Advanced Fuel Cycle Cost Basis Report:

Module D1-6A Contact-Handled All-U Metal or U-Metal Alloy Uranium Fuel Fabrication

Module D1-6B Contact-Handled U,Pu Metal Alloy Fuel Fabrication

Nuclear Fuel Cycle and Supply Chain

Prepared for

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Systems Analysis and Integration

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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004		Version of AFC-CBR in which this module first appeared: 2004 as Module D1-6. In the 2017 update (Dixon et al. 2017), the name was changed from "Metallic or Alloyed Fast Reactor Fuel Fabrication" to "Metallic or Alloyed Fuel Fabrication." This reflects the fact metal fuel is being considered for thermal light-water reactors (LWRs) in addition to fast reactors. In this 2021 update version, Module D1-6 has been split into Module D-1-6A for contact-handled uranium metal fuels and Module D1-6B for those contact-handled fuels containing both metallic Pu and U.
			Latest version of module in which new technical data was used to establish cost ranges: this will be the first AFC-CBR update with cost basis discussion and selection of "what-it-takes" unit cost ranges for uranium fuel types of various U-235 content or "U-235 assay." Among the cost references utilized was a 1979 fuel fabrication study by Oak Ridge National Laboratory (ORNL) (Olsen et al. 1979c).
			• New technical/cost data which has recently become available and will benefit a next revision: - Continuing development and testing of Lightbridge (now EnFission) all-metal LWR fuel - Continuing studies (Adams 2017; Merrifield and Leidich. 2018; Tschiltz and Pierson. 2018) on use of HALEU (high-assay low-enriched uranium) for use in Generation IV reactor concepts, small modular reactor concepts, and microreactor concepts and for starting a fleet of fast reactors - Further economic studies on ATFs (accident tolerant fuels), some of which are uranium metal-based - Further economic feasibility studies on microreactors (Siciliano and Siegel 2019; Williams 2018; Nichol and Desai 2019) and space reactors.
			• Forthcoming Module C3 will discuss HALEU enrichment and deconversion/metallization of the resulting EUF6 product: - These steps are important front-end precursor steps to fabrication of HALEU-metal fuels.

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ACKNOWLEDGEMENT

This latest version of *Module D1-6A Contact-Handled All-U Metal or U-Metal Alloy Uranium Fuel Fabrication and Module D1-6B Contact-Handled U,Pu Metal Alloy Fuel Fabrication* is the cumulative effort of many authors who have contributed to the *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 developing and writing this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. Jason Hansen (Idaho National Laboratory, jason.hansen@inl.gov) and Edward Hoffman (Argonne National Laboratory, ehoffman@anl.gov) can be contacted with any questions regarding this document.

ACRONYMS

AFC-CBR	Advanced Fuel Cycle Cost Basis Report
ALARA	as-low-as reasonably achievable
ANL	Argonne National Laboratory
ANL-W	Argonne West
ATFs	accident tolerant fuels
ATR	Advanced Test Reactor (INL)
BWXT	BWX Technologies, Inc.
C	Celsius or centigrade
CaF_2	fluorspar (calcium fluoride)
CANDU	Canada deuterium uranium
CEA-NEA	French Atomic Energy Commission-Nuclear Energy Agency
CM	contact maintenance
CRBRP	Clinch River Breeder Reactor
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
DU	depleted uranium
DUF6	depleted-uranium hexafluoride
EBR	Experimental Breeder Reactor
EBR-I	Experimental Breeder Reactor-I (aka CP-4)
EBR-II	Experimental Breeder Reactor-II
ERDA	Energy Research & Development Agency
EU	European Union
EU	enriched uranium
EUF6	enriched-uranium hexafluoride
F2	molecular fluorine gas
FCF	Fuel Conditioning Facility (INL)
FCRD	Fuel Cycle Research and Development (Program of DOE-NE)
FFTF	Fast Flux Test Facility
FMEF	Fuels Manufacturing and Examination Facility
FMF	Fuel Manufacturing Facility
FOAK	first-of-a-kind
FP	fission product
F	fissium

GE	General Electric
GNEP	Global Nuclear Energy Partnership
HALEU	high-assay low-enriched uranium
HA	higher actinide
HEU	highly enriched uranium
HF	hydrogen fluoride
HFIR	High-Flux Isotope Reactor (ORNL)
HM	heavy metal
HTGR	high-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
IFR	integral fast reactor
INFCE	international nuclear fuel-cycle evaluation
INL	Idaho National Laboratory
KRUSTY	Kilopower Reactor Using Stirling Technology (NASA)
LAMPRE-I	Los Alamos Molten Plutonium Reactor Experiment
LEHEU	low-assay high-enriched uranium
LEU	low-enriched uranium
LEUOX	low-enriched uranium oxide
LMFBR	liquid metal fast breeder reactor
LWR	light-water reactor
MAGNOX	MAGnesium Non-Oxidizing (a UK fuel for AGRs)
MEU	medium-enriched uranium
MFFF	MOX Fuel Fabrication Facility
MOX	mixed oxide fuel
MP	melting point
MPC&A	material protection, control, and accountability
MT	metric ton or tonne
MTF	INL's Manufacturing Test Facility
MTHM/yr	metric ton of heavy metal/year
MTU	metric tons of uranium
MTW	metropolis works (U3O8 to UF6 conversion facility in S. Illinois)
MW	megawatt
MWe	megawatt electrical
MWth	megawatts thermal
NA	North American

NASAP	Nonproliferation Alternative Systems Assessment Program
NATU	natural uranium
NFS	Nuclear Fuel Services (Erwin, TN)
NNSA	National Nuclear Security Administration
NOAK	Nth-of-a-kind
NRC	Nuclear Regulatory Commission (U.S.)
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PHWR	pressurized heavy-water reactor
PRISM	high-energy neutron (fast) reactor (a GE concept)
Pu	plutonium
PUREX	plutonium uranium reduction extraction
PWR	pressurized-water reactor
R&D	research and development
RD&D	research, design, and development
REPU	reprocessed uranium
RM	remote maintenance
RO	remote operations
ROSATOM	Russian Atomic Energy Agency
RR	research reactor
SA&I	Systems Analysis & Integration Team
SBIR	Small Business Innovation Research
SFR	sodium-cooled fast reactor
SMR	small modular reactor
SNF	spent nuclear fuel
SRS	Savannah River Site
SWU	separative work units
Th	thorium
TRIGA	Training, Research, Isotopes, General Atomics
U	uranium
UC	uranium carbide
UF_4	uranium tetrafluoride (aka “green salt”)
UF_6	uranium hexafluoride (aka “hex”)
UK	United Kingdom
UNH	uranyl nitrate hexahydrate

UO_2	uranium dioxide
UOC	uranium ore concentrate
UOX	uranium oxide
USAEC	United States Atomic Energy Commission
USNRC	United States Nuclear Regulatory Commission
VTR	Versatile Test Reactor (proposed INL project)
WG	weapons-grade
WIT	what-it-takes
Zircatec	Zircatec Precision Industries, Inc. (Canada)
Zr	zirconium

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Module D1-6A
Contact-Handled All U-Metal or Metal Alloy Uranium Fuel Fabrication

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MODULE D1-6A CONTACT-HANDLED ALL U-METAL OR METAL ALLOY URANIUM FUEL FABRICATION

MODULE D1-6A: SHORT DESCRIPTION OF THE METHODOLOGY USED FOR THE REESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant U.S. Dollar (USD or $) Base Year 2020 for this Fiscal Year (FY) 2021 Update.**
- **Nature of this FY-21 Update from Previous Advanced Fuel Cycle Cost Basis Report (AFC-CBR) Versions:** Module D1-6A was created to separate uranium (U) metal fuels from those containing both U and plutonium (Pu) (Module D1-6B). This module also contains significantly more technical background and fuel manufacturing and usage history, fabrication process descriptions, cost basis information, and inclusion of unit cost in the what-it-takes (WIT) format used for all other AFC-CBR modules.
- **Estimating Methodology for Latest (2017) Technical Update Which Escalated this FY-21 Update:**
  - No cost data were presented in the 2017 version (Dixon et al. 2017); hence, no escalation is applied here.
  - The 1978 NASAP life cycle cost data (Olsen et al. 1979c) for depleted-uranium (DU) metal blanket fuel fabrication has been analyzed and escalated to support this FY-21 update.
  - Unit fuel fabrication costs for U-metal fueled, non-electricity producing reactors are discussed briefly in this update.
  - The 2017 AFC-CBR (Dixon et al. 2017) mentioned the ongoing Lightbridge Corporation effort to develop all-metal LWR fuel; however, no unit fabrication cost information or business case information was available. This FY-21 update includes some economic justification information from the Lightbridge presentations.

D1-6A.1. BASIC INFORMATION

In previous AFC-CBDs and updates, this “Basic Information” section (Section D1-6.1) constituted most (only one page) of the total Module D1-6, since no or little metal fuel cost information was available for further analysis and subsequent discussion. For this expanded module, this introductory section will be used to describe some of the characteristics, advantages, and disadvantages of U-metal alloy fuel. Below we will deal with uranium containing only fissile material in the form of the isotope U-235 at various assays in the overall U part of the fuel meat. U-233, like Pu, is a man-made fissile material, and it is produced by irradiating thorium-232. It has only been made in small quantities (< 10 MTU) and is not likely to enjoy large scale use in reactor systems for several decades from now. Depending on the irradiation scheme used to prepare it, and the separations flowsheet required to recover it, U-233 may require remote-handling to fabricate fuel from it. For these reasons, it is not discussed any further in this module. Thorium/U-233 use is discussed in Module D1-8 of the 2017 AFC-CBR (Dixon et al. 2017). (Module D1-8 is not being updated for this revision.)

Characteristics of U-Metal as a Fuel Material. U metal is the most dense (19.1 g/cm3) chemical form of U and therefore enables a high-fissile U-235 density (g of U-235 per cm3) of fuel meat (depending on enrichment level). This criterion is best for assuring a critical mass in the smallest possible volume. U-metal has a melting point of 1132°C, which is lower than that of its ceramic compounds such as UO2 (melting point [MP] of 2865°C) and UC (MP of 2350°C). It is a somewhat reactive metal which is readily oxidized in air and water with reaction rates depending on its morphology and temperature. Finely divided U-metal such as shards and powders are pyrophoric and readily ignite in the open air. The advantages of U-metal are (1) high-thermal conductivity compared to ceramic fuels, allowing a low fuel rod centerline temperature, (2) the ease with which metallurgical operations, such as alloying, extrusion, casting, and forging, can be accomplished, (3) due to its high-fissile density, the capability for high burnup associated with the possibility of higher neutron fluxes (provided issues of fuel swelling, fission gas behavior, and cladding performance) can be resolved, and (4) the considerable industrial experience over the past 75 years in its handling and fabrication. A short U-metal fabrication and in-reactor usage history will be given below. Disadvantages include (1) bare U oxidizes readily in air and water, especially at higher temperatures and high humidity, (2) generally requires the alloying of U with zirconium (Zr), aluminum (Al), molybdenum, or other non-radioactive metals to reduce corrosion and the fuel rod-deforming stresses of irradiation—one of which is swelling, and (3) the need to provide a cladding with a less reactive metal and an interfacing method for readily transferring heat from the fuel meat to the clad, such as the use of sodium bonding as a fabrication process step.

