0.52	140.3
$(Pu,Th)O_2/ThO_2$	95	0.48	128.9
$(^{233}U,Th)C/ThC$	95	0.85[b]	143.1[b]
(Pu,U)C/UC	95	103	173.9
(Pu,Th)C/ThC	95	0.85	143.1
$^{233}U,Th/Th$	100	0.98[b]	164.9[b]
Pu,U,Zr/U	100	1.17	198.0
Pu,Th/Th	100	0.98	164.9

[a] Y. A. Chang, Argonne National Laboratory, personal communication to J. C. Cleveland, Oak Ridge National Laboratory (April–May 1978).
[b] Assumed values; data not available.

Figure D1-4-3. Design details of the SFR (aka LMFBR) driver fuel in the NASAP study (Judkins and Olsen 1979). First column with numbers is for U,Pu MOX fuels.

D1-4-8. THE LATE 1970S NONPROLIFERATION ASSESSMENT SYSTEMS ANALYSIS PROGRAM REPORTS ON NUCLEAR FUEL FABRICATION FOR MULTIPLE FUEL CYCLES

After India exploded a nuclear weapon based on weapons-grade plutonium separated from the power reactor (PHWR) spent fuel, nonproliferation became a major policy issue for Western governments. The INFCE and NASAP programs were undertaken by the IAEA and the U.S. government (DOE's predecessor agency ERDA) to identify fuel cycles which would be more attractive from a nonproliferation standpoint. Many once-through, partially closed, and fully closed fuel cycles were examined in detail from the standpoint of technical feasibility, proliferation resistance, resource requirements, and life cycle costs. These NASAP studies and reports, such as (Olsen et al. 1979) and (Judkins and Olsen 1979) which were generated therefrom, are discussed in more detail in the Preface (*Module D1-PR*) to the set of Fuel Fabrication "D" Modules in the newest FY Rev 0 AFC-CBR module updates.

One useful result to come out of these NASAP studies was a level-playing-field analysis of several types of nuclear fuels where the emphasis was on the comparative fuel design complexity and fabrication facility regulatory, operational, and equipment requirements for the manufacture of each. From a detailed "bottom-up" life cycle cost estimate and analysis for a 520 MTHM/yr hypothetical ceramic UO2 (UOX) PWR fuel fabrication plant (summarized in *Module D1-1*), a levelized unit cost of production ($/kgHM) for that fuel type was calculated via a "revenue-requirements" type FORTRAN economic model (Delene 1980). For non-UOX cylindrical clad fuels modifications to the UOX "reference" fuel design and "subject" fuel fabrication facility design were made on the basis of fuel meat composition, fuel structure complexity, material-handling difficulty, radiation environment, process building safety and security requirements, and recurring resource requirement differences (manpower, purchased materials, and utility usage). All of the "reference LWR UOX fuel" to "alternate subject fuel" plant design changes were embodied in ORNL-developed algorithms (Lotts and Washburn 1968) written in a mid-1970s FORTRAN computer code called FABCOST. The computer-generated life cycle costs for each fabrication plant type were then tabulated and published in a set of NASAP documents published by ORNL from 1978–1980. The U-Pu MOX driver fuel and depleted-UO2 blanket fuel for a breeder-reactor (LMFBR-type SFR) fuel cycle represented one of the cases examined in this study. Both ceramic (oxide and carbide) and metal fuels were considered for the overall LMFBR cases.

All of the fuels were assumed produced in very large (-500 MTHM/yr) centralized, Nth-of-a-kind (mature technology) facilities capable of supporting a fleet of several tens of gigawatt class breeder reactors**. The fact that these studies were conducted by the same set of engineers and cost estimators for all fuel types gave the author of this FY 2020 supplementary report confidence that the unit costs generated could be compared, and any differences in unit cost were due entirely to technical factors, such as fuel complexity and manufacturing environment, rather than gross differences in production rates, institutional cost estimating practice among different fabricators, and general economic factors**. The FCRD-SA&I author's task then became that of adapting the 1978 life cycle cost data (for 1978 economic conditions) to the conditions of today's (2017) economy and safety, environmental, and security regulations. The following paragraphs discuss the procedure and results for the U,Pu MOX LMFBR driver fuel. *Module D1-6A* (Uranium-only metal fuels) describes the same type of analysis for the all-metal depleted or natural uranium blanket fuels which would be manufactured for long term use in the breeder fuel cycle. The relatively low blanket unit fabrication cost presented in *Module D1-6A* should also apply to depleted or natural ceramic UO2, and the NASAP-based analysis is discussed in this *Module D1-4* update. The manufacture of all-HALEU metal or UOX HALEU "startup" driver fuel was not addressed in the NASAP study but is discussed for metal in *Module D1-6*, "Part-A" of

the latest (Rev 0) AFC-CBR. The unit fabrication costs for HALEUO2 manufacture should be only slightly higher than those for HALEU metal but considerably higher than for LWR UOX manufacture if the U-235 assay is greater than 10%. This statement assumes that the feed to the fabrication facility is clean U-metal shards. If HALEUF6 is the feed to the metal fuel fabrication plant, a considerable cost must be added from reduction (aka deconversion) of the UF6 to metal. This additional cost is discussed in new *Module C3*, "HALEU Enrichment and Deconversion." HALEUOX SFR fuel costs are discussed in a later section of this supplement, following discussion of U,Pu SFR MOX below.

Once the process and operating environment differences between PWR UOX manufacture (NASAP reference fabrication technology) and higher specific activity and higher-fissile SFR (U,Pu) MOX driver manufacture were understood and analyzed, equipment lists and building modification specifications were prepared by the ORNL engineers working on NASAP, and the resulting equipment laid out on the floor (design footprint) of a single-story process building of the proper safe, secure, and licensable design. Among the process differences and similarities identified for going from LWR LEUOX to SFR U,Pu MOX fuel fabrication for the same approximate annual MTHM capacity are the following:

- Criticality considerations are more serious for the higher-fissile content of U,Pu MOX SFR drivers (15 to 20%) than for all conventional LEUOX LWR fuel (3 to 5% U-235) or conventional LWR MOX fuel (4 to 10% fissile isotopes).
- The UF6 to UOX conversion step for preparation of the depleted or natural UO2 diluent blendstock powder, which comprises most of the mass of U,Pu MOX fuel, is a relatively simple semi-continuous process in use by LWR UOX fabricators today. The very low U-235 enrichment associated with natural or depleted U makes criticality a nonexistent design issue. In a Category III facility, the product of the UF6 to UOX process is drummed UO2 powder of suitable purity and powder morphology for blending and pelletization in a Category I facility with the high-quality pure PuO2 recovered from plutonium uranium reduction extraction (PUREX) reprocessing of LWR or SFR SNF.
- The plutonium oxide (PuO2) feedstock to the U,Pu FR MOX blend might need to be converted from some other chemical form if the Pu is derived from aqueous reprocessing is not in the form of PuO2, which might be the case with some aqueous reprocessing facilities. Such a form might be plutonium nitrate crystals or other Pu salt solutions such as oxalates.
- The UO2-PuO2 blending step and other process steps (granulation, pressing, sintering, pellet finishing, and rod loading) are basically the same as for LWR MOX (*Module D1-2*). The higher-fissile content of the process material, however, mandates smaller batch sizes.
- The additional less complex and less hazardous DUO2 (DUOX) blanket plant discussed in this module produces both complete radial fuel assemblies and additional slugs or pellets to be loaded in the ends of HALEUOX or U,Pu MOX driver assemblies to serve as the axial blanket. Natural UOX diluent pellets or radial blanket assemblies could also be processed in a similar Category III plant.
- An SFR finished U,Pu MOX driver pellet is much smaller than a finished LWR UOX or LWR MOX pellet. The same may not be true of the UO2 blanket pellets for more recent SFR designs. The NASAP study had most SFR blanket pellets the same size as the driver pellets.
- More (smaller diameter and shorter) pellet-loaded rods are handled and bundled for fuel loaded in SFRs as compared to similar-sized LWRs.
- The U,Pu MOX driver fabrication plant requires gloveboxes for most operations. For all uranium HALEUOX SFR startup drivers and all uranium oxide SFR blanket fuel, hoods and use of inert gases may be required to minimize fire hazards and for personnel protection from airborne alpha-containing dust inhalation.

- Stainless-steel cladding rather than zirconium-alloy cladding is required for compatibility with the liquid sodium coolant environment.
- In *Module D1-1*, it was noted the fabrication of LEUOX fuel containing reprocessing-derived separated uranium (REPU) was somewhat more difficult and expensive than fabricating LEUOX derived from "virgin" or unirradiated uranium derived from unirradiated U which has only undergone mining, milling, conversion, and enrichment. A similar situation exists for the fabrication of MOX fuels (LEU MOX or SFR MOX) derived from separated PuO2 from SFR-SNF reprocessing (or LWR MOX SNF reprocessing) as compared to the fabrication of LWR or SFR MOX fuels utilizing PuO2 derived from LWR UOX SNF reprocessing. Pu derived from MOX fuel reprocessing will have higher concentrations of HAs and higher-Z plutonium radioisotopes. This "refabricated" or "second SFR irradiation" pass material will require more complex and expensive glovebox and other shielding for personnel protection from higher gamma and spontaneous neutron fields associated with higher-Z radioisotopes.

After the ORNL NASAP engineers laid out the process equipment (including gloveboxes and shielding), the following area requirements (Table D1-4-5) were calculated for the various process areas of the three SFR-related single-story plants (the NASAP reference PWR UOX fuel fabrication plant values are shown in the first data column for comparison).

Table D1-4-5. Comparative process areas required for 2 MTU/day Capacity (520 MTU/yr) average production -PWR-UOX Fuel Fabrication Facility (Reference Plant) and 480 MTHM/yr average production SFR U,Pu MOX driver fuel fabrication, driver fuel refabrication, and SFR blanket fuel facilities (subject plants).

Operation	"Hands-on" PWR UOX "Reference Plant" based on NASAP bottom-up estimate: Area in square feet per Ref D1-4. (3 to 5% "virgin" LEUOX fuel)	Glovebox-type U,Pu MOX SFR driver fuel fabrication plant: Area in square feet per Ref D1-4._ (PuO2 derived from PUREX LWR SNF reprocessing)	Enhanced shielding glovebox U,Pu MOX driver fuel "refabrication*" plant Area in square feet per Ref D1-4._ (PuO2 derived from PUREX SFR-SNF reprocessing)	DUOX SFR blanket fuel Area in square feet per Ref D1-4._ (DUO2 derived from deconversion of enrichment plant tails DUF6)
Feed receipt areas (LEUF6 for UOX, DUF6 and PuO2 for MOX)	5,500	5,304	5,304	2,350
Powder milling for UOX. Powder milling & blending for MOX	4,700	9,360	11,388	2,350
Powder granulation and pelleting	1,900	4,914	7,332	1,900
Pellet sintering, grinding, and inspection for UOX & MOX	5,850	32,253	48,048	5,850

Table D1-4-5. (continued).

Operation	"Hands-on" PWR UOX "Reference Plant" based on NASAP bottom-up estimate: Area in square feet per Ref D1-4. (3 to 5% "virgin" LEUOX fuel)	Glovebox-type U,Pu MOX SFR driver fuel fabrication plant: Area in square feet per Ref D1-4._ (PuO2 derived from PUREX LWR SNF reprocessing)	Enhanced shielding glovebox U,Pu MOX driver fuel "refabrication*" plant Area in square feet per Ref D1-4._ (PuO2 derived from PUREX SFR-SNF reprocessing)	DUOX SFR blanket fuel Area in square feet per Ref D1-4._ (DUO2 derived from deconversion of enrichment plant tails DUF6)
Fuel rod loading and welding	2,780	18,044	25,701	3,170
Fuel rod inspection and storage	7,000	42,900	61,100	7,740
Fuel assembly fabrication	3,000	34,130	45,890	7,500
Fuel assembly weighing, cleaning, and inspection	3,400	6,630	7,072	2,500
Fuel assembly packaging and shipping	4,000	62,400	104,000	2,436
Scrap recovery and waste processing	2,000	13,000	19,500	1,500
Operational support including hardware fabrication	20,065	114,498	167,668	186,50
Stores (warehouse)	2,000	2,600	2,600	4,000
Facility support	9,135	91,598	171,020	14,920
Change rooms for contaminated areas	2,005	2,005	4,000	2,005
Quality control labs	7,000	9,100	53,792	7,000
Maintenance	19,665	114,497	335,335	18,650
Total area in ft'	100,000	563,293	1,069,750	102,521
*Refabrication plant for reprocessed SFR U,Pu MOX requires extra glovebox shielding and some hot-cell robotics for remote equipment maintenance				

Equipment and operations adjustments were made to recognize the higher complexity of the fuel itself, through the use of "complexity factors" that were developed as part of the 1978 NASAP analysis. Many of the FORTRAN-based economics algorithms in the ORNL NASAP documentation were converted to Excel spreadsheets by the author of this module. This allowed a verification that the original, late 1970s, life cycle costs and fabrication unit costs were correctly calculated. The late 1970s costs then

had to be escalated to USD (2017) using adequate historical escalation factors (Dixon et al. 2017) for nuclear projects. The G4-ECONS-FCF economic model (Williams 2007) was then utilized to calculate the levelized unit cost for both U,Pu ceramic MOX SFR driver and DUOX blanket fabrication facilities with a 50-year life and 3% real discount rate for capital recovery (Table D1-4-6), as was done for LWR MOX in *Module Dl-2*. Two types of driver fuel plants were examined: one with LWR-SNF reprocessing-derived PuO2 feed called "fabrication" and one with SFR-SNF reprocessing-derived, "dirtier" PuO2 feed called "refabrication" The all-DUO2 blanket plant was similar to the "reference" CAT-III LWR LEUOX plant, but with smaller but more numerous pellets, smaller fuel assemblies, and fewer criticality safety considerations.

D1-4-9. RESULTING LARGE SFR U,PU MOX FUEL "FABRICATION" AND "REFABRICATION" PLANTS

The "driver" fuel assembly plants were designed for a nominal 2 MTHM/day production capacity which, including downtime, translates to an average production capacity of 480 MTHM/year. The blanket plant with less downtime has an average production capacity of 520 MTU/yr. Single-story fabrication process buildings, housing the feed conversion, any powder blending processes, and all pelletizing, rod loading, and bundling operations were both found to require footprints of over 563,000 ft2 and 1,070,000 ft2, respectively for the higher-complexity SFR drivers. The lower-complexity, all-DUO2 blanket fabrication plant required ~102,000 ft2 which is close to the reference LWR UOX plant area of 100,000 ft2. Table D1-4-5 shows the major required process building areas as calculated in the 1978 ORNL reports and verified on Excel spreadsheets by the authors of this report. When Columns 2 and 3 of this table are compared to Column 1, it can be seen that the need for nearly all glovebox operations for "fabrication" and the addition of remote robotic maintenance and more glovebox shielding for "refabrication" greatly increases the plant footprint as compared to the "reference" LWR-UOX facility of the same throughput, There is also the need to fabricate a more complex fuel assembly and smaller and more numerous SFR MOX pellets, as well as the need for additional O&M staff.

The treatment of the economics and calculation of the unit fabrication cost in the 1978 report (Ref. Dl-4S.1) (summarized in Table D1-4-6 and Table D1-4-7) reflects prevailing financial conditions and taxation regulations in effect at that time for a privately owned greenfield plant. As with the reference LWR-UOX plant (in *Module D1-1*), a simple economic model for today's (2017) economic conditions (also shown in Table D1-4-6) was developed utilizing the G4-ECONS economic analysis tool (Williams 2007) as applied to fuel cycle facilities.

Table D1-4-6. Life cycle cost transitioning from 1978 "Reference" CAT-III LWR LEUOX Fabrication Facility to 2017 "Subject" CAT-I U,Pu MOX Driver Fabrication and Refabrication Plants.

Facility and Life Cycle Cost Attributes	Reference PWR LEUOX 1978 USD & 1978 Financial assumptions (NASAP)	Reference PWR LEUOX 2017 USD & 2017 Financial assumptions (G4-ECONS)	U,Pu MOX SFR Ceramic Driver Fabrication 1978 USD & 1978 Financial assumptions (NASAP)	U,Pu MOX SFR Ceramic Driver Fabrication 2017 USD & 2017 Financial assumption (G4-ECONS)	U,Pu MOX SFR Ceramic Driver Refabrication 1978 USD & 1978 Financial assumptions (NASAP)	U,Pu MOX SFR Ceramic Driver Refabrication 2017 USD & 2017 Financial assumptions (G4-ECONS)
Production rate adjusted for downtime	520 MTU/yr	520 MTU/yr	480 MTHM/yr	480 MTHM/yr	480 MTHM/yr	480 MTHM/yr
Process building area (ft2)	100,000 ft2	100,000 ft2	363,293 ft2	363,293 ft2	1,069,750 ft2	1,069,750 ft2
Total civil structure cost incl. indirects and contingency ($M)	$31.9	$239	$465	$3167	$1239	$8319
Total equipment cost incl. indirects and contingency ($M)	$34.2	$269	$232	$1821	$362	$2155
Total facility overnight capital cost incl. preoperational costs ($M)	$86	$629	$736	$5221	$1642	$10720
Plant life	20 y	50 y	20 y	50 y	20 y	50 y
Annual recurring costs ($M/year)	$36.4	$148M	$102	$448	$115	$462
Financing basis (r=annual real discount rate)	Government guaranteed, private financing, r= 8.8%	Government guaranteed private financing, r=3%	Commercial, financing, r= 8.8%	Government financing, r=3%	Commercial, financing, r= 8.8%	Government financing, r=3%
Unit fabrication cost ($/kgHM)	$100	$334	$420	$1,413	$600	$1,948

Table D1-4-7. Life Cycle Cost Transitioning from 1978 "Reference" LWR LEUOX Fabrication Facility to 2017 "Subject" UOX Blanket Pellet & Fuel Assembly Fabrication Facility.

Facility and Life Cycle Cost Attributes	UOX SFR Blanket Assy Fabrication USD 1978 & 1978 Financial Conditions	UOX SFR Blanket Assy Fabrication USD 2017 & 2017 Financial Conditions
Production rate adjusted for downtime (MTU/yr)	520	520
Process building are (ft2)	102,521	102,521
Total civil structure cost ($M)	31.6	191
Total equipment cost ($M)	33.6	264
Total capital facility cost including preoperations ($M)	84	566
Plant life (years)	20	50
Annual recurring costs ($M/yr)	46.4	184
Financing basis (real discount rate)	Government guaranteed private financing: r=8.8%	Government: r=3%
Unit fabrication cost ($/kg U or HM)	120	401

D1-4-10. UNIT FABRICATION COST VS. AVERAGE PLANT THROUGHPUT SCALING

As discussed in Section D1-4 (Scaling Considerations), the unit cost of fabrication is expected to scale with plant annual production capacity. Using cost-scaling exponents from the NASAP report (Olsen et al. 1979), the "unit fabrication cost versus average annual production rate" table below was derived. The scaling methodology used is now described. A standard scaling equation for estimating cost as a function of capacity or average throughput is:

$$CS = CR\ (XS/XR)^{Y} \quad (1)$$

where

CS = cost of the subject plant in a given life cycle cost category

CR = cost of the reference plant in a given life cycle cost category

XS = production capacity of the subject plant

XR = production capacity of the reference plant

Y = scaling factor or exponent for the particular life cycle cost category.

The scaling factors used for the NASAP study and this AFC-CBR study are:

Y = 0.6 for contact-handled fabrication facility capital costs

Y = 0.8 for remote-handled & maintained fabrication facility capital costs

Y = 0.7 for equipment capital costs in fabrication plants

Y = 1.0 for recurring expendable materials and expendable hardware costs in fabrication plants

Y = 0.8 for recurring costs, including personnel, in fabrication plant operating costs.

Scaling factors are affected by a number of variables, such as criticality, magnitude of facility throughput, reliability of equipment, and differences in facilities due to the type of fuel meat material being processed. Scaling factors may vary widely with equipment type and application and generally are not used beyond a tenfold range of capacity in either direction. The scaling factors presented above represent what are believed to be reasonable values over the threefold range (2 to 6 MTHM/operating day) of large plant capacities considered for cylindrical fuel types for the NASAP studies. In terms of average annual throughput, this range is from ~500 to 1,500 MTHM per year. Using a factor of 10 plant size applicability for the AFC-CBR study, a low annual throughput of 150 MTHM/yr could be assumed. (The "reference" plant size for PWR UO2 fuel is 520 MTHM/yr and for both LWR and SFR U,Pu MOX fuels is 480 MTHM/yr.)