Factors Affecting Unit Cost. Since this document deals with life cycle costs, the multiple factors affecting the unit cost ($/kgU) for metal fuel must be addressed. These are:

- The temperature and neutron flux to which the fuel will be exposed (i.e., the irradiation robustness of the fuel).
- The coolant and moderator to which the hot fuel will be exposed.
- The scale of production (MTU/yr). In this report, we are interested in Nth-of-a-kind (NOAK) unit production cost for producing enough fuel in a stand-alone facility to support a fleet of reactors with a particular mature fuel design.
- The level of U enrichment (percent of fissile U-235) in the fuel. Because of criticality safety, physical security, material accountability, regulatory, and national security issues, the enrichment level has a large effect on life cycle costs for a facility. The fuels we will be discussing below have U-235 assays ranging from DU (U235 < 0.71%) for fast reactor (FR) target fuel rods to highly enriched U (or HEU) (HEU > 20% U-235) for small compact reactors. For nonproliferation policy reasons, use of fuel greater than 20% U-235 is highly discouraged for any new civilian reactor designs. High-assay low-enriched U (HALEU) in the range 5% <U-235 < 20% is presently of the most interest for new, advanced reactor concepts.
- The complexity of the final fuel product. For some research reactor (RR) fuels, the fuel form is highly complex requiring multiple metallurgical processing steps.
- The source and form of the feed to the manufacturing facility. Chemical treatment or conversion might be required for some feed forms such as UF6, U3O8, or reprocessed U salts. Ore, or yellowcake or natural U3O8, natural U3O8 to natural UF6 conversion, and enrichment (separative work) costs are not to be included in the unit fabrication cost. These costs are considered in separate AFC-CBR modules.
- The complexity of the non-fuel meat hardware in the rod and fuel assembly. Both alloying metal and hardware (purchased and on-site manufactured) costs should be included in the unit fabrication cost.

Potential Markets for U-Metal-Based Fuels. The following uses for U-metal or U-metal alloy fuels could provide future markets for this fuel type or the continuation of existing markets.

- Future metal-fueled sodium-cooled FRs might operate in a Pu-breeding mode, where DU-metal or natural U (NATU)-metal target rods are required for the radial blankets and DU-metal slugs required for the ends of the enriched-U driver fuel rods, thereby constituting an axial blanket function. The irradiated blankets and drivers would be reprocessed to recover fissile Pu for refabrication into (U, Pu) metal alloy rods, the subject of Module D1-6B. The market provided by a fleet of breeder reactors could be large but probably decades in the future. Depleted metal handling is a mature, state-of-the-art technology with this material being fabricated into military tank armor, armor-piercing ordnance, counterweights, and bulk radiation shielding. Brown, Croff, and Haire (1997) discuss beneficial uses of DU.
- Mostly or all-metal U-alloy rods are being studied for use in existing and future light-water reactors (LWRs) The Lightbridge/EnFission fuel concept (Malone 2011; Totemeier 2018) would utilize HALEU of around 19.95% U-235. Advantages of this metal fuel would include the ability to remove heat rapidly, with power uprates as a possibility, and higher fuel burnup with less refueling downtime and less fuel usage. The market for this type of fuel could develop as a growing substitution market for ceramic U oxide (UOX) LWR fuel. The issue of HALEU and its availability is discussed in the preface to the overall D Modules (Module D1-PR) and in a new AFC-CBR Module C3.
- Many advanced reactor concepts require metallic HALEU as a fuel source. (HALEU enrichments range from greater than 5% U-235 up to 19.95% U-235). Nuclear Energy Institute (NEI) has estimated (Herczeg 2019) a cumulative need for ~600 metric tons of U (MTU) of this material through 2030. Much of it will be needed for commercialization of advanced concepts such as the sodium-cooled fast reactors (SFRs), which would likely be started up on HALEU until a (U,Pu) metal fabrication technology could be commercialized (also addressed in Module D1-6B). Future Pu metal would have to be recovered from the reprocessing of LWR used nuclear fuel and chemical reduction of the resulting PuO2 or nitrate solutions. Starting up a series of FRs in the United States might require HALEU-metal fuel fabrication capacity in the range 600 to 1,200 MTU/yr. Eventually these reactors would be converted over the burning of multi-actinide (U, Pu, Np, Am, Cm) refabricated metal fuels requiring remote refabrication.
- Some microreactors (of < 1 MW power capacity) would require the use of HALEU or possibly even the use of LEHEU (low-assay high-enriched U) of assay range 20 to 50% U-235 (Williams 2018). Other specialty uses of this class of U-metal include RRs (a 5+MTU/yr market) and targets for fission product (FP)-derived radiopharmaceutical production. An international effort has been underway to convert most of the world's RRs from enrichments greater than 20% (HEU) to enrichments less than 20%. This change is driven by nonproliferation objectives.
- Other specialty uses for metal fuel include the fabrication of HEU into fuel for military production reactors (a former use), maritime propulsion reactors, and space reactors. A few large RRs, such as High-Flux Isotope Reactor (HFIR) and Advanced Test Reactor (ATR) in the United States, still utilize HEU to maintain high neutron fluxes for research customers. These HEU-metal fuel applications also constitute a specialty fuel fabrication market of a few MTU per year.

History of U-Metal Fuel Fabrication. The following historical information is given to provide the reader with the wide international scope of experience in the fabrication of U-metal fuels over the last 77 years:

- The first fission reactor (CP-1) constructed at Stagg Field at the University of Chicago in the fall of 1942 contained 4.9 MT of NATU in the form of multiple pseudospheres enclosed by graphite moderator blocks. Also 41 MT of UOX was used in this 0.5-watt(th) reactor which did not have a coolant or a biological shield. Most of this U and UO2 were provided by a quickly constructed processing plant and foundry operated by Mallinkrodt Chemical Company in St. Louis, MO.
- The Graphite Reactor, constructed at Oak Ridge, TN in 1943 to demonstrate Pu production as part of the Manhattan Project, was fueled with ~30 MT of extruded NATU slugs jacketed with Al. This relatively low-power 500kW(th) reactor required fuel jacketing with Al to prevent corrosion of the U and the small amount of Pu produced in each slug. Mallinkrodt provided the U-slugs and Alcoa the Al jacketing. At full production, the Graphite Reactor required a fuel feedrate of 0.3 MTU/day.
- The Manhattan Project production reactors at Hanford, WA, such as the "B" Reactor were based on the same fueling concept as the Graphite Reactor. The 1-inch diameter by 3-in.-long slugs were also jacketed with Al. The B reactor had a core of 180 MTU. The Hanford reactors were graphite-moderated and utilized NATU fuel. Later Hanford reactors utilized slightly enriched 0.85 to 1.3% U-235 to provide more neutrons for Pu production.
- The UK developed the magnesium non-oxidizing (MAGNOX) (Jensen and Nonbel. 1998; WNA 2023) gas-cooled reactors to provide both electricity and Pu for their nuclear weapons program. Because of the higher temperature needed for thermodynamically efficient power production, the NATU fuel had to be clad with a more heat and radiation resistant material which would still effectively contain FPs. The temperature was limited to 415°C; hence the thermodynamic efficiency of the reactors was low (~28%) compared to today's LWRs achieving 33+%. MAGNOX also reacted with water, so the reactors were cooled with dry CO_2, with a graphite moderator, and the spent fuel could not be kept in pools. This fuel required immediate reprocessing. The fuel fabrication took place at the Springfields Plant in the northwest of England. Over a 50-year period, over 5-million NATU MAGNOX fuel elements were produced. Each element is a cast U bar approximately 2.8 cm in diameter and 1 meter long. Figure D1-6A.1 (BNL 1968) shows a photo of a MAGNOX fuel rod.

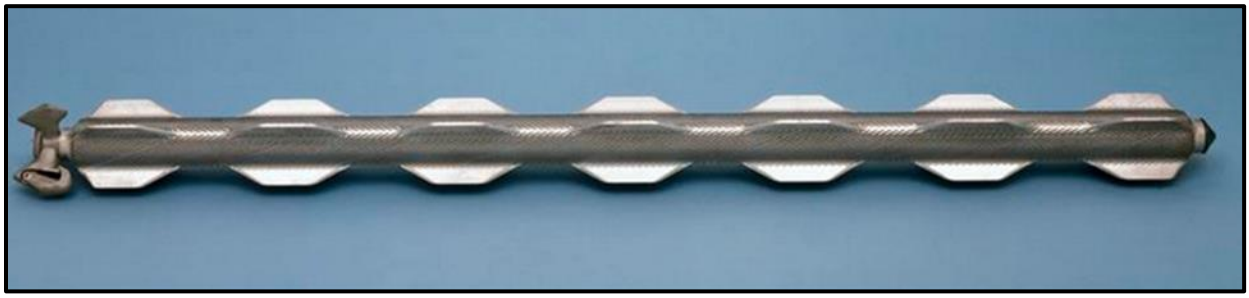


Figure D1-6A.1. A Uranium-based MAGNOX fuel rod of the type used at Sizewell A in the UK.

The MAGNOX cladding has fins to provide efficient heat transfer to the CO2 coolant. The fleet of MAGNOX reactors required a fuel fabrication production rate (at the Springfields) of over 1,000 MTU/yr, which is comparable to a large low-enriched UOX (LEUOX) fuel fabrication plant in the United States. In the later years of the Springfields operation, Westinghouse was the operating contractor.

- Second generation production reactors in the United States were fueled with HEU). The "P," "K," and "L" reactors constructed in the 1950s at the Savannah River Site (SRS) near Aiken, SC were low-temperature heavy-water moderated and cooled, with no electricity production, thus Al could be used for the cladding. Targets of DU were also prepared for efficient Pu production. The driver fuel

and targets were concentric U tubes, co-extruded with Al cladding. The fuel was very amenable to aqueous reprocessing for separation of Pu and separation of reprocessed U which still was highly enriched and valuable. Several other sites contributed to fuel/target manufacturing:

- The Fernald (National Lead Co) conversion facility and foundry site in southwest Ohio for U-slugs (U.S. DOE 1996).
- The Ashtabula (northeast Ohio) Plant (operated by Reactive Metals, Inc.) for rough extrusion of U-metal tubes (U.S. DOE 2022).
- The 300-M-area fuel plant at SRS for final U metal co-extrusion with the Al cladding for both driver fuel and targets. Over 2,000 MTU/yr was processed at SRS.

When this military production enterprise was at full operations (1950s through 1988) over 100 MTU/yr were handled, some of it DU material and some of it highly enriched U.

- Many small RRs, such as owned by universities and smaller research institutions, are operated with U-metal alloy fuel which is generally more complex in design and to manufacture than the slug type fuel used for materials production and power applications. RR fuel takes several chemical forms, with the most common being U-Al alloys, and UOX or U silicide dispersed in an Al matrix, as well as the quasi-metallic U-Zr hydride fuels used by Training, Research, Isotopes, General Atomics (TRIGA) (TRIGA n.d.) reactors. The fuel geometry is often in the form of plates or tubes made by extrusion and rolling operations. New fuel technologies are under development to provide a higher U density in the fuel meat to enable the HEU to low-enriched U (LEU) conversion, for nonproliferation objectives, of certain high performance RRs. These high-density fuels may also provide an option for reducing fuel-cycle costs, even for those reactors that can operate with existing fuel types. Most RR fuels are produced by privately owned specialty fuel fabricators and sold to RR operators as a complete package that includes both fuel fabrication and the enriched U. TRIGA HEU reactor fuel was manufactured from the 1950s until 1996 by General Atomics Corp in La Jolla, CA. This fuel is now manufactured in France by CERCA, a subsidiary of AREVA, at Romans-sur-Isere. Babcock and Wilcox also manufacture RR fuel in their Category I facility at Lynchburg, VA. (Fuel facility safeguards and security Categories I-III are discussed in the “HALEU Considerations” section of Module D-1.PR in this series of 2021 update reports.) Small reactor fuel manufacturing campaigns are generally less than 1 MTU/yr.
- The 1.1 MWth Experimental Breeder Reactor-I (EBR-I aka CP-4) was commissioned near Idaho Falls, ID in 1951 and operated until 1963 (Vam Jaaftem and Turner 1979). The EBR critical mass consisted of 52 kg of U-235 HEU in the form of pins and was about the size of a U.S. football. The total U mass would have been around 100 kgU with an enrichment of over 50% U-235. U-metal fuels used in EBR-I consisted of unalloyed HEU (Core 1) and U-Zr alloys (Cores 2 and 3). Cylindrical pin diameters were slightly less than 1 cm for all three U cores. (A fourth core using a metallic Pu-Al alloy was introduced toward the end of the EBR-I campaign.) The first two cores were clad in stainless steel and the last two with zircalloy. Zr was found to enhance the radiation resistance of the fuel, resulting in less geometric deformation of the pins. This reactor was the first to demonstrate that breeding could produce more fissile atom than are consumed. The fuel pins were fabricated and clad in a small manufacturing facility also on the Idaho Falls reservation.
- The 62 MWth Experimental Breeder Reactor (EBR-II) was commissioned near Idaho Falls, ID in 1964 and operated until 1994. It was intended to demonstrate the concept of breeding Pu using a heterogeneous driver/blanket fuel arrangement in the reactor core, and its adjacent support facilities were operated to demonstrate non-aqueous, or dry, pyrochemical reprocessing of spent fuel and its refabrication (a subject covered in Module D2/F2 and Trybus et al. 1993). The fuel consisted of stainless-steel clad U-containing rods 5 millimeters in diameter and 33 cm (13 inches) long. A typical rod had a mass of 65 to 70 grams of U. Enriched to 52 to 70% U-235 when fresh, the U-235 concentration dropped a few percent upon discharge due to fissioning. Most of the metal alloy rods

also contained 10% Zr; however, the early cores contained 5% fissium (Fs), a non-radioactive group of elements meant to act as a surrogate for real FPs. This substitution was done to study cladding-FP interactions under irradiation. Each fuel element is placed inside a thin-walled stainless-steel tube along with a small amount of sodium metal. The tube is welded shut at the top to form a unit 73 cm (29 in.) long. The sodium-bonding functions as a heat-transfer enhancement agent. As more and more of the U rod undergoes fission, it develops fissures, and the sodium enters the voids. Excellent production history information was available from References D1-6A.28 through D1-6A.32. The enriched-U fuel was manufactured on the Idaho Falls site, with over 120,000 metal fuel rods (~8 MTU) produced on the Idaho site. In addition, 48,000 of these HEU fuel pins were produced by on-site contractors Aerojet General Nuclear and Atomics International using contact-handled fabrication, as well as at the Argonne West (ANL-W) (Idaho) coldline. The 35,000 pins were remotely fabricated in the EBR-II Fuel Cycle Facility (ANL-W hotline). The maximum annual fabrication rate was on the order of 1.6 MTU/yr. Five cores were produced with the following compositions: Mark I U-5%Fs, Mark II U-10%Zr and U-5%Fs, Mark III U-10%Zr, Mark IV U-10%Zr with different clad, and Mark V U-20%Pu-10%Zr. Clusters of the pins inside hexagonal stainless-steel jackets 234 cm (92 in.) long were assembled honeycomb-like; each multi-pin unit has about 4.5 kg (10 lb) of U. Altogether, the core contains about 308 kg (680 lbs.) of U fuel.

- The Fast Flux Test Facility (FFTF) is a 400 MWth, liquid-sodium-cooled, nuclear test reactor owned by the U.S Department of Energy (DOE) (WNA n.d.; Adams 2017). It does not generate electricity. It is situated in the 400 Area of the Hanford Reservation in the state of Washington. The construction of the FFTF was completed in 1978, and the first criticality took place in 1980. From April 1982 to April 1992, it operated as a national research facility to test various aspects of commercial reactor design and operation, especially relating to breeder reactors; however, the FFTF is not a breeder reactor. The FFTF tested advanced nuclear fuels (both metal and ceramic), materials, non-fuel components, nuclear power plant operations and maintenance protocols, and reactor safety designs. The reactor at first operated with ceramic oxide fuels (see Module D1-4) but was converted over to metal fuel toward the end of its operating life. Over 1,000 U-Zr and U-Pu-Zr fuel rods were irradiated at FFTF. Over 800 HT9-clad U-10Zr fuel elements, 91.4 cm tall, were irradiated at FFTF. This addressed the concern that longer rods (> than the 33 cm in EBR-II) may not behave as well as short ones. Burnups of up to 14 atom percent were reached, with peak cladding temperatures up to 651°C without slumping or cladding breach issues. Metal fuel for this reactor was provided from ANL-W. (Earlier mixed-oxide fuel [MOX] was provided from a Babcock and Wilcox facility in Apollo Township, PA.) Fuel production rates were small (i.e., only a few MTU/yr).
- The prototype commercial fast breeder reactor (FBR) Fermi 1 (Monroe, Michigan) unit was under construction and development at its Lake Erie site from 1956 to 1963. Initial criticality was achieved on August 23, 1963. On October 5, 1966, Fermi 1 suffered a partial fuel meltdown. Two of the 92 fuel assemblies were partially damaged. There was no abnormal radioactivity released to the environment. Fermi 1 was a liquid metal (sodium)-cooled FBR design for electricity production. It could produce 200 megawatts thermal (MWth) power or 69 MW electrical power with 26% enriched metallic U fuel. The enriched-U section of the reactor (core) was a 30-inch diameter cylinder by 30 in. high and contained 92 fuel assemblies. The core was surrounded by 548 additional assemblies containing DU. These assemblies were about 2.5 in. square by about 8 ft tall. Only the core section contained the enriched U while DU was placed above and below within the assemblies. The core also contained two control rods and eight safety rods. The plant was designed for 430 MWt and 125 MWe using a newer UOX fuel, but the plant was closed before the UO2 fuel was ever ordered. No information on the manufacturer of the U-metal fuel for Fermi-I could be found.
- Other countries showing interest in U-metal fuels are South Korea, Russia, and India. The French and Japanese have shown a preference for oxide fuels with transition to U,Pu MOX as the objective.

- The following conclusions regarding U-metal fuel production capability and rates can be drawn from the above history:
  - DU and NATU have been handled in 1,000s of MTU/yr production rates, and the fabrication technology is mature. Category III facilities with minimal security and criticality regulations could readily be constructed with little regulatory ratcheting.
  - Except for MAGNOX in the UK, there is very little U-metal fabrication experience in the enrichment range of 1.3 to 5% U-235. LWRs and pressurized-heavy-water reactors (PHWRs) to date all use ceramic oxide fuels (UOX).
  - There is more experience in the upper end of the HALEU range (10 to 19.95% U-235). Most have been specialty FR fuels produced at rates of a few MTU/yr. Considerable regulatory and deployment issues associated with Category II facilities will exist for this fuel type if it is deployed at a larger scale (100s of MTU/yr) for commercial reactor use in LWRs or FRs.
  - Most of the considerable experience with HEU-metal fuels (U-235 content > 20%) was in the late 1940s through the late 1980s. Most of these manufacturers are out of the business. Only RR fuel manufacturers with Category I facilities are still active with a total production capability of 1 MTU/yr or less.
  - Most countries having nuclear weapons still have the capability to handle and fabricate HEU. The Oak Ridge (TN) Y-12 Plant operated by Consolidated Nuclear Security, LLC maintains this capability in the United States and has fabricated U-metal for a prototype space reactor core for NASA such as KRUSTY (Potter 2018). BWX Technologies, Inc. (BWXT) (Lynchburg, VA) and Nuclear Fuel Services (NFS) (Erwin, TN) are both private Category I facilities which could be modified for HEU and HALEU operations.
  - In October of 2022, Global Nuclear Fuel-Americas (GNF-A) and TerraPower announced an agreement to build the Natrium Fuel Facility at the site of GNF-A's existing LWR fabrication plant site near Wilmington, NC. The Natrium SFR plans to use all-metal HALEU fuel during its early deployment (Allen 2022).

D1-6A.2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

The U metal of U metal alloy fuel has the advantage of enabling rapid heat removal from the fissioning reactor fuel because of the high-thermal conductivity of metal as opposed to pressed and sintered ceramic powder. This capability compensates for the lower MP (1132°C) of U vis-à-vis UO_2 (2865°C). The number of steps in a metal-based fuel fabrication process is also smaller than the step count for a process involving ceramic powder handling, so there should be some life cycle cost advantages. Metal fuel is now the preferred fuel type for SFR development in the United States because of its compatibility with pyrochemical reprocessing flowsheets and the integral fast reactor (IFR) concept. For FRs, U metal fuel would be used for blanket positions in the reactor and as start-up driver fuel (Walters, Hays, and Carmack 2015) until enough metal Pu is available for the preparation of U,Pu-alloy drivers. U metal fuel is also being developed for use in LWRs but has not yet been tested in a U.S. reactor. U fuel also enjoys extensive use in RRs, Russian maritime reactors, and isotope production reactors. Several Generation IV, small modular reactor (SMR), and microreactor concepts also call for the use of U metal fuel. Contact-handling fuel fabrication is assumed for all the U metal fuels discussed in this module. In most cases, the fuel handling is hands-on with use of hoods or gloveboxes where inert atmosphere is required.