Using the above scaling equation, the U,Pu SFR MOX capital and recurring costs for the non-baseline "subject" sizes for a particular fuel type are calculated (i.e., "cost-scaled") from the reference size costs for the same type of fuel at ~500 MTU/yr. The spreadsheet then calculates the new overall life cycle costs by category and levelizes them over the assumed plant life for the desired new "non-reference capacity" or "subject capacity" to obtain the average "subject plant" $/kgHM unit fabrication cost. All of this was done in 1978$ for the NASAP studies for 20 year life plants under 1978 economic conditions, and in 2017$ over a 50-year plant life for the AFC-CBR studies, with the latter under today's (2017) lower interest rate economic conditions. Table D1-4-8 below shows the results of the unit cost versus average plant throughput calculation for SFR U,Pu MOX driver fuel and SFR DUOX blankets over a range 100 to 2,000 MTHM/yr annual production (average throughput). Other types of cylindrical, ceramic, and pelletized oxide fuels from other AFC-CBR fuel fabrication modules are included for comparison. A considerably wider 50 to 2,000 MTHM/yr throughput range (as compared to the 150 to 1,500 MTHM/yr used in the NASAP study) was utilized, since the SFR fleet sizes (# of reactors) and fuel requirements now envisioned for an SFR fleet are not well known. It is likely to be 100 or less MTHM/yr per fabrication plant in the earliest years of SFR technology deployment.

Table D1-4-8. Unit fabrication cost in 2017$ vs. average annual throughput for oxide fuel fabrication plants of different fuel types (based on recasting of 1978 NASAP cost data for today's economic conditions).

Average Throughput in MTHM/yr	*Module D1-1* "Reference" Fuel Fab Technology PWR LEUOX ("virgin" or non-REPU) 2.5 to 4.95% fissile (all U-235) CONTACT-HANDLED:All hands-on NASAP CASE DESIGNATOR: LEU (235U,U)O2 ($/kgHM or $/kgU)	Module D1-2 PWR U,Pu MOX (PuO2 derived from PUREX-reprocessed PWR LEUOX SNF; for first MOX pass in PWR) 5 to 10% fissile REMOTE-HANDLED THROUGH GLOVEBOX with CONTACT MAINT of EQT NASAP CASE DESIGNATOR: (Pu,U)O2 (RO/CM) ($/kgHM)	*Module D1-2* PWR U,Pu "refab" MOX (PuO2 derived from PUREX-reprocessed PWR MOX SNF; for 2nd MOX pass in PWR) 6 to 12% fissile REMOTE-HANDLED THROUGH ENHANCED GLOVEBOX with REMOTE MAINT of EQT NASAP CASE DESIGNATOR: (Pu,U)O2 (RO/RM) ($/kgHM)	*Module D1-4* SFR U,Pu MOX drivers (PuO2 derived from PUREX-reprocessed PWR LEUOX SNF; for 1st MOX pass in SFR) 15 to 17% fissile REMOTE-HANDLED THROUGH GLOVEBOX with CONTACT MAINT of EQT NASAP CASE DESIGNATOR: (Pu,U)O2 (RO/CM) ($/kgHM)	*Module D1-4* SFR U,Pu "refab" drivers (PuO2 derived from PUREX-reprocessed SFR MOX drivers and blankets; for 2nd MOX pass in SFR) 16 to 20% fissile REMOTE-HANDLED THROUGH ENHANCED GLOVEBOX with REMOTE MAINT of EQT NASAP CASE DESIGNATOR: (Pu,U)O2 (RO/RM) ($/kgHM)	*Module D1-4* SFR NAT UOX or DUOX radial blanket assemblies and UO2 pellets for axial blanket assemblies 0.2 to 0.72% fissile CONTACT-HANDLED All hands-on NASAP CASE DESIGNATOR: UO2 Radial Blanket ($/kgHM or $/kgU)
50	485	1,359	1,910	2,013	2,877	519
100	429	1,176	1,647	1,791	2,537	477
200	383	1,023	1,427	1,606	2,249	441

300	361	946	1,314	1,511	2,102	423
400	346	895	1,241	1,450	2,006	411
480	339	865	1,197	1,413	1,948	404
520	334	853	1,179	1,397	1,924	401
750	318	798	1,098	1,330	1,817	388
1,000	307	758	1,040	1,281	1,740	378
2,000	284	673	915	1,117	1,573	358
Diluent UOX for all U,Pu MOX drivers assumed to be depleted U or natural U. Unit cost expressed in reference year 2017 US$ Average fuel burnups and fissile contents representative of technology projected for late 1970s and 1980s. Oxide-fueled, loop-type SFRs assumed to operate in “breeder” mode.						

D1-4-11. REVISITING THE "WHAT-IT-TAKES" UNIT COST DATA FOR MODULE D1-4 BASED ON NEWLY-ACQUIRED DATA FROM THE NASAP ANALYSIS AND DOMESTIC AND INTERNATIONAL SFR MOX FUEL FABRICATION EXPERIENCE

Selection of the "what-it-takes" (WIT) unit fabrication cost values (a "vector" of reference, low, mode, high, and mean $/MTHM numbers, and a distribution type) is based on the rigorous examination of design and cost data for actual facilities and upon reliable cost estimates for hypothetical planned facilities. Before examining the results of the NASAP analysis described above, it is useful to examine ongoing world experience with MOX FR fuel and consider three countries, Russia, India, and China, which are still pursuing U,Pu MOX SFR power reactors in the near term and thus are procuring or have procured a fuel supplier. The United States, the United Kingdom, Belgium, Germany and France have all pursued MOX-based demonstration SFR power reactor and/or fuel production programs in the past but have delayed or cancelled their programs. The United States has shifted its program toward actinide-burning, metal-fueled modular SFRs.

India and China have demonstration power SFRs which are nearly complete and for which initial MOX fuel loads are now being manufactured. Unfortunately, no life cycle cost data on foreign fuel manufacturing is publicly available. Table D1-4-6 below summarizes the SFR and MOX fuel information available concerning these three nations. Much of this data comes from the World Nuclear Associations' Country Profiles (WNA 2021). A more recent publication (Sokolski 2021) discusses some of the proposed and under-construction SFR-related facilities in China and their implications for nonproliferation.

Table D1-4-9. Data on three countries currently pursuing large-scale SFR power demonstration projects using U,Pu MOX Fuel.

SFR U,Pu MOX Fuel Attributes	India	Russian Federation	China
Names of power-producing FR(s) that utilize at least partial MOX cores or are operating or will be commissioned in next few years	PFBR	BN-600, BN-800	CFR-600 aka CDFR
Reactor Location	Kalpakkam 1	Beloyarsk-3, Beloyarsk-4	Xiapu, Fujian
Power capacity (MWth and MWe)	970 MWth, 470 MWe	560 MWe and 789 MWe, respectively	1,500 MWth, 600 MWe
Year of first criticality	2020	1980, 2014	2023
Fuel assembly mass (kgMOX)	50	49	n/a
% PuO2 in MOX and Pu type	24.4, reactor grade	26, weapons grade	n/a
Avg. burnup (GW-d/MTHM)	68	n/a	100 GW-d/MTHM
Blanket material	UO2 and ThO2	DUO2	UO2
Fuel supplier (existing or planned)	DAE	TVEL	TVEL/Elemash in Russia

Table D1-4-9. (continued).

SFR U,Pu MOX Fuel Attributes	India	Russian Federation	China
Fuel fabrication plant location	Tarapur & FCFRF Kalpakkam	Zheleznogorsk Mining and Chemical Combine	Elektrostal Machine Building Works near Moscow, Russia and Sanmen, China
Existing MOX fuel plant capacity (MTHM/yr)	n/a	60 MTHM/yr	n/a
MOX Fuel plant startup year	n/a	2015	n/a
Pins per driver fuel assembly	217	127	n/a
Pin spacing geometry in fuel assembly	hexagonal	hexagonal	hexagonal
Overall fuel pin length (m)	4.5	3.5	n/a
Fuel assembly width (cm)	n/a	9.6	n/a
Pellet outer diameter (mm)	5.55	5.95	n/a
Pellet height (mm)	7	9	n/a
Cladding material	stainless steel	stainless steel	stainless steel
Cladding thickness (mm)	0.45	0.4	n/a

Russia has constructed a 60 MTHM/yr commercial Russian Federation-MOX fuel fabrication facility (RF-MFFF) in an existing 200-meter-deep mountain tunnel which was a former nuclear defense factory (Mining & Chemical Combine) from the Cold War. It is located at Zheleznogorsk, formerly Krasnoyarsk-26 (WNN 2021). It is operated by the Mining and Chemical Combine (MCC) and began production in 2015 as Russia's contribution to the former Joint US-RF Weapons-Grade Plutonium Disposition Project. (This former project for the disposition of 34 MT of WG-Pu by each nation is discussed *Module D1-2*, since the United States planned to manufacture LWR MOX fuel on its own, but now cancelled, MFFF at Savannah River.) Rosatom constructed this underground facility for a capital cost of 9.6 billion Russian rubles or $200 million (at an exchange rate of 48 rubles/US$). It will make 400 pelletized MOX fuel assemblies per year for the BN-800 SFR and eventually the BN-1200 SFR. The first MOX fuel from Zheleznogorsk was accepted for reactor insertion in 2018. The RF stated it was investing 80 billion rubles over 20 years in MOX at MCC. In US$, this comes to around $80M/yr. A total life cycle of $200M + (20y* $80M/yr) results in a total LCC of US$1.8B. This total LCC spread over 20 yr x 60 MT/yr = 1.2 million kgHM of total production gives a levelized unit production cost of $1,500/kgHM, assuming zero interest. The RF plutonium processed is relatively clean material derived from reprocessing of VVER (LWR) fuel or weapons material. This RF unit cost falls within the NASAP-derived 1,301 to 2,233 $/kgHM range for "first SFR pass" MOX fuel shown in Table D1-4.8 above. It is on the low end since the use of existing tunnels at Zheleznogorsk eliminated the need for a new expensive and highly secure building, and personnel costs in Russia are significantly lower than those in Western nuclear facilities.

SFR MOX fuel has been made in the United States in small quantities (less than 30 MTHM total in the 1970s) for irradiation testing in the now mothballed Fast Fuel Flux Facility test reactor at Hanford, WA. Kerr-McGee corporation manufactured SFR MOX at a plant in Sequoyah, OK and Babcock and Wilcox Corp (Heer 1978; Williams and Rice 1980) at a plant in Parks Township in Western

Pennsylvania. A few other small companies, such as United Nuclear of Pawling, NY (now decommissioned), participated in the early phases of this HEDL (Hanford Engineering Development Laboratory)-led fuel development project. The constructed but never operated SAF line at Hanford was also supposed to manufacture initial SFR MOX fuel for the CRBRP. No useful life cycle cost information, actual or projected, was found on these U.S. facilities. The Belgonuclaire MOX plant at Dessel in Belgium also made multi-MT/yr quantities of MOX for European LWR and SFR programs. No cost data on this now decommissioned facility could be found either. Japan has a small SFR MOX plant at Tokai capable of a few MTHM/yr of production for its SFR development programs such as MONJU, a non-electric power test reactor that is now shut down.