There are two basic metallurgical techniques for U- and U-alloy fuel manufacture: casting and extrusion.

- **Casting.** After the alloy blend is prepared in the molten state, a set of evacuated upside-down quartz tubes is inserted in the melt and the molten alloy driven upward into them by a pressure differential (see Hausman 2011; Figure D1-6A.3). After cooling, the quartz tubes (essentially acting as molds) are

broken away, and the resulting U-alloy slugs are cut to the proper pellet or slug length for cladding with stainless steel. As part of the cladding process, a tiny amount of molten sodium is forced into the slug-rod interface to provide a conductive metal interface for the slug or pellet stack to clad heat transfer. This process is known as sodium bonding. A helical wrap can be added outside of the clad slugs to enhance heat transfer from the rod to the SFR liquid-sodium coolant. Figure D1-6A.2 and Figure D1-6A.3 in the next subsection illustrate the overall injection casting process. Development of a continuous casting process is being funded under DOE's Small Business Innovation Research (SBIR) program (U.S. DOE 2016).

- **Extrusion.** In this method, a U-metal billet, and perhaps another jacketing metal is placed in the press and die system where the still-solid metals are heated until they are plastic and can be forced through the custom die. Cladding and Na-bonding steps are similar to those for cast slugs. Figure D1-6A.5 in the subsection below shows an extrusion system used for a metal fuel development project (Lavender et al. 2013). TerraPower and Idaho National Laboratory (INL) are performing some test extrusions for metal U fuel at INL's Manufacturing Test Facility (MTF) (MFC. n.d.; Levesque 2016).

D1-6A.3. PICTURES AND DIAGRAMS

The figures below illustrate the two basic processes mentioned above. The center of Figure D1-6A.3 shows the EBR-II fuel pin product from an injection casting process.

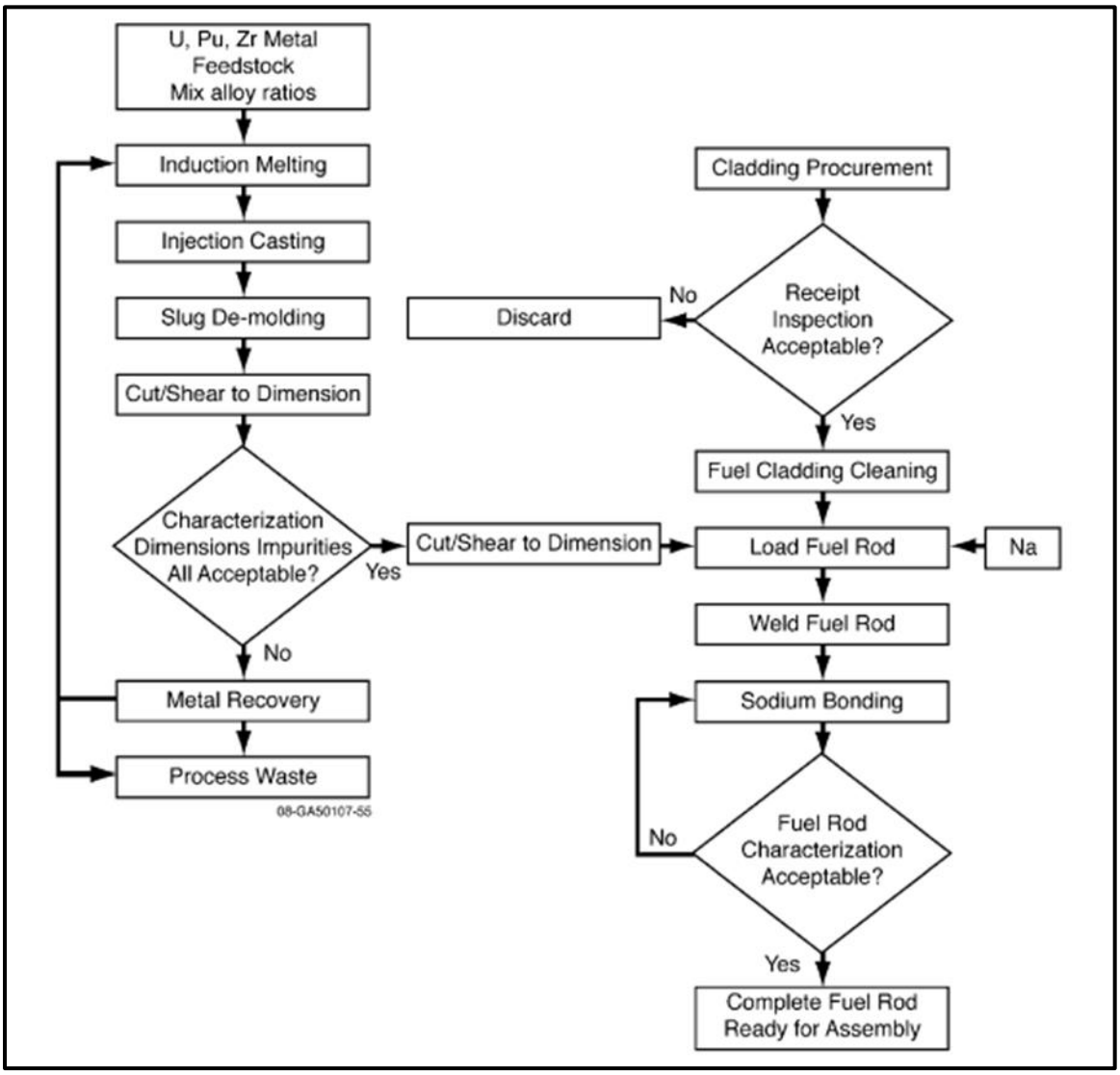


Figure D1-6A.2. Steps in the injection casting method used for the preparation of EBR-II fast reactor fuel (both U,Zr and U,Pu,Zr alloys) from Burkes et al. 2009.

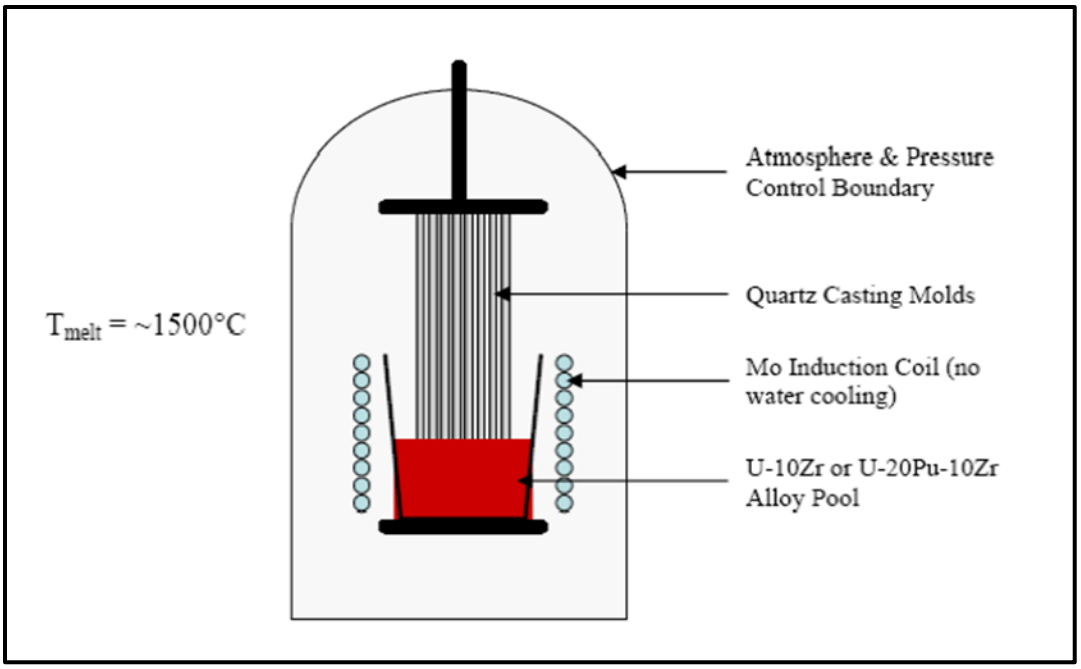


Figure D1-6A.3. Simplified Injection Casting Equipment Concept from Hausman 2011.

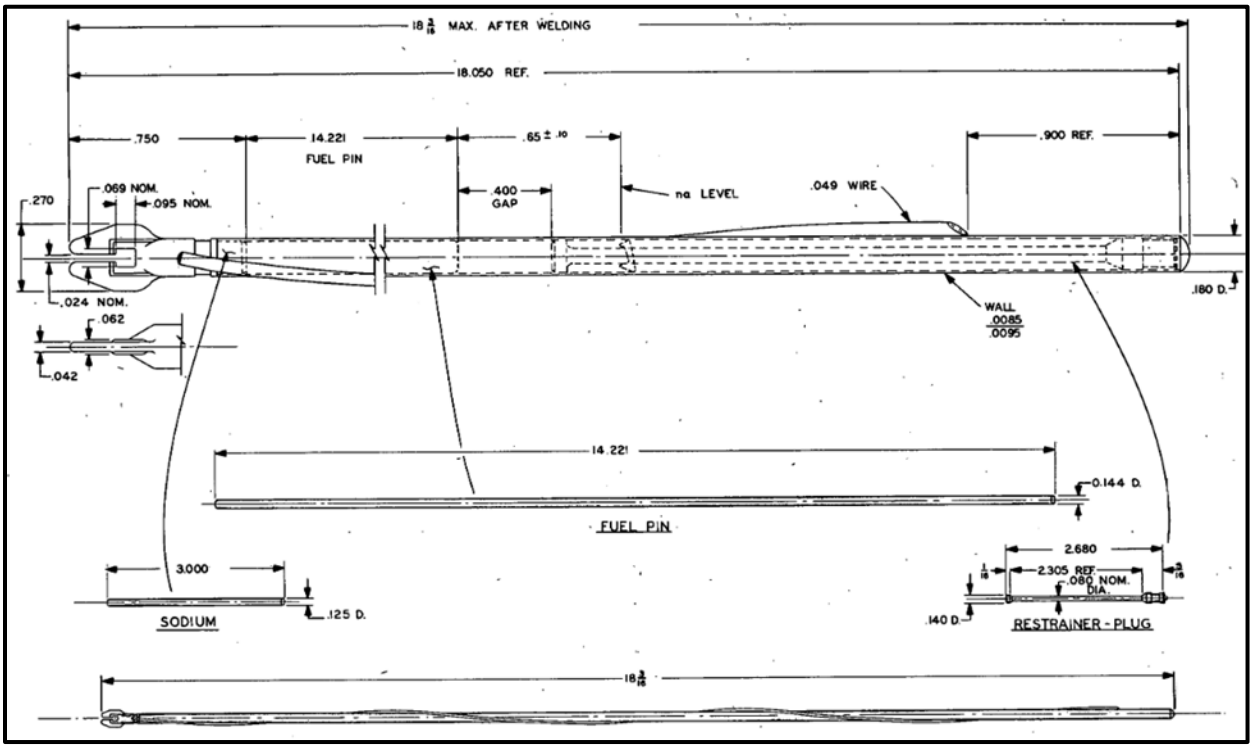


Figure D1-6A.4. Dimensions and components of an EBR-II fuel rod from Shuck and Ayer 1961.

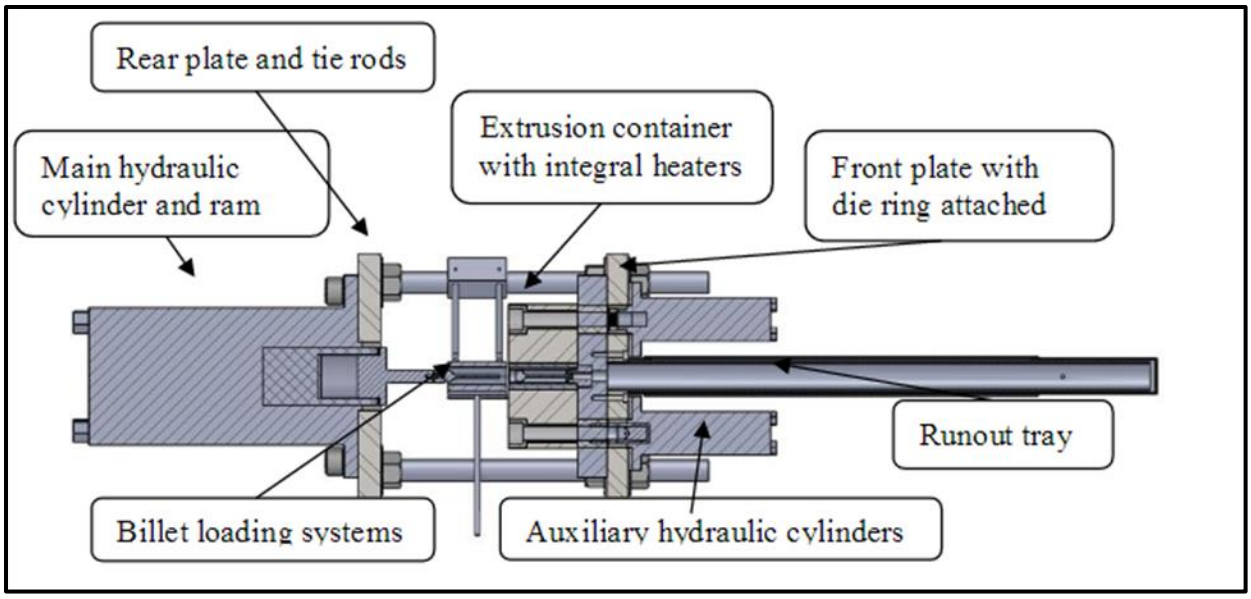


Figure D1-6A.5. Diagram of Extrusion Apparatus (Lavender et al. 2013).

D1-6A.4. MODULE INTERFACES

For once-through commercial LWR fuel cycles, there is a distinct separation between fuel fabrication and the conversion and enrichment fuel steps that precede it. Both conversion and enrichment have very large stand-alone facilities that provide these two services. For more specialized U-metal fuel fabrication, the distinction between predecessor fuel-cycle steps and fabrication is less distinct from a cost/pricing standpoint. (In these D Modules, the intent is to isolate and discuss the true cost of the fabricating and bundling service up to the point of transporting the packaged fuel to the reactors that burn it.) The unit fabrication cost presented should not include the cost of producing the nuclear feed material to the process. For metal U fuels, however, the price often includes the feedstock U metal and any services required to render a previous chemical form or shape to the desired metal form or shape. This situation exists because U fuel fabrication is a relatively small lot size specialty business (or government enterprise) and enrichment and conversion needs themselves are diverse. The fact that U-metal fuels vary anywhere from 0.2% U-235 (blanket fuel rods) to 90% U-235 (very small reactors requiring HEU) means the source material probably comes from multiple sources under various purchasing or ownership options. As will be discussed later, much of this material has associated sunk costs such as those for surplus weapons-grade (WG) HEU. The following describes the likely sources of U metal for various enrichment levels, starting from low to high.

- **DU (0.15 to 0.6% U-235).** Huge stockpiles (hundreds of thousands of MTU) of DU exist as enrichment plant tails in the form of UF6 or U3O8. A reduction step to go from UF6 or U3O8 to U metal is required. Reduction is generally a batch process requiring the exothermic reaction of the U compound with an alkali metal. In this case, the reduction cost (5 to 15 $/kgU) would be included as part of the fabrication cost. The DUF6 would likely be provided at no cost from government stockpiles, since it is considered a waste, and any beneficial use is an avoided cost to the government for storage and geologic disposal. In the more distant futures, U enrichers may ultimately charge for UF6; however, the unit cost would be expected to be less than that for U ore.

- **NATU (0.71% U-235).** The yellowcake (U ore concentrate of mostly U3O8) would be purchased on the open market (see Module A). Reduction (conversion) to metal would be required at a cost similar to that for DU compounds. The reduction to metal cost would likely be included in the overall fabrication cost. Reduction to metal is a two-step process: (1) continuous defluorination of UF6 to UF4 green salt and (2) batch reduction of solid UF4 to metal in refractory crucibles using an alkali metal.
- **LEU from 0.9 to 5% U-235.** Ore purchase, U3O8 to UF6 conversion, and enrichment services would be purchased on the open market and not be part of the fabrication cost. The reduction of the EUF6 from the enrichment plant would be considered part of the fabrication cost, just as the conversion of EUF6 to UOX is part of the fabrication cost for ceramic LEUOX fuel.
- **HALEU from 5 to 19.95% U-235.** Since no enrichment plants presently exist in the United States producing the required U-235 assays, the HALEU feedstock presently must come from another source.
  - Presently, U.S. manufacturers of RR fuel utilize surplus HEU from military programs. Most of this material is already in metal form as unclassified, non-weapon shapes and exists at the Oak Ridge Y-12 Plant (aka Y-12 National Security Complex) at U-235 assays from tens to 90+ % U-235. Most of this material is very clean in the sense that it has never been irradiated and reprocessed; hence, there are no U-236, trace FPs, or trace transuranics to complicate material handling. For a fee, a National Nuclear Security Administration (NNSA) government owned contractor operated facility (the Y-12 Plant) blends down this high-assay material to 19.95 % U-235 or less and provides it in the form of small metal bullets to RR fuel manufacturers, with BWXT Nuclear in Lynchburg, VA being the largest. NFS of Erwin, TN also is licensed to handle HEU as a Category I facility, and most of its work has been for the naval reactors program and the blend-down of reprocessed HEU to LEU fuel for use in Tennessee Valley Authority's Browns Ferry Nuclear Plant (Project BLEU).
  - From the early 1950s until the end of the Cold War, the U.S. government's production reactors at Savannah River utilized HEU fuel drivers for Pu and tritium production. The U solutions and dry salts resulting from reprocessing (aqueous separation in the SRS canyons) are also possible HEU sources for blend-down to HALEU; however, because of trace amounts of transuranics, FPs and U-236 build-in, the material is more difficult to convert and fabricate using contact-handling methods. HEU naval reactor fuel and Idaho Test Reactor fuels were also aqueously reprocessed at the Idaho Chemical Processing Plant and some of the resulting separated U converted to UF6 and re-enriched. Presently, spent naval fuel is stored at INL and will ultimately be safely isolated in a new dry storage facility. Pyrochemical reprocessing of some of this spent naval fuel and other spent fuel from INL reactors has been suggested as a source of HEU for blend-down to HALEU (WNN 2018; Yurman 2018).
  - Around 35,000 of the spent EBR-II fuel pins were reprocessed at ANL-W (now INL) using pyrochemical separations technology. The HEU-metal ingots resulting from the first salt-based electrochemical separation step in the overall pyrochemical process are relatively clean and capable of contact handling. INL proposed both the blend-down and fabrication of this recovered U metal material into fuel pins for a prototype FR start-up fuel, and an environmental analysis has been prepared (U.S. DOE 2019).

- Once enrichment capacity for HALEU is established in the United States, clean HALEUF6 will need to be deconverted to U metal. No present commercial facility presently exists for this purpose in the United States. It is likely that the U-metal fabrication facility for FR start-up U-metal fuel might need to include this reduction step as part of the fabrication process. Just as with LEU fuel, the fuel buyer for virgin HALEU will need to consider the costs of ore, U3O8 to UF6 conversion, and enrichment (separative work or SWUs) in the overall front-end fuel-cycle costs. Centrus Energy and Urenco USA are considering the development and construction of future domestic HALEU enrichment capacity. Research and development (R&D) on a more economic process for reduction of HALEUF6 to metal is also underway (Durazzo et al. n.d.). Deconversion of HALEU is discussed in detail in Module C3.

- **HEU (U-235 assay > 20%).** Very small specialty reactors such as space reactors and microreactors may require assays > 20%. The large government RRs such as HFIR at Oak Ridge and ATR at Idaho will continue to need HEU-metal fabrication services. The likely feed material sources would be the providers of government-owned surplus HEU as listed in the HALEU paragraph above. In this case, lot sizes would be very low, and specialty blending and conversion steps would be needed in addition to the fabrication steps. High-security Category I facilities would be needed.

For government-provided feedstocks, such as surplus HEU, the question arises as to the feed material cost to the fabricator/user. Essentially, the costs of the ore, natural U3O8 to UF6 conversion, enrichment, and EUF6 to metal conversion are sunk costs to the government, which were spent during the Manhattan Project and the subsequent Cold War. For research, design, and development (RD&D) projects, surplus nuclear source material of this type is likely provided from the surplus stockpile at little or no cost. Only the costs of further processing, security, and transportation are accrued to the new user. It is unclear as to whether this DOE-NNSA procurement practice will continue.

D1-6A.5. SCALING CONSIDERATIONS

The unit cost for the fabrication of a particular design of U or U-alloy fuel will be a function of facility size (average MTU/yr production). As with most manufactured items, there is an economy-of-scale. In the next subsection, a scaling relationship for the manufacture of SFR DU-metal blanket fuel will be given in graphical form (Figure D1-6A.6). In this case, life cycle cost data was developed for plants ranging from a few hundred to thousands of MTU annual production capacity.

For other U fuels, such as SFR-driver fuel for FR start-up and RR fuels, the MTU/yr demand for a hypothetical facility is likely to be at least one order of magnitude smaller. As the enrichment level goes up, the fuel demand per MWth of reactor goes down, since higher enrichment cores are smaller, and fuel burnup is higher. No size/capacity scaling relationships were found for these fuels.