Selection of What-It-Takes Unit Fabrication Costs for SFR Driver U,Pu MOX Fuel

The above referenced 1977–1980 NASAP studies and Tables D1-4.5, D1-4.6, and D1-4.8 above form the new basis for the Rev 0 Update to *Module D1-4*. The methodology discussed above was used to update the 1978$ unit costs to 2017$. **These values above replace the higher unit cost ranges reported in the *2017 AFC-CBR Module D1-4***. The tables above and Table D1-4.10 below also differentiate between whether the SFR MOX fuel is derived from PUREX-reprocessed LWR UOX SNF (fabrication) or PUREX-reprocessed SFR MOX SNF (refabrication). Table D1-4-10 shows the resulting low, mode (most likely), high, and calculated mean unit costs assuming a triangular probability distribution for the low, mode, and high $/kgHM values. Justification for the selection of the values appears on the table.

Table D1-4-10. What-it-takes 2017$ unit fabrication costs for SFR driver U,Pu MOX fuel.

Fuel Type	Reference Unit Fabrication Cost and Source ($/kgHM)	WIT Low Unit Fabrication Cost and Justification ($/kgHM)	WIT Mode Unit Fabrication Cost and Justification ($/kgHM)	WIT High Unit Fabrication Cost and Justification ($/kgHM)	WIT Calculated Mean Unit Fabrication Cost Based on Triangular Distribution ($/kgHM)
Generic SFR U,Pu MOX from *2017 AFC-CBR* (all Pu derived from PUREX reprocessing of LWR or SFR SNF, for first or later pass in SFR). Burnup typical of breeder mode.	No value given in *2017 AFC-CBR*. Table of unit cost values was derived from other publications listed.	2,700	4,900	7,600	5,067
"Fabricated" SFR U,Pu MOX for this *2020 Module D1-4* update (all Pu derived from PUREX aqueous reprocessing of LWR SNF). Fuel intended for "first pass" insertion in SFR operating in breeder mode.	1,413 From adjusted NASAP RO/CM case for 480 MTHM/yr	1,177 From adjusted NASAP RO/CM case for 2000 MTHM/yr very large plant with	1413 From adjusted NASAP RO/CM "reference capacity case" (480 MTHM/yr)	2,013 From adjusted NASAP RO/CM case for 50 MTHM/yr small plant with lesser	1,534

Fuel Type	Reference Unit Fabrication Cost and Source ($/kgHM)	WIT Low Unit Fabrication Cost and Justification ($/kgHM)	WIT Mode Unit Fabrication Cost and Justification ($/kgHM)	WIT High Unit Fabrication Cost and Justification ($/kgHM)	WIT Calculated Mean Unit Fabrication Cost Based on Triangular Distribution ($/kgHM)
(When escalated to 2020$ this data will be the WIT values for the Rev 0 Update)		economy of scale		economy of scale	
"Refabricated" SFR U,Pu MOX for this *2020 Module D1-4* update (all Pu derived from PUREX aqueous reprocessing of SFR SNF). Fuel intended for "second pass" insertion in SFR operating in breeder mode. (When escalated to 2020$ this data will be the WIT values for the Rev 0 Update)	1,948 From adjusted NASAP RO/RM case for 480 MTHM/yr	1,573 From adjusted NASAP RO/RM case for 2000 MTHM/yr very large plant with economy of scale	1,948 From adjusted NASAP RO/RM "reference capacity case" (480 MTHM/yr)	2,877 From adjusted NASAP RO/RM case for 50 MTHM/yr small plant with lesser economy of scale	2,133

D1-4-11.1 Selection of What-It-Takes Unit Fabrication Costs for SFR all UOX Driver Fuel and UOX Blanket Fuel

The above referenced 1977-1980 NASAP studies form the new basis for the SFR Blanket Fuel unit cost in the *2020 Update* to *Module D1-4*. The methodology discussed above was used to update the 1978$ unit costs to 2017$. These values replace the similar blanket UOX unit cost ranges reported in the *2017 AFC-CBR Module D1-4*. Startup all-HALEU or MEU oxide fuel fabrication costs are based on the analysis made for metal HALEU fuels in *Module D1-6A* (U-metal fuels). (A table of EU unit cost versus U-235 enrichment level appears in that report.) The metal-based values taken from the WIT table of *Module D1-6* were increased somewhat to account for the higher fabrication cost for oxide vis-à-vis metal, Table D1-4-11 shows the resulting low, mode (most likely), high, and calculated mean unit costs assuming a triangular probability distribution for the low, mode, and high $/kgU values. Justification for selection of the values appears on the table.

Table D1-4-11. What-it-takes 2017$ unit fabrication costs for all UOX SFR driver fuels and blanket fuel (base year for constant $ costing is the year the FCRD-SA&I estimate was prepared.)

Fuel Type SFR HALEUOX DRIVERS FOR	Reference Unit Fabrication Cost and Source ($/kgHM or U)	WIT Low Unit Fabrication Cost and Justification	WIT Mode Unit Fabrication Cost and Justification	WIT High Unit Fabrication Cost and Justification	WIT Calculated Mean Unit Fabrication Cost Based on

Table D1-4-11. (continued).

SFR STARTUP		($/kgHM or U)	($/kgHM or U)	($/kgHM or U)	Triangular Distribution ($/kgHM or U)
Generic SFR MEU (15 to 25% U-235) UOX SFR startup fuel **from *2017 AFC-CBR***. U assumed derived from "virgin", never-irradiated U. Ore, conversion, and enrichment costs not included, (These *2017 AFC-CBR* values are in 2017$.)	None given in *2017 AFC-CBR*. Values on right based on subjective complexity factor applied to LEUOX.	520	900	1,290	903
"Fabricated" SFR HALEUOX (10 to ~20% U-235**) for this *2020 Module D1-4* update**. HALEUOX assumed fabricated in Category II facility from "virgin" EUF6. (2019$) (When escalated to 2020$, this will become WIT data for Rev 0 Update.)	Values in columns to right from HALEU metal analyses in *Module D1-6A* of 2020 update to AFC-CBR. HALEU unit fab cost for all U metal increased by factor of 1.065 to account for higher oxide fab cost.	1,100 metal 1,172 oxide Lower U-235 enrichments 13 to 15% U-235. Large plant (several hundred MTU/yr)	1,300 metal 1,385 oxide Medium HALEU enrichments 16 to 17% U-235	1,500 metal 1,598 oxide Higher HALEU enrichments 17 to 19.95% U-235 (50 to 100 MTU/yr)	1,300 metal 1,385 oxide
"Refabricated" SFR HALEUOX (10 to 20% U-235) for this 2020 D1-4 Update. HALEUOX assumed fabricated in Cat-II facility from PUREX-derived Reprocessed EU (REPU) with minor FP, U-232, and TRU contaminants. (2019$) (When escalated to 2020$, this will become new WIT data for Rev 0 Update.)	Values in columns to right from HALEU metal analyses in unit cost vs U- assay Table of *Module D1-6A* of 2020 update to ADC-CBR. HALEU unit fab cost increased by factor of 1.065 to account for higher oxide fab cost.	1,800 metal 1,917 oxide Lower U-235 enrichments 13 to 15%. Large plant (several hundred MTU/yr)	2,100 metal 2,237 oxide Medium HALEU enrichments 16 to 17% U-235	2,500 metal 2,663 oxide Higher HALEU enrichments 16 to 17% U-235	2,100 metal 2,272 oxide

Table D1-4-11. (continued).

Low-assay HEU oxide (LAHEUOX) 20 to 35% U-235 Prepared from "virgin", blended HEU, or REPU in CAT-I facility. Ore, conversion, and enrichment costs not included in fabrication cost. (2019$) (When escalated to 2020$, this will become new WIT data for Rev 0 Update.)	Values in columns to right from HEU metal analyses in unit cost vs. U-assay Table of *Module D1-6A* of 2020 update to ADC-CBR. Overhead costs overwhelm difference between metal and oxide fab costs, so all U metal unit costs from *Module D1-6A* used.	5,000 Large plant 20 to 25% U-235	7,000 25 to 30% U-235	12,000 Small plant or 30- to 35% U-235	8,000
DUOX or Natural UOX for Radial Blanket Assemblies and Axial Blanket Pellets (These *2017 AFC-CBR* data are in 2017$/kgU.)	Values found in multiple fuel cycle publications.	270	500	690	485
DUOX or Natural UOX for Radial Blanket Assemblies and Axial Blanket pellets. New values from NASAP-based analyses for *2020 AFC-CBR Update* (2019$) (When escalated to 2020$ this will become new WIT data for Rev 0 Update) CAT-III facility assumed.	401 From adjusted NASAP "reference" capacity case (520 MTU/yr) for oxide blankets.	358 2000 MTU/yr	401 520 MTU/yr	519 50 MTU/yr	426

D1-4-12. DATA LIMITATIONS

Technology Readiness Level. FR MOX or HALEUOX pellet fuel production technology in the United States could reasonably progress quickly to the pilot plant stage; however, changing requirements

would link FR MOX progress to that for LWR MOX. Considerable fuel qualification would be required before industrial scale implementation in the United States.

Identification of Gaps in Cost Information. If the benefits and risks of closed fuel cycles vis-à-vis open cycles are to be well understood, the fabrication costs for fuels arising from closed cycles must be better understood. Unfortunately, there is little U.S. experience in operating large-scale facilities, and what work has been done to date is mostly on LWR or thermal MOX. The most recent U.S. FR cost studies have been for plants preparing metal fuel, with the feeds coming from an adjacent dedicated fuel reprocessing facility on the reactor site (i.e., the GE/MFC[b] integral FR cycle associated with the GE PRISM metal-fueled concept [discussed in *Module F2/D2*]). Therefore, they add little to the database for ceramic FR fuels. It is also difficult to separate fabrication costs from reprocessing costs for such studies involving co-located integrated facilities using electrochemical process technology.

It is likely that FR ceramic (such as liquid-metal reactor MOX) fuel fabrication plants will need to be tied in closely or be part of a reprocessing complex for fabrication unit costs to decrease. This collocation allows fixed costs for regulatory considerations, such as CAT-I security and radiochemical hazard protection, to be distributed over more fuel cycle operations and also greatly decreases spent fuel packaging and transportation requirements and costs. Some preconceptual designs for collocated facilities need to be prepared by an architect-engineering firm to enable this assumption to be validated. The only other studies that might have limited use are Russian design/cost studies on small FR pelletized fuel facilities to support the burning of 17–25% fissile MOX fuels in the BN-600 reactor which formerly supported the joint U.S./Russian Federation weapons plutonium disposition program.