It will be seen that there is a relationship between the unit cost of U-metal fuel and its U-235 content (enrichment level). As the enrichment level goes up, and more precautions must be taken in U handling, the following cost factors increasingly come into play and result in higher unit cost ($/kgU):

- Criticality and the need for smaller batch sizes and equipment.
- Safeguards, security, and plant physical protection (evolution from Category III to Category II and Category I facilities).
- Plant construction and operation regulations for Category I, II, and III facilities: these categories are defined in the preface for Module D1 under the HALEU subsection and in Merrifield and Leidich (2018) and Tschiltz and Pierson (2018). (HALEU in the less than 10% U-235 category requires a Category III facility with fewer regulations. HALEU from 10 to 19.99 % U-235 requires a Category II facility with greater security and safeguards compliance required. Category I applies to HEU, U-233, and Pu and is the most stringent category in terms of regulatory requirements.)

- Quality assurance and waste management.
- Increased engineering development costs and engineering oversight costs amortized into the unit cost.

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

To develop WIT unit cost ranges for various types of U-metal fuels, an extensive literature review was undertaken. Unfortunately, most of the historical information accessed and summarized above did not include cost experience information. Commercial manufacturers usually do not publish such information, and government materials production programs, such as those for the U.S. nuclear defense complex, do not publicize such information for political and national security reasons. As with other fuel types such as LEUOX (Module D1-1), LWR-MOX (Module D1-2), and PHWR-UOX (Module D1-7), the late 1970s Nonproliferation Alternative Systems Assessment Program (NASAP) fuel cycle studies turned out to be the best source of comparable life cycle cost projections.

D1-6A.6.1. Natural U, SEU, AND LEU FUELS < 5% U-235

The U.S. Hanford Production Reactor Program, the UK MAGNOX Program, and Russian Maritime reactor programs were the largest users of this class of metal fuel. No publicly available cost experience data were found on any of these fuel types.

D1-6A.6.2. Depleted-Uranium Target and SFR Depleted-Uranium Blanket Fuels

Savannah River made extensive use of tubular DU targets for Pu and tritium production in the P, K, and L heavy-water production reactors. No cost information on the fabrication cost for these targets was found.

For civilian RD&D programs on FR systems, which have been underway since the 1950s, there is considerably more design and cost information available, especially in older U.S. national laboratory technical reports, which fortunately have been archived, scanned, and made available on the Web. These older reports (Judkins and Olsen 1979a; Judkins and Olsen 1979b; Olsen et al. 1979a; Olsen et al. 1979b) from the late 1970s to the early 1990s are most useful for this module, since the objective of FR technology development at that time was Pu breeding via the irradiation of manufactured DU axial blanket pellets and full radial blanket assemblies. (Today's FR concepts are more oriented toward actinide burning in SFRs and the destruction of higher actinides that present a problem in a geologic repository. Today's U.S. SFR concepts also prescribe the use of on-site integrated fuel recycle using dry pyrochemical reprocessing.) In the late 1970s, a prototype FBR, the Clinch River Breeder Reactor (CRBRP), was envisioned to be the prototype for a fleet of FBRs for which an oxide or metal-based fuel-cycle was possible. HALEU-based driver fuel (15 to 20% U-235) cores would be quickly transitioned to U,Pu-based cores, for which the U-235 plus Pu-239 fissile content would in the 15 to 19% range. Essentially, zero-source cost blanket U fuel could have been converted and fabricated from the huge government DUF6 tails stockpile resulting from decades of U.S. U-enrichment operations. A prototype fuel fabrication plant, the SAF-line in the Hanford Fuels Manufacturing and Examination Facility (FMEF), was actually constructed (but never operated) for initial CRBRP fuel fabrication, and a Pu-U reduction extraction (PUREX)-based aqueous reprocessing plant was on the drawing board for recycle of the Pu recovered from CRBRP driver and target fuels. (The existence of only traces of higher actinides, minimal higher Pu isotopes, and traces of FPs in the refabricated fuel feed would allow glovebox contact handling.) In the 1970s, optimism for the growth of nuclear power was high, and over 1,000 operating 1,000 MWe-class power reactors were predicted for the year 2000. The breeder fuel-cycle was seen as the solution to a perceived shortage of U ore at that time. Pu-239 would substitute for increasingly less available U-235 as NATU resources were exhausted.

After India exploded a nuclear weapon based on Pu separated from power reactor spent fuel, nonproliferation became a huge policy issue for Western governments. The international nuclear fuel-cycle evaluation (INFCE) and NASAP programs were undertaken by the International Atomic Energy Agency (IAEA) and the U.S. government 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 from the standpoint of technical feasibility, proliferation resistance, resource requirements, and life cycle costs. These NASAP studies and the reports (Judkins and Olsen 1979a; Judkins and Olsen 1979b; Olsen et al. 1979a; Olsen et al. 1979b) which were generated there from are discussed in the preface (D1-PR) to this set of Fuel Fabrication D Modules. 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 complexity and regulatory requirements for the manufacture of each. From a detailed bottom-up life cycle cost analysis of a hypothetical ceramic UO_2 (UOX) PWR fuel fabrication plant, a levelized unit cost of production for that fuel type was calculated via revenue-requirements type economic model.

For non-UOX cylindrical, metal-clad fuels modifications to the UOX reference fuel design and fuel fabrication facility were made on the basis of fuel complexity, material-handling difficulty, radiation environment, process building safety and security requirements, and resource requirement differences (manpower, purchased materials, and utility usage). All the reference UOX to alternate subject plant changes were embodied in algorithms in a mid-1970s FORTRAN computer code called FABCOST. The computer-generated life cycle costs for each plant type were then tabulated and published in a set of documents (Judkins and Olsen 1979a; Judkins and Olsen 1979b; Olsen et al. 1979a; Olsen et al. 1979b) published by Oak Ridge National Laboratory from 1978–1980. The U-Pu metal driver fuel and DU-metal blanket fuel for a breeder-reactor fuel-cycle represented one of the cases examined in this study. Both ceramic (oxide and carbide) and metal fuels were considered for the overall liquid metal FBR (LMFBR) cases. All the fuels were assumingly produced in very large (~500 metric ton of heavy metal/year [MTHM/yr]) centralized, and NOAK (mature technology) facilities capable of supporting a fleet of tens of GWe-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 authors of this 2021 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 and general economic and project execution factors.

The Fuel Cycle Research and Development (FCRD) author's task became that of adapting the 1978 life cycle cost data (for 1978 economic conditions) to the conditions of today's economy and regulations. The following paragraphs discuss the procedure and results for the all-U metal blanket fuel. Module D1-6B will describe the same for the all-metal U,Pu,Zr driver fuels which would be manufactured for long-term use in the breeder fuel-cycle. **The manufacture of all-U metal HALEU start-up driver fuel was not addressed in the NASAP study**. For this Module D1-6A, however, a unit cost is needed for this fuel type. In later paragraphs below, a methodology for roughly estimating this cost based on the analysis of other fuel types is discussed.

Once the process differences between PWR-UOX manufacture and DU-metal blanket manufacture were understood and analyzed, equipment lists were prepared by the Oak Ridge National Laboratory (ORNL) engineers working on NASAP, and the resulting equipment laid out on the floor of a single-story process building. Among the process differences identified for going from LEUOX to DU fabrication for the same annual MTU capacity are the following:

- No criticality considerations required for DU.
- A more complex DUF6 to DUF4 to batchwise DU-metal conversion process is needed. This is more complex than the semi-continuous LEUF6 to LEUO2 conversion step for LEUOX fuels.

- The post-conversion metal handling steps (melting, injection casting, and slug shearing) are simpler and fewer than those for LEUOX (powder prep, granulation, pressing, sintering, and pellet finishing) and involve less dust.
- The DU-blanket plant produces both complete radial fuel assemblies and additional slugs or pellets to be loaded in the ends of HALEU or U,Pu driver assemblies to serve as the axial blanket.
- The DU-blanket fuel must be sodium-bonded to the cladding. The loaded fuel pins also require wire wrapping to enhance heat transfer to the liquid-sodium coolant. There is currently considerable interest in developing sodium-free metal fuels. Such development could result in lower manufacturing costs and make post-irradiation handling easier.
- A DU-blanket pellet is much smaller and more dense than a finished UOX pellet.
- More (and shorter) rods are handled for fuel loaded in SFRs.
- Neither the LEUOX fabrication plant nor the DU-blanket plant requires gloveboxes. Hoods and use of inert gases may be required to minimize fire hazards and for personal protection from airborne dust inhalation.

After the ORNL NASAP engineers laid out the equipment, the following area requirements were calculated for the various process areas of the two plants.

Table D1-6A.1. Comparative process areas required for 2 MTU/day capacity (520 MTU/yr average production) PWR-MOX Fuel Fabrication Facility (Reference Plant) and SFR metal fuel DU-blanket facility (subject plant).

Fabrication Facility Operation	Ceramic PWR UOX: Area in Square Feet	DU-Metal Blankets: Area in Square Feet
Feed receipt areas (LEUF6 for UOX, DUF4 for metal)	5,500	2,975
Milling for UOX; blending and reduction for metal	4,700	2,975
Powder granulation and pelleting; not applicable for metal	1,900	0
Pellet sintering, grinding, and inspection for UOX; slug casting & shearing for U	5,850	10,000
Fuel rod loading and welding	2,780	3,640
Fuel rod inspection and storage	7,000	6,000
Fuel assembly fabrication	3,000	8,720
Fuel assembly weighing, cleaning, and inspection	3,400	2,720
Fuel assembly packaging and shipping	4,000	4,000
Scrap recovery and waste processing	2,000	4,000
Operational support including hardware fabrication	20,065	22,515
Stores (warehouse)	2,000	4,000
Facility support	9,135	18,010
Change rooms for contaminated areas	2,005	2,005
Quality control labs	7,000	10,005
Maintenance	19,665	22,515
Total area in ft^2	**100,000**	**124,080**

Equipment and operations adjustments were made to recognize the higher hardware complexity of the non-UOX PWR fuel itself, using complexity factors that were developed in the late 1970s as part of the NASAP analysis. Many of the life cycle cost 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 unit cost were correctly calculated. The late 1970s costs then had to be escalated to 2017 and ultimately USD (2020) using adequate historical escalation factors for nuclear projects (Ganda et al. 2016). The G4-ECONS economic model (Generation IV Nuclear Forum 2007) was then utilized to calculate the levelized unit cost for a DU-metal fabrication facility with a 50-year life and 3% discount rate (Table D1-6A.2), as was done for LWR-UOX in Module D1-1 and PHWR-UOX in Module D1-7.

D1-6A.6.3. Resulting Reference DU-Metal Blanket Fabrication Plant

The base NASAP contact-handling fabrication plant was designed for a nominal 2 MTHM/day production capacity which, including downtime, translates to an average production capacity of 520 MTU/year. A single-story DU-metal blanket fabrication process building, housing the feed conversion, any alloy blending process, and all metallurgical and bundling operations, was found to require a footprint of over 124,000 ft2. Table D1-6A.1 above shows the major required process building areas as calculated in the 1979 ORNL reports. When column 2 of this table is compared to column 1, the need to fabricate a more complex fuel assembly (with sodium bonding) and more numerous U-metal slugs and/or pellets, as well as the need for additional operations staff, somewhat increases the facility footprint.