To increase the proliferation resistance of closed fuel cycles, the idea of not separating plutonium from other transuranic actinides (“grouped” actinides) in the aqueous reprocessing plant has been advanced. The UREX 1a reprocessing concept is one such process. This means that the ceramic FR fuel that would be refabricated from this material would contain neptunium, americium, and perhaps other actinide (curium and trace californium) oxides in the MOX. Sometimes referred to as “dirty” MOX, this material would impose special and more stringent requirements on the fuel fabrication facility from the standpoints of personnel radiation exposure, heat management, criticality, and materials accountability. The resulting plants would more appropriately fall under *Module F2/D2* (remote-handled fuels). These additional costs of more automated or remote handling are not known; however, if a “dirty MOX” economic study is done for thermal reactor fuel, such as (Pu,Np,U)O2 or for higher actinide LWR targets, the results will have similar impacts on FR MOX plants. Similar considerations would apply to other mixed actinide ceramic fuel types, such as carbides or nitrides.

D1-4-13. COST SUMMARIES

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

The WIT data from previous AFC-CBRs is summarized below, followed by the latest data for this Rev 0 Update. **This historical data is provided to show how FCRD-SA&I's data gathering and calculational life cycle cost gathering efforts has progressed over the years since the 2009 public release document.**

***2009 AFC-CBR* Cost Summary**. The *2009 AFC-CBR* (Shropshire 2009a) *Module D1-4* cost information is summarized in the WIT cost summary in Table D1-4-12. The summary shows the reference cost basis (constant year US$), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of the *2009 AFC-CBR* for additional details on the cost estimation approach used to construct the WIT table.

Table D1-4-12. 2009 Cost summary table for fast reactor pelletized ceramic fuels.

What-It-Takes Table (2007 Constant $)			
Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
$2,400/kgHM from centralized, private 50-MT/yr facility with loan guarantee and market guarantee	$3,200/kgHM Blanket: $350/kgU	$6,000/kgHM Many of same factors affecting SRS-MFFF would affect this cost (see *Module D1-2*). Blanket: $700/kgU	Core driver fuel: $4,000/kgHM Blanket: $500/kgU
No reliable and validated data on plant capital costs	Same as for LWR MOX; use of low assay HEU (HALEU) in 15 to 25% U-235 range would be cheaper (fabrication cost) than plutonium use.	25% higher than for LWR MOX nominal cost	20% higher than for LWR MOX nominal cost

***2012 AFC-CBR* Update Cost Summary**. The following set (Table D1-4-13) of "WIT" year 2012 values and a corresponding probability distribution is recommended for use in future fuel cycle studies:

Table D1-4-13. Low, nominal, and high suggested fabrication cost (*2012 AFC-CBR* update).

Fuel Type	Low (2012 $/kgHM)	Mode (2012 $/kgHM)	High (2012 $/kgHM)
FR (High-end LEU To Low-end MEU U-235 Content) Pelletized Ceramic Driver Fuel	475	825	1,180
FR Pelletized Ceramic (U,Pu) Driver Fuel such as MOX	2,500	4,500	7,000
FR Pelletized Ceramic $NATUO_2$ or DUO_2 Blanket Fuel	250	450	630

For uncertainty analyses, triangular distributions should be used with each row's values in the table above. The first row of Table D1-4-13 above provides suggested fabrication costs for the enriched, stainless-steel clad ceramic UO_2 fuel that might be used for the startup of the first FRs in a fleet. Uranium enrichment costs, which would be significant for the 15 to 25% U-235 levels required, are not included in this cost. The complexity factor approach based on 1979 ORNL data (Olsen et al. 1979) was also used to assign the low and high values, in addition to the nominal value as was explained above.

Assignment of costs for the (U,Pu) driver FR ceramic fuel required more subjective judgment and comparison to other fuel types, especially LWR MOX fuel because of the fabrication process similarity. The LWR MOX values in *Module D1-2* were based on better life cycle cost estimates, and it is assumed by the author of this module that FR (SFR) MOX fuel will not be any cheaper to manufacture than LWR MOX. The unit costs in the second row reflect this thinking and are also somewhat higher than the *2009 AFC-CBR* values due to the inflation in O&M costs and purchased commodities. Projected costs for ceramic blanket fuel have been added to this *2012 AFC-CBR* and are shown in the third row of the table. The "complexity factor" method was again used to assign the low, nominal, and high values.

***2017 AFC-CBR* Cost Summary**. Table D1-4- 14 shows the year 2017 values; 2017 is the last CBR for which *Module D1-4* cost data are based on a mix of small plant historical data, unit cost projections from 1980s–1990s U.S. government programs, and subjective estimates of processing complexity.

Table D1-4- 14. WIT low, mode, mean, and high suggested unit fabrication costs from *2017 AFC-CBR* in 2017$.

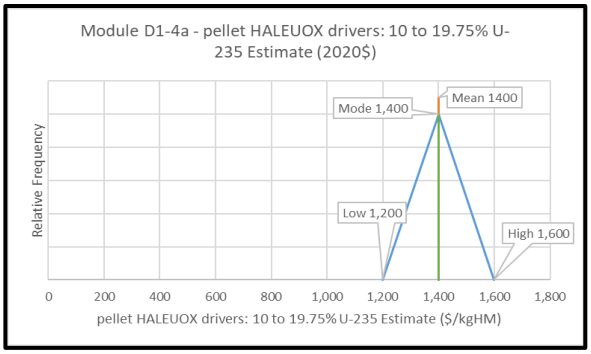
Fuel Type	Low ($/kgHM)	Mode ($/kgHM)	Mean ($/kgHM)	High ($/kgHM)
2017$				
FR (High-end LEU To Low-end MEU U-235 Content) Pelletized Ceramic Driver Fuel	520	900	903	1,290
FR Pelletized Ceramic (U,Pu) Driver Fuel such as MOX	2,700	4,900	5,060	7,600
FR Pelletized Ceramic $NATUO_2$ or DUO_2 Blanket Fuel	270	500	487	690

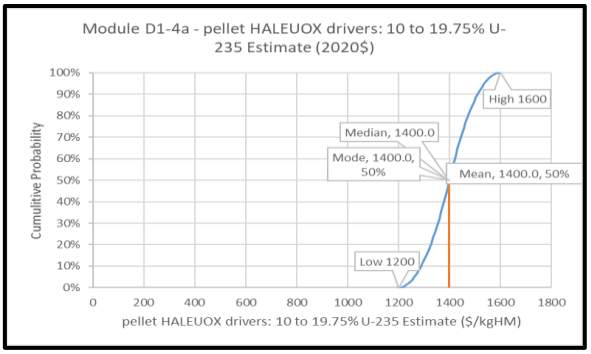
Rev 0 AFC-CBR Update WIT Unit Fabrication Cost Summary. The latest, now NASAP-informed, unit cost data for *Module D1-4* are in Table D1-4.15 below. Basically, this is the same data in the last two data rows of Table D1-4.10 and data rows 2,4, and 6 of Table D1-4.11, except that the unit cost values have now been escalated from either 2017$ or 2019$ to year 2020$. An escalation factor of 1.052 was used to escalate from 2017$ to 2020$ and a factor of 1.01 to escalate from 2019$ to 2020$. **The U,Pu MOX and UOX blanket data all benefit from the comparative 1978 NASAP study**. The all HALEUOX data are less reliable in the sense that there is no definitive cost estimate for such a facility capable of fabricating a large number of SFR startup cores. The numbers presented were based on interpolation of a unit cost versus U-235 assay plot presented in *Module D1-6A* for metal fuels. The all uranium metal unit costs in *Module D1-6A* were increased by a factor of 1.065 to account for the higher process complexity of a ceramic pellet process above that of the simpler casting process for metal fuel.

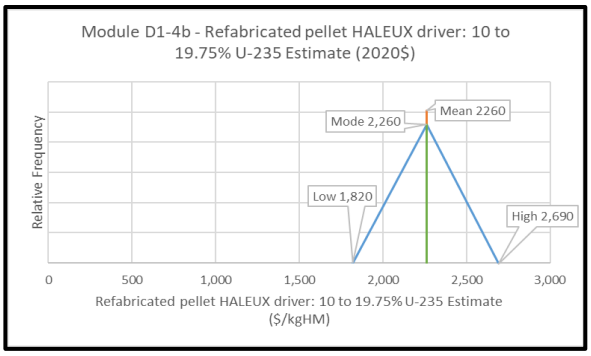
Table D1-4.15. What-it-takes low, mode, mean, high, and unit fabrication cost distribution type for all six *Module D1-4* SFR fuel variants (all levelized unit fabrication costs in 2020$/kgHM).

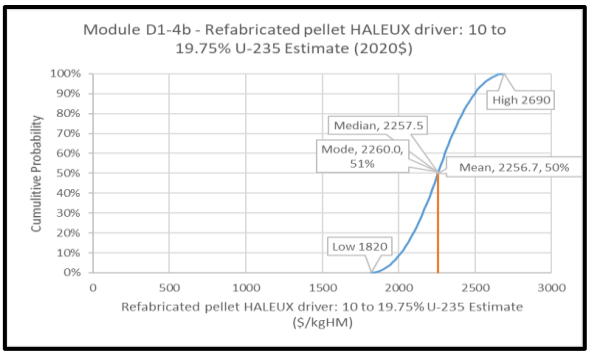
SFR ceramic oxide fuel variant	Low	Mode	Mean	High	Distribution type
Virgin pellet HALEUOX drivers: 10 to 19.75% U-235	1,183	1,398	1,398	1,613	Triangular
Refabricated pellet HALEUOX drivers: 10 to 19.75% U-235	1,818	2,259	2,255	2,689	Triangular
Lower assay HEUOX pellet drivers: 20 to 35% U-235	5,050	7,070	8,080	1,2120	Triangular
Fabricated U,Pu pellet MOX drivers (first pass: Pu from LWR-SNF aqueous reprocessing)	1,238	1,486	1,614	2,118	Triangular
Refabricated U,Pu pellet MOX drivers (second pass: Pu from SFR-SNF aqueous reprocessing)	1,655	2,049	2,244	3,027	Triangular
Pelletized DUOX or NATUOX SFR blanket fuel (0.2 to .71% U-235)	377	422	448	546	Triangular

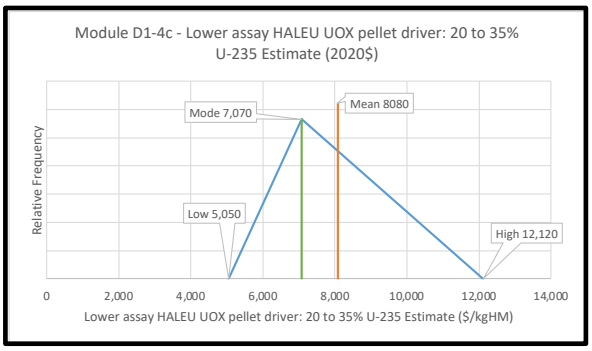
The triangular distributions based on the costs in Table D1-4- 14 are shown in Figure D1-4-4.