The treatment of the economics and calculation of the unit fabrication cost in the 1978 report (Judkins and Olsen 1979a) (summarized in Table D1-6A.2) reflects prevailing financial conditions and taxation regulations in effect at that time for a privately owned greenfield plant. As with the reference UOX plant (in Module D1-1), a simple economic model for today's economic conditions (also shown in Table D1-6A.2) was developed utilizing the G4-ECONS economic analysis tool (Generation IV Nuclear Forum 2007).

The USD (2017) unit fabrication cost of $362/kgU falls well within the WIT unit cost range (270 to 690 $/kgU) for U-metal blanket fuel fabrication in the 2017 Module D1-4 of (Dixon et al. 2017). This strengthens the confidence in both the 2017 AFC-CBR range and in the (Olsen et al. 1979c) SA&I adjusted NASAP estimate.

Table D1-6A.2. Life cycle cost transitioning from 1978 reference ceramic LEUOX fabrication facility to 2017 subject DU-metal blanket fabrication plant.

Facility and Life Cycle Cost Attributes	PWR LEUOX 1978 USD & 1979 Financial Assumptions (NASAP)	PWR LEUOX 2017 USD & 2017 Financial Assumptions	DU-Metal Blankets 1978 USD & 1979 Financial Assumptions (NASAP)	DU-Metal Blankets 2017 USD & 2017 Financial Assumptions
Production rate adjusted for downtime	520 MTU/yr	520 MTU/yr	520 MTU/yr	520 MTU/yr
Process building area	100,000 ft2	100,000 ft2	124,080 ft2	124,080 ft2
Total civil structure cost incl indirect & contingency	$36.1M	$239M	$44.8M	$266M

Facility and Life Cycle Cost Attributes	PWR LEUOX 1978 USD & 1979 Financial Assumptions (NASAP)	PWR LEUOX 2017 USD & 2017 Financial Assumptions	DU-Metal Blankets 1978 USD & 1979 Financial Assumptions (NASAP)	DU-Metal Blankets 2017 USD & 2017 Financial Assumptions
Total equipment cost incl. indirect & contingency	$45.2M	$269M	$41.8M	$249M
Total facility overnight capital cost incl. preoperational costs but no interest during construction	$102M	$629M	$88.7M	$528M
Plant life	20 yr	50 yr	20 yr	50 yr
Annual recurring costs incl. annualized eqt. replacements	$38.1M/yr	$147M/yr	$43.2M/yr	$165M/yr
Financing basis	Government, financing, r = 8.8%	Government financing, r = 3%	Government, financing, r = 8.8%	Government financing, r = 3%
Unit fabrication cost	$100/kgHM	$334/kgHM	$110/kgU	$362/kgU

As discussed in Section D1-6A.5 (Scaling Considerations), unit cost of fabrication is expected to scale with plant production capacity. Using cost-scaling exponents from the NASAP reports (Olsen et al. 1979a; Olsen et al. 1979b; Judkins and Olsen 1979b), the following unit fabrication cost versus average production rate curve was derived.

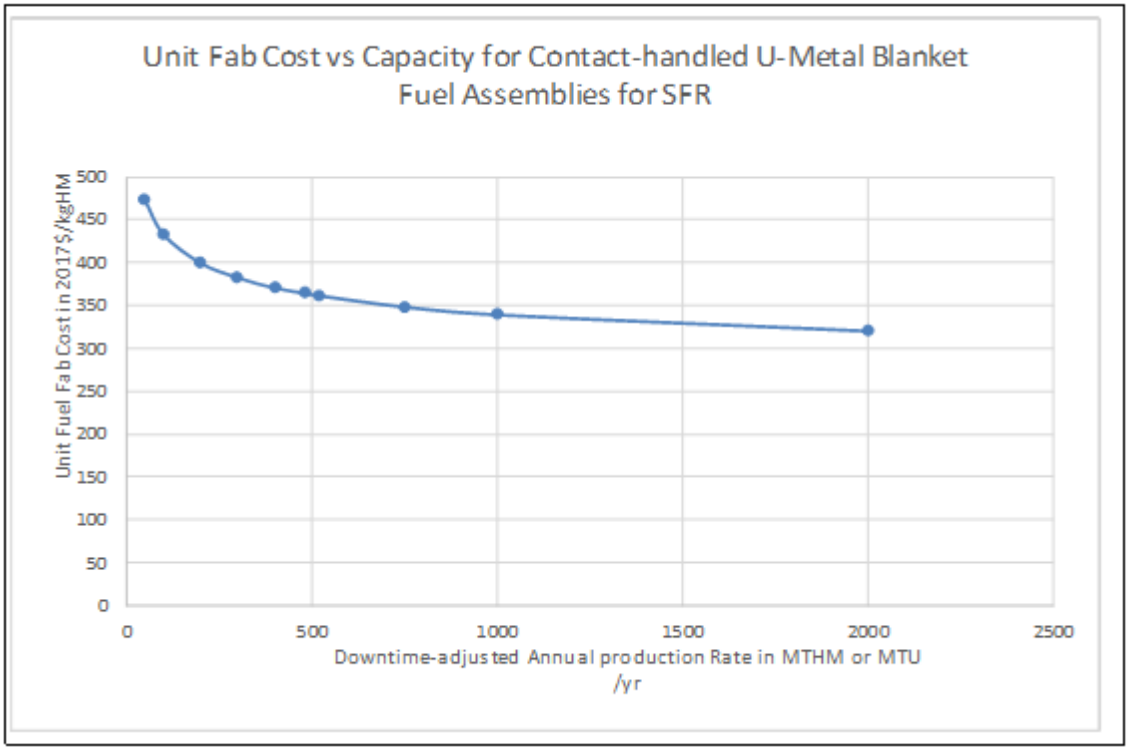


Figure D1-6A.6. Unit fabrication cost scaling with average annual production for DU-metal blanket fuel fabrication plant.

D1-6A.6.4. Uranium Metal-Only Based LWR and SFR Fuels

Lightbridge Corporation (now EnFission) has been pursuing the use of U metal fuel for LWRs for the last 5 years. The fuel consists of a co-extruded rod with a U-metal core and a directly bonded metal jacket or cladding. It has a cruciform cross section to allow efficient loading in a fuel assembly and a twisted rod shape to enhance heat transfer. Figure D1-6A.7 and Figure D1-6A.8 below show these concepts. The following information has been gleaned from Lightbridge and other literature sources (WNA. n.d.; Chakraborty n.d.; Malone, Totemeier, Shapiro, and Vaidyanathan 2012) on accident tolerant fuels (ATFs):

- The fuel burnup can be higher than for UOX fuel and rod life greater than 18-months, thus requiring fewer refueling outages.
- The amount of U in a fuel assembly will be less than for UOX; however, the enrichment required will be in the upper HALEU range (15 to 19.95% U-235).
- Heat can be more efficiently removed from metal fuel, thus allowing power uprates of 10 to 30% in LWRs for existing or new LWR fuel assembly positions in the core.
- Lightbridge is preparing the U.S. Nuclear Regulatory Commission (USNRC) regulatory paperwork needed for possible testing a few rods in an existing LWR.
- One of the options for LWRs involves both U-metal drivers and fertile oxide pellets in the same fuel assembly. More advanced concepts are all metal. This seed-blanket concept was investigated in Russia for thorium utilization and for Pu disposition in LWRs. Fuel Fabrication Module D1-8 (Thorium fuels) describes one such concept.

- AREVA is now a partner in the EnFission consortium formed in 2018
- No unit cost information or pricing information on Lightbridge fuel is available.
- Details of the safety case for this type of fuel can be found on the Lightbridge website (Chakraborty, S. Dr. n.d.).

The use of HALEU as opposed to 3 to 5% U-235 in LWR-UOX in Lightbridge metal fuel suggests that the unit cost of HALEU fabrication will be higher due to the need for a Category II fabrication facility and its higher capital and operational costs. This does not mean, however, that the fuel will be non-competitive. What is important is the fuel-cycle component of the levelized unit cost of electricity ($/MWe) for the whole nuclear system. Higher fuel burnup and longer fuel residence time result in less fuel consumption per MWe, (i.e., the lower average annual consumption of fuel over the operating life of the reactor counteracts the higher unit cost paid for the fabrication service).

Some SFR advanced concepts also may also require the use of HALEU-metal fuel. Among these are:

- The Versatile Test Reactor (VTR) planned for INL. At present, it appears that HALEU, Pu, Zr fuel may need to be used for start-up, since it is anticipated that HALEU alone will not suffice from the standpoint of neutronics. At one time, HALEU only was envisioned for the start-up of this SFR project.
- Advanced SFRs: TerraPower announced on Sept 15, 2020, that it plans to work with Centrus Energy to establish commercial-scale production facilities for the HALEU needed to fuel many advanced reactor designs (ANS 2020). TerraPower and its partners plan to establish a new Category II metal fuel fabrication facility to meet the needs of TerraPower's Natrium demonstration program, including possible lead test assemblies. No cost estimates for such a facility have been made available.
- BWXT plans a new RR production line at Lynchburg VA for U-Mo HALEU RR fuels (WNN 2021). Lower enrichment (19.75% U-235 or less) RR fuels are now in demand because of nonproliferation concerns. No cost information is yet available.

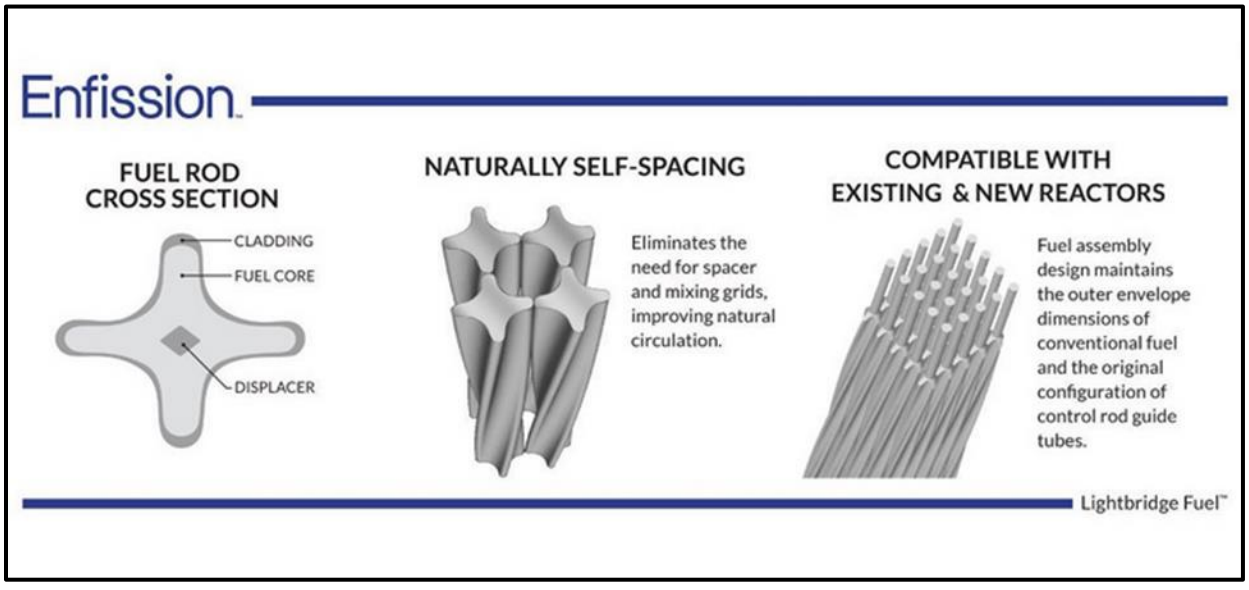


Figure D1-6A.7. Lightbridge/EnFission concept for uranium metal fuel for LWRs.