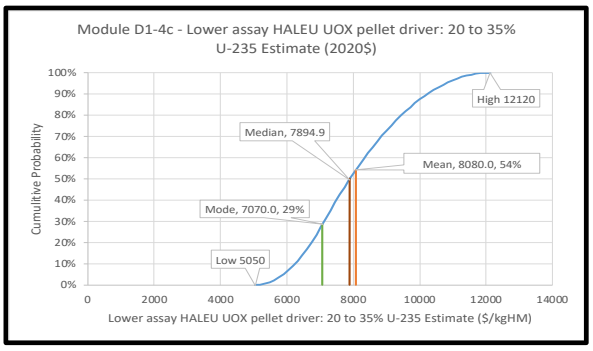

Module D1-4a - pellet HALEUOX drivers: 10 to 19.75% U-235 Estimate (2020$)
Relative Frequency
Mode 1,400
Mean 1400
Low 1,200
High 1,600
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
pellet HALEUOX drivers: 10 to 19.75% U-235 Estimate ($/kgHM)

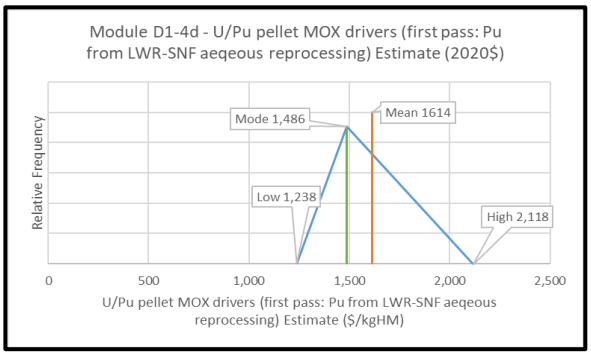

Module D1-4a - pellet HALEUOX drivers: 10 to 19.75% U-235 Estimate (2020$)
Cumulitive Probability
High 1600
Median, 1400.0
Mode, 1400.0, 50%
Mean, 1400.0, 50%
Low 1200
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
200
400
600
800
1000
1200
1400
1600
1800
pellet HALEUOX drivers: 10 to 19.75% U-235 Estimate ($/kgHM)

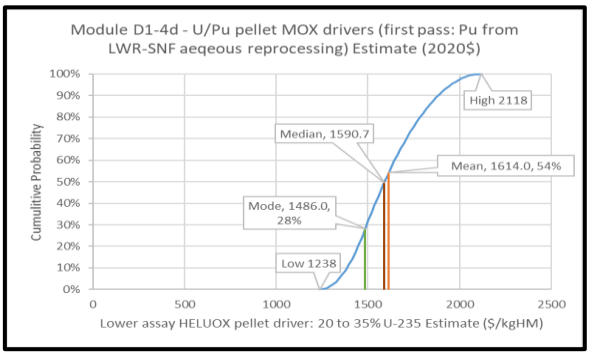

Module D1-4b - Refabricated pellet HALEUX driver: 10 to 19.75% U-235 Estimate (2020$)
Relative Frequency
Mode 2,260
Mean 2260
Low 1,820
High 2,690
0
500
1,000
1,500
2,000
2,500
3,000
Refabricated pellet HALEUX driver: 10 to 19.75% U-235 Estimate ($/kgHM)


Module D1-4b - Refabricated pellet HALEUX driver: 10 to 19.75% U-235 Estimate (2020$)
Cumulitive Probability
High 2690
Median, 2257.5
Mode, 2260.0, 51%
Mean, 2256.7, 50%
Low 1820
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
500
1000
1500
2000
2500
3000
Refabricated pellet HALEUX driver: 10 to 19.75% U-235 Estimate ($/kgHM)


Module D1-4c - Lower assay HALEU UOX pellet driver: 20 to 35% U-235 Estimate (2020$)
Relative Frequency
Mode 7,070
Mean 8080
Low 5,050
High 12,120
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
Lower assay HALEU UOX pellet driver: 20 to 35% U-235 Estimate ($/kgHM)


Module D1-4c - Lower assay HALEU UOX pellet driver: 20 to 35% U-235 Estimate (2020$)
Cumulitive Probability
High 12120
Median, 7894.9
Mean, 8080.0, 54%
Mode, 7070.0, 29%
Low 5050
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
2000
4000
6000
8000
10000
12000
14000
Lower assay HALEU UOX pellet driver: 20 to 35% U-235 Estimate ($/kgHM)


Module D1-4d - U/Pu pellet MOX drivers (first pass: Pu from LWR-SNF aeqeous reprocessing) Estimate (2020$)
Relative Frequency
Mode 1,486
Mean 1614
Low 1,238
High 2,118
0
500
1,000
1,500
2,000
2,500
U/Pu pellet MOX drivers (first pass: Pu from LWR-SNF aeqeous reprocessing) Estimate ($/kgHM)


Module D1-4d - U/Pu pellet MOX drivers (first pass: Pu from LWR-SNF aeqeous reprocessing) Estimate (2020$)
Cumulitive Probability
High 2118
Median, 1590.7
Mean, 1614.0, 54%
Mode, 1486.0, 28%
Low 1238
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
500
1000
1500
2000
2500
Lower assay HELUOX pellet driver: 20 to 35% U-235 Estimate ($/kgHM)

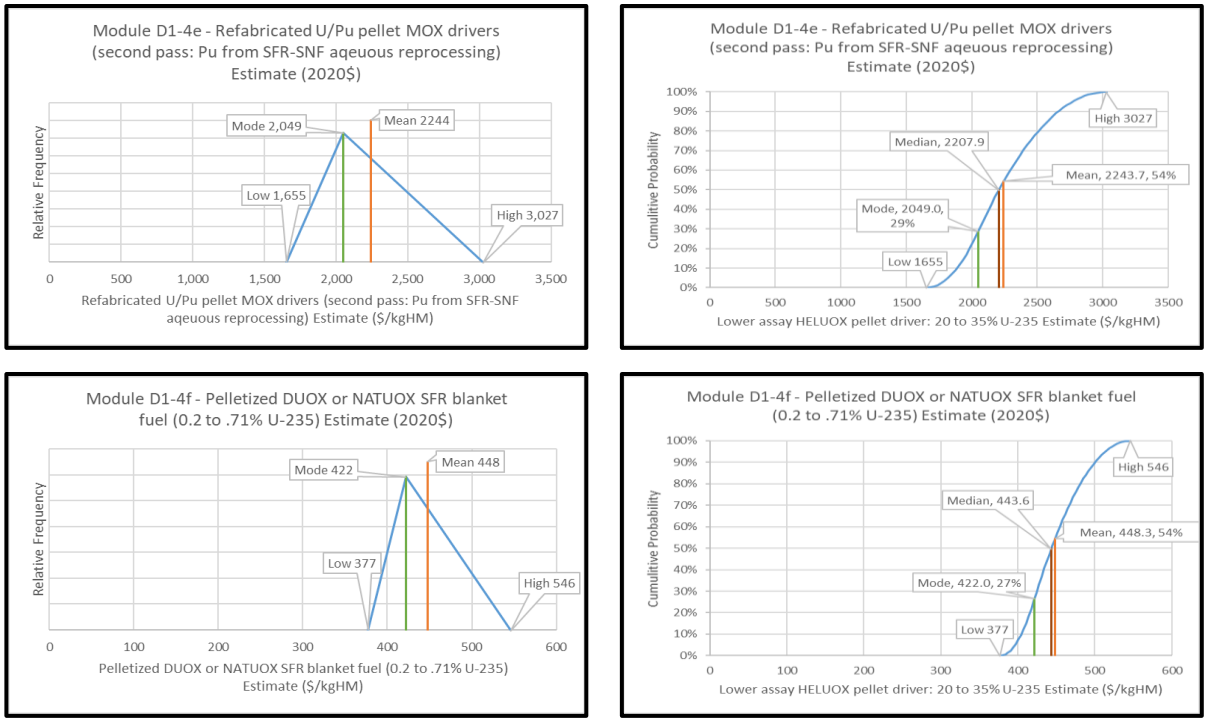


Figure D1-4-4. Ceramic pellet fast reactor fuel estimated cost frequency distributions.

D1-4-14. SENSITIVITY AND UNCERTAINTY STUDIES

Other than the NASAP cost versus plant size data discussed above, no other sensitivity studies were found in the literature or were performed by the author for this fuel type.

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Module D1-5
Ceramic Vibrocompacted Fuel Fabrication

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Module D1-5
Ceramic Vibrocompacted Fuel Fabrication

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

- **Constant $ base year 2020 for this FY-21 update.**
- Nature of this FY-21 module update from previous AFC-CBRs: this module includes a few new references and a somewhat expanded discussion of vibrocompaction fuel fabrication technology. The WIT values for VIPAC are pegged directly to those for conventional LWR and SFR pelletized U,Pu MOX (note that this module now includes VIPAC MOX fuel for LWRs in addition to SFRs). Based on information from Russia, where VIPAC has been studied extensively, the unit costs are expressed as a percentage of those in the new updated *Module D1-2* (pelletized U,Pu MOX) and new updated *Module D1-4* (pelletized U,Pu MOX) for large NOAK fabrication facilities of the same production capacity. Since both ceramic pelletized MOX *Modules D1-2* and *D1-4* benefitted from analysis of 1970s NASAP data, by extension this *Module D1-5* also benefits.
- Estimating methodology for latest (*2012 AFC-CBR*) technical update from which this 2017 update was escalated: Because of a simpler process flowsheet, NOAK VIPAC fuel unit costs assumed to be 10% lower than ceramic fast reactor fuel costs in *Module D1-4* and ceramic thermal reactor MOX costs in *Module D1-2*. In Russia, VIPAC fuel is at the pilot plant stage of development. Unit costs are given are for a hypothetical NOAK VIPAC facility in a robust process building under regulatory regime similar to current European pelletized MOX plants such as MELOX in France.

D1-5-1. BASIC INFORMATION

***2009 AFC-CBR* Status.** A vibrocompacted or VIPAC fast reactor fuel assembly appears identical to a pelletized ceramic fuel assembly on the outside. The fuel rods, however, initially contain vibrationally compacted, dense ceramic granulate (UOX or MOX) instead of stacked pellets. (Some metallic powder "getter" may be added to the oxide mix to improve the fuel performance characteristics.) As the VIPAC fuel is irradiated, the reactor thermal heat sinters the granulate into what is essentially a long pellet. The technical and cost advantage of this type of fuel is the elimination of the costly pressing, sintering, and pellet grinding/finishing steps in the usual MOX fuel fabrication process. This process was investigated on a bench scale in the United States several decades ago, and some fuel was irradiated in the Saxton (Pennsylvania) test reactor. There is still considerable interest in this process for fast reactor MOX in Russia and Japan. The Japanese have funded some Russian MOX vibro-fabrication work at the Russian Institute for Atomic Reactors (RIAR aka NIIAR) in Dimitrovgrad, and some test rods have been irradiated locally in the BN-60 and BN-600 at Beloyarsk (Mayorshin et al. 2000; Herbig et al. 1993). Figure D1-5-1. RIAR (Federal State Unitary Enterprise "State Scientific Center of Russian Federation–Research Institute of Atomic Reactors." Vibropacking technology description and advantages).

describes the purported advantages of vibropack technology as presented by RIAR. At one time, this technology was slated to play a role in the joint U.S./RF plutonium disposition program which has now been terminated.

There are several variations of VIPAC technology. Early techniques focused on granulate produced by crushing sintered ceramic pellets. More recent work outside Russia has focused on the use of sintered gel-spheres, and the associated technology is known as Sphere-Pac in reference to the resulting spherical

feed. The East German–Russian variant promoted vigorously by NIIAR uses a crushed glassy granulate resulting from electrochemical deposition of UO_2 or (U,Pu) O_2 out of a molten-salt solution.

VIPAC fuel fabrication is often paired with electrochemical fuel reprocessing (*Module F2/D2* type process but with ceramic rather than cast-metal fuel) in proposed fuel cycles because of the nature of the processes as explained below. One such fuel cycle is for the STAR-H2 reactor (the Secure Transportable Autonomous Reactor for Hydrogen, Electricity, and Potable Water Production). This is one of the metal-cooled reactor, ceramic-fueled concepts that has been studied under the Generation IV program by Argonne National Laboratory (Wade 2005) and would use a U,Pu-nitride fuel.

D1-5-1.1 2012 AFC-CBR Status

In this case, nothing has changed from the *December 2009 Advanced Fuel Cycle Cost Basis Report* in the areas of the basic industrial process under development for FR vibrocompacted (VIPAC) fuel fabrication and its interfaces to other fuel cycle steps. The method is still under consideration for the eventual production of some (Pu,U) O_2 driver fuel for the BN-800 series of FRs being constructed in Russia. As part of the former joint U.S./Russia Pu disposition agreement, the United States was to have made funds (~$400M) available to Russia for this now defunct non-proliferation program. Some of these funds were likely to have been used for design and construction of a pilot contact-handling fuel fabrication facility for BN-800 fast reactor mixed oxide fuel.

Functional and Operational Description

Vibrocompaction equipment (sieve-sizing, feeding, shaking) replaces pellet fabrication equipment for this type of fuel. Feed powder preparation, however, may be somewhat more complex for vibrocompaction than for pelletization and may arise from different sources. In Russia, the feed powder is usually in the form of tiny irregular shards rather than round or nearly-round particles. The oxide powder would actually be produced from an electrochemical process where oxide crystals are interspersed with other salts on an electrode. These other salts must be separated or washed away before the irregularly shaped shard-powder is sieved and prepared for vibrational compacting into fuel rods.

Particle fuel can also be used in the “sphere-pac” vibrocompaction process. In this case, the tiny spherical “kernels” would be produced by a sol-gel process that is essentially the front-end of the process for production of TRISO fuel. Particle fuel is discussed in *Module D1-3*, where a flowsheet for kernel production is presented.

D1-5-2. PICTURES AND DIAGRAMS

Figure D1-5-2 shows a conceptualized view of the “sphere-pak” VIPAC process. In the diagram, three particle sizes are chosen. Some VIPAC processes, such as the Russian RIAR one, have five particle sizes. The RIAR particles are not actually round, however, and exist as irregular shards that can be sized by sieving.

Figure D1-5-3 shows the overall VIPAC process as practiced at RIAR and how it meshes with their “dry” electrochemical reprocessing technology.

Fuel rods containing granulated fuel are fabricated using a standard vibropacking procedure (in glove-boxes or hot cells) which have been used at RIAR for about 20 years.

The main advantages of the vibropack technology and fuel rods with vibropack fuel are as follows:

- Simplicity and reliability of the production process due to a smaller amount of process and control operations facilitating automation and remote control
- Granulate of homogeneous composition can be used as well as in the form of mechanical mixture
- Lower (as compared with a pellet stack) thermal-mechanical impact of vibropack fuel on the cladding
- Less stringent requirements for the inner diameter of fuel rod claddings.

The fuel column is a mechanical mixture of (U,Pu) O_2 granulate and uranium powder, the latter having the function of a getter, and is added to a fuel-weighted portion at the stage of agitation before pouring. Getter addition for the regulation of the fuel oxygen potential and elimination of the effects of process impurities allowed for complete solution of the problem of chemical interaction of vibropack oxide fuel and cladding. The process provides for a 100% fuel column quality control including distribution of plutonium and density along the fuel column length. The uniform getter distribution is ensured by the vibration technology.

A number of studies were performed to verify the performance of fuel rods with vibropack oxide fuel, including the optimization of the fabrication and control technology as well as the performance of all required reactor tests (BOR-60, BN-350, BN-600) and post-irradiation material science examinations. Based on the testing results performed in the SM, BOR-60 and BN-350 reactors the basic parameters of fuel rod design for the BOR-60 and BN-600 reactors were optimized as well as the technological processes for production and control with consideration of remotely controlled operation.

Due to the fuel rod design optimization the world record burnup of 30% was achieved in the BOR-60 reactor.

Figure D1-5-1. RIAR (Federal State Unitary Enterprise “State Scientific Center of Russian Federation–Research Institute of Atomic Reactors.” Vibropacking technology description and advantages).

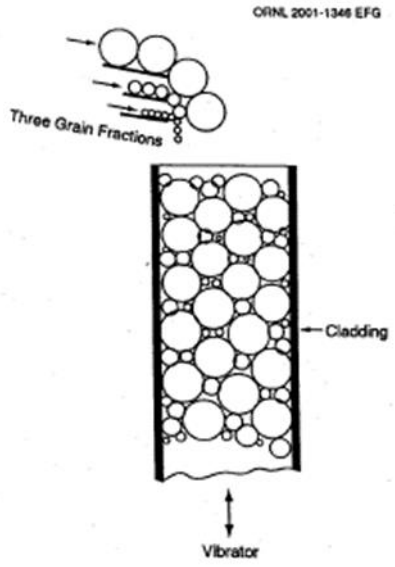

Figure D1-5-2. Conceptualized view of "sphere-pac" VIPAC as envisioned by ORNL researchers.

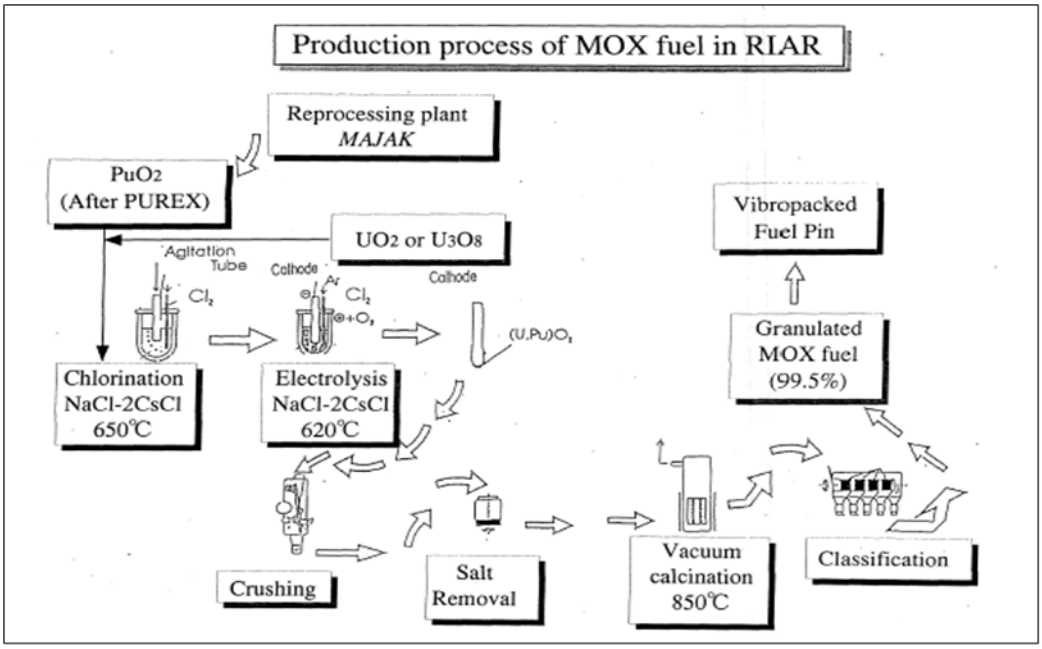

Figure D1-5-3. The VIPAC process and its relation to pyrochemical reprocessing technology as envisioned by the Scientific Research Institute of Atomic Reactors, Dimitrovgrad, Russia.

The Fuel Cycle section of the World Nuclear News website (WNA 2020) presents an excellent synopsis of MOX-based SFR fuel fabrication work worldwide, and it includes several mentions of current work in Russia on vibrocompaction.

D1-5-3. MODULE INTERFACES

The feed MOX mixture fed to the vibrator/tube-filler must have a very well-defined particle size distribution (enabled by sieving) and particle shape characteristics (small shards or crystals for the RIAR version or round kernels for "sphere-pac"). The powder characteristics of material coming from

electrochemical reprocessing techniques are better suited for the RIAR VIPAC scheme; however, it is still quite possible to modify the morphology of aqueous precipitation-derived MOX powders for VIPAC fabrication.

VIPAC feasibility has been examined for LWR fuels including UO_2. A DOE-NERI report (Kazimi 2002) suggests that spheroidal powder could be vibropacked ("sphere-pac") into annular cladding as one of several fuel options, which would allow higher power density and extended burnup with their beneficial economic consequences The higher fabrication costs for annular fuel are predicted to be overcome by the lower $/kWh fuel cycle cost component of the cost of electricity resulting from the use of less fuel. No detailed cases with cost numbers were presented in the report.

D1-5-4. SCALING CONSIDERATIONS

No data directly applicable to VIPAC were available. Any scaling would be similar to fast reactor pelletized MOX fuel facilities. Such data appears in *Modules D1-2* and *D1-4*.

D1-5-5. COST BASES, ASSUMPTIONS, AND DATA SOURCES

No direct unit fabrication cost information was found for Western or Japanese vibropacked fast reactor fuels; however, it is known that the Japanese considered VIPAC in their feasibility study (JAEA 2006) for commercialization of fast reactor fuel cycle systems. All that can be said is that proponents have roughly estimated that VIPAC unit costs should be 10 to 20% lower than for pelletized fuel unit costs. This NOAK estimate for mature technology does not include all the additional research and development, fuel qualification, and process qualification costs that would be involved with this type of fuel, and which might need to be amortized into the price of the fuel.

In 1998, Russian engineers prepared an unpublished 1998 cost estimate (IPPE 1998) for converting and operating the BN-600 Fast Reactor to a partial MOX core of vibropacked fuel as part of the joint U.S./RF Plutonium Disposition Program (Russian participant: State Scientific Center of Russian Federation–IPPE). Their estimate concluded that a BN-600 VIPAC fuel assembly could be produced for less than $100,000 per unit. Because each fuel assembly contains approximately 28.7 kg of heavy metal (MOX with >20% Pu O_2), a unit cost of ~$3,500/kgHM could be calculated for production from the pilot-plant sized facility (tens of kgHM/yr) that would need to be operated to supply these assemblies. Because this is a pilot scale facility number, it would be expected that a large fuel fabrication plant of this type could produce fuel at a lower cost. Converting the above Russian number to the U.S. wage rate and industrial conditions, however, would elevate the cost. Regulatory costs in the United States would also be higher.

An OECD report (NEA/OECD 2006) gives unit cost projections for advanced fast reactor fabrication and reprocessing steps in an integrated (one building) facility. For the fabrication step, which involved production by gelation[c] and vibrocompaction of spherical kernels, the following unit costs are given:

Present (2001): $4,900/kgHM

Future: $1,600/kgHM

These data are based on Japanese sources such as ICONE 8 papers.

c. Gelation of aqueously reprocessed derived U,Pu solutions rather than electrochemistry produces "rounder" particles which can be vibrationally compacted. Such a process is sometimes called "spherepak or sphere-pac."

D1-5-6. DATA LIMITATIONS

The Russian Federation is likely to have some limited cost data. However, it may be difficult to convert it to U.S. dollar equivalents for deployment in the West. The Russian VIPAC process is still at the bench scale level of development. Yet, funding from and cooperative work with Japan may allow for some larger scale fabrication. Via the Generation IV Economic Modeling Working Group (EMWG) JAEA could make available some cost projections on VIPAC fuel fabrication, which was part of one of the four fuel-cycle scenarios studied as part of their fast reactor fuel-cycle analysis (JAEA 2006).

D1-5-7. COST SUMMARIES

***2009 AFC-CBR* Cost Summary (*Module D1-5-1*).** The summary shows the reference cost basis (constant year US$), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this 2009 report for additional details on the cost estimation approach used to construct the WIT table.

Table D1-5-1. What-it-takes cost summary table.

What-It-Takes Table				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
Plant capital cost: No data available	N/A			N/A
Unit production cost: no validated data available	No data available	Could be cheaper process than pelletization (fewer steps)	Difficulties in development/ automation	$3,600/kgHM if VIPAC assumed 10% cheaper than the nominal pellet fast reactor MOX in the *2009 AFC-CBR*

***2012 AFC-CBR* Update Cost Summary.** The nominal unit fabrication cost of $3,600/kgHM in the *2009 AFC-CBR* was based on the assertion, largely derived from Russian sources, that the unit fabrication cost would be 10% lower than for pelletized contact-handled ceramic MOX FR fuel. If the same logic is applied the new value for VIPAC FR fuel fabrication will be a reduction of 10% from the 2012 (*Module D1-4*) nominal ceramic MOX FR value of $4,500/kgHM. The resulting *Module D1-5* value of $4,050/kgHM is rounded to $4,000/kgHM to indicate that the value is a rough approximation for a technology still under development. The same ~10% reduction is also applied to the low and high values.

It is important to note that VIPAC fuel fabrication would be more amenable to remote-handling (RH) FR fuel production than pelletization because of process simplicity. The Russians have studied this method as a refabrication process in conjunction with electrochemical reprocessing at Dimitrovgrad.

Table D1-5.2. Year 2012$ "what-it-takes" vibrocompacted fast reactor fuel fabrication unit.

Fuel Type	Low Value (2012 $/kgHM)	Medium or Ref Value (2012 $/kgHM)	High Value (2012 $/kgHM)

(U,Pu) O_2 VIPAC MOX Fuel	2300	4000	6300

***2017 AFC-CBR* Update Cost Summary.** Since the VIPAC unit costs are estimated at ~10% lower than pellet MOX (*Module D1-2*), it was necessary to reset these *Module D1-5* costs as a result of the lowering of the 2017 *Module D1-2* "WIT" costs from those of the *2012 AFC-CBR*. This D1-2 unit cost reduction was the result of removing the deleterious U.S. cost and schedule experience with the SRS-MFFF.

The following Table D1-5.2 updates the *Module D1-5* costs in year 2017 dollars to be consistent with the *Module D1-2* NOAK, mature European experience unit costs.

Table D1-5-3. Year 2017$ "what-it-takes" vibrocompacted fast reactor fuel fabrication unit.

Fuel Type	Low Value (2017 $/kgHM)	Mode (2017 $/kgHM)	Mean (2017 $/kgHM)	High Value (2017 $/kgHM)
(U,Pu) O_2 VIPAC MOX Fuel	720	900	1020	1440

***2020 AFC-CBR* Update Cost Summary**. For this 2020 update a quick web-based literature survey was conducted to see if new cost data, particularly from Russian sources, was available. No new cost data was found, however other useful deployment plans for VIPAC were found. It is known that Russia has successfully irradiated full VIPAC fuel assemblies in their BN-600 SFR at Beloyarsk and is also considering their use in the larger BN-800 SFR. They have recently announced that VIPAC fuel will be used for the 100 MW(th) MBIR materials test SFR at RIAR in Dimitrovgrad. Since the VIPAC WIT unit costs are keyed to the *Module D1-4* pelletized U,Pu SFR MOX unit costs (a 10% reduction in unit cost from pelletized SFR MOX), it was deemed necessary to similarly key the 2020 WIT VIPAC unit costs in this document to the new NASAP-informed 2020 WIT costs presented in *Module D1-4*. The same 10% reduction factor is applied thereto. Since VIPAC has also been suggested as a production technology for LWR U,Pu MOX fuel, a set of WIT values has also been calculated by taking a 10% reduction from the "first-pass" LWR pelletized U,Pu MOX WIT unit cost values in *Module D1-2*. Table D1-5.4 presents these revised WIT VIPAC unit costs in year 2020 dollars:

Table D1-5.4. Year 2020$ what-it-takes unit fabrication costs for VIPAC U,Pu SFR and LWR U,Pu MOX fuel for *Module D1-5* of this *AFC-CBR* ($/kgHM).

Fuel Type	Reference Unit Cost	Low	Mode	High	Distribution Type	Calculated mean
a) VIPAC U,Pu SFR MOX	n/a	1114	1338	1906	Triangle	1453
b) VIPAC U,Pu LWR MOX	n/a	637	819	1287	Triangle	914

These unit costs assume the granulated feed material is supplied to the fabricator at no cost. Any special spheroidization or conversion costs are in another part of the overall fuel cycle. It should be recognized that the unit costs above are for a mature, developed VIPAC technology deployed in a NOAK facility support in a large fleet of SFRs or LWRs. Since the intent of this is to do a technoeconomic evaluation based on fuel attributes and process differences in fuel fabrication methods, the use of the 10%

reduction factor from palletization technology was felt to be appropriate for NOAK plants of the same capacity. An unknown factor is whether the cost reductions due to pellet processing steps eliminated by use of VIPAC might be offset by the need for more smaller rod diameter fuel assemblies than required by pellet technology. The reduced fissile heavy metal density associated with VIPAC could result in lower burnup and increased annual fuel consumption by the reactor.

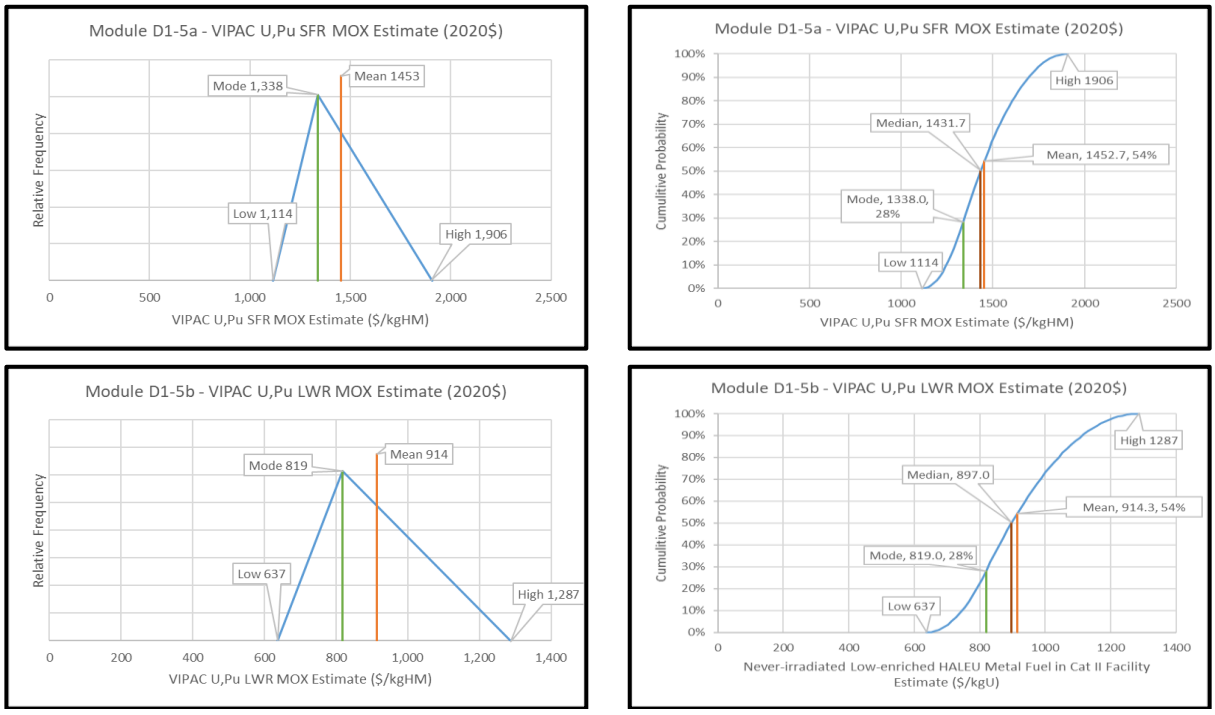

Figure D1-5-4. Probability distribution for VIPAC MOX unit fuel fabrication cost.

D1-5-8. SENSITIVITY AND UNCERTAINTY ANALYSIS

No new data provided at this time. The unit cost versus plant capacity sensitivity would be very similar to that presented in *Modules D1-2* for LWR MOX and D1-4 for SFR MOX.

D1-5-9. REFERENCES

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