Figure D1-6A.8. A prototype Lightbridge/EnFission fuel assembly.

D1-6A.6.5. Research Reactor Fuels

U Small RR fuel is a specialty item which is produced in small quantities, 1 to 10 MTU/yr, and is usually 19.95% U-235 HALEU to produce the most neutrons for research and still being considered LEU-fueled. Early RRs for universities, private non-utility industries, and non-AEC government research institutions usually utilized HEU fuel greater than 40% U-235, since this maximized the neutron production per mass of fuel required. For Western nations, the U.S. Atomic Energy Commission (USAEC) and its successor agencies (Energy Research & Development Agency [ERDA] and DOE) owned the fuel and loaned it to the reactor users. The costs of the ore, U3O8 to UF6 conversion, and enrichment costs, which were quite substantial, were not charged to the user. Handling and transportation costs were still charged, however. The fabrication charges were paid by the user, and private manufacturers charged fees that depended on the complexity of the fuel design, the lot size, the enrichment level, and the required regulatory fees and other overheads. In the United States, General Atomics and Babcock and Wilcox (now BWXT) were major providers of the fabrication service. The IAEA (2010) has published a technical document regarding cost issues associated with RR fuel. A cost range of $10,000 to $30,000 per kg U is given for typical RR fuel such as that for TRIGA reactors. A major cost issue now being addressed is the conversion of RRs using HEU > 20% U-235 to HALEU (i.e., enriched material < 20% U-235). This Reduced Enrichment for Research and Test Reactors transition program is a major U.S. and IAEA nonproliferation program and, in most cases, will involve redesign of the reactor to accommodate a higher mass LEU core. The necessary redesign of the fuel to still provide a fissile density high enough for efficient neutron production is another cost issue. The use of LEU (HALEU in most cases) may involve lower unit fabrication cost ($/kgU) that for HEU > 20% due to simpler Category II facility design and operating requirements compared to Category I facility for HEU; however, more HALEU fuel will need to be purchased for the same reactor.

It should be remembered that the ore, U3O8 to UF6 conversion, and enrichment (SWU) costs for these RR fuels will be very high if the source HALEU or HEU is not made available gratis from government surplus stockpiles with already sunk costs. Table D1-6A.3 below shows how these costs add up for virgin (never-irradiated) enrichment plant product EUF6 at various enrichments.

The price of fuel fabrication is sensitive to the type of RR fuel involved and the competitive structure of the fuel market, since some types of RR fuels are available from a single supplier, while others can be supplied by a number of competing fabricators. The price of RR or material testing reactor fuel fabrication can range from $10,000 to $30,000 per kg U, excluding the cost of the enriched-U feedstock. The wide range is due to the variety of RR fuel designs, as is discussed below. The range of prices for other kinds of highly specialized fuel elements could be much higher than those related to more common RR fuel types, due to the complexity and limited opportunities for economies of scale in the production factories.

Table D1-6A.3. Non-fabrication front-end fuel-cycle unit costs for EU at various U-235 assays if surplus EU is not available at no cost (EU assumed in form of EUF6, so for U metal, reduction costs for UF6 to UF4 to U metal must be added to the fabrication cost; for enrichment calculation, assumed U-235 tails assay is 0.25%).

Percent U-235 in EU	$/kgEU attributable to ore, U308 to UF6 conv, and DUF6 to U308 conv and disposal	$/kg EU attributable to enrichment	TOTAL $/kgEU without fabrication
5	1,212	990	**2,203**
10	2,510	2,357	**4,867**
15	3,808	3,767	**7,575**
19.95	5,093	5,183	**10,276**
35	9,000	9,550	**18,550**
90	23,277	26,004	**49,281**
Above table assumed front-end FC unit costs from 2017 AFC-CBR (mode values) in 2017 USD:			
Ore (mine & mill)		33.1 $/lb U308	
U308 to UF-6 conv		13 $/kg NATU	
SWU		125 $/SWU	
E-plant DUF6 to U308 conv + disp		6.5 + 14.1 $/kg DU	
Fabrication		0 $/kg EU	

(Note for above table: The unit cost of SWU for producing HALEUF6 could be higher because of the additional safety and Category II material protection, control, and accountability (MPC&A) costs associated with the higher enrichment end of the enrichment cascade. Effects of HALEU enrichment levels on the unit SWU cost is examined in forthcoming Module C3.)

Larger RRs, such as those at DOE's national laboratories, can also have very complex fuel designs for the generation of high neutron fluxes required for research and radioisotope production. Two of these larger reactors, HFIR at ORNL and ATR at INL, still use HEU on high-security government sites. Plans for their transition to LEU are uncertain. It is interesting to note that a recent newspaper article (Munger 2009) regarding ORNL's HFIR gave a fabrication cost of $1.5 million (in 2015 USD) for the production of the curved plate type fuel elements (see Figure D1-6A.9 below) totaling a mass of 9.4 kg U-235 (~10kg total U for the 93.8% U-235). BWXT in Lynchburg, VA manufactures the core from UOX material provided by the Y-12 Plant in Oak Ridge, TN. Y-12 performs the step of converting surplus metal HEU billets to a blended (to lower enrichment if specified by the buyer) metal or oxide form for use by BWXT. A processing charge in the $1,000 to $5,000 per kgU of blended product is made for this service depending on manufacturer fuel specifications.

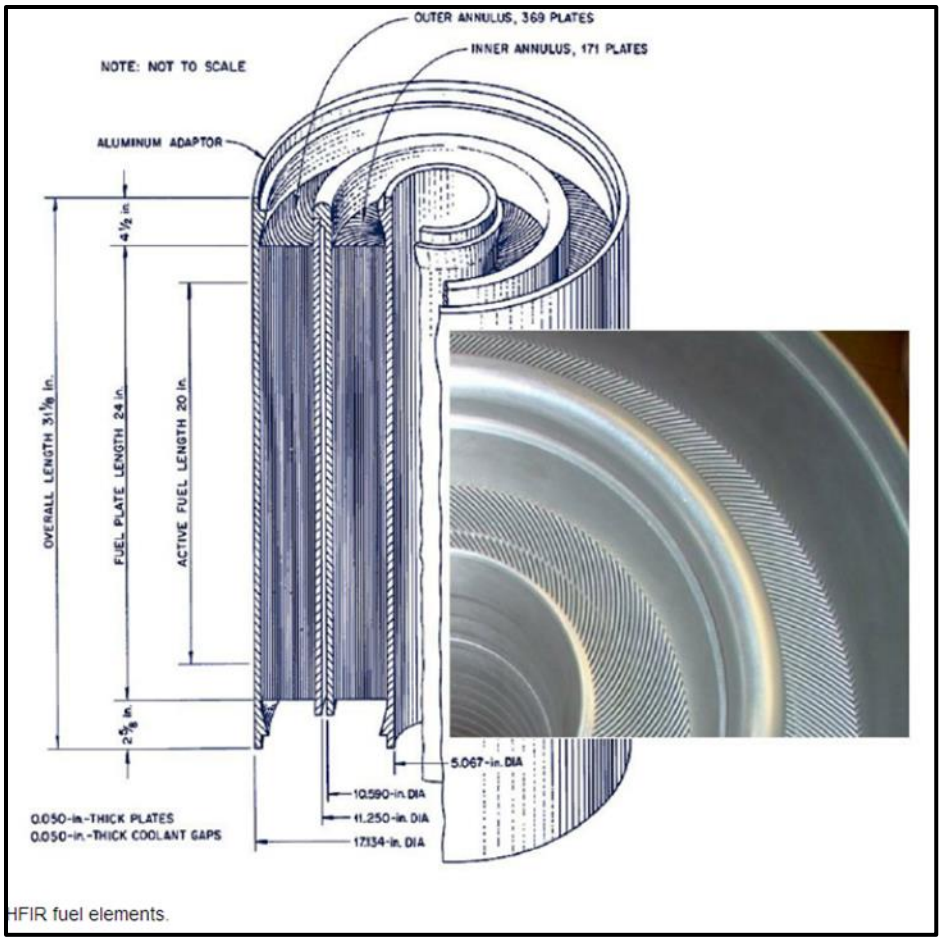


Figure D1-6A.9. The HFIR HEU core with curved fuel elements.

The reader may be somewhat surprised that this 2019 Update AFC-CBR deals with small, non-power reactor fuels in this module. It turns out RR fuel unit cost information was available, and the provided HEU unit costs help set an upper bound for the projected unit cost for U fuels to be produced in higher quantities (higher production rates) and at HALEU-level lower U-235 enrichment levels. Since more cost data is also available on DU (blankets and targets) and very low enrichment U fabrication, lower unit cost bounds are also available. As will be seen in the section below, the intent is to project the unit cost of fabrication for U metal fuel in the upper HALEU (10 to 19.95% U-235) range for which little or no manufacturing experience and cost data are available. Since the start-up of several types of advanced reactors (fast and thermal) may depend on this material, its manufacture in the tens to hundreds of MTU/yr will become necessary until enough Pu becomes available from reprocessing of LWR-UOX spent fuel. IPFM (2019) discusses nonproliferation HALEU-related usage issues in the United States.

D1-6A.7. DATA LIMITATIONS

A major limitation is that none of these fuel types have been recently produced in the West (United States and Organization for Economic Co-operation and Development [OECD] countries) in large quantities, so no data from fuel users could be obtained. Producing any of these types in production quantities, other than RR fuel, will require re-establishing dormant fuel fabrication industries under new sets of regulations (Category II) and financing arrangements. Fortunately, the 1978 NASAP study provided a basis for at least producing comparable unit cost estimates based on technical complexity and manufacturing difficulty. Escalation to 2017 constant USD and applying economic factors typical of today's economy was uniformly applied to all of these NASAP cases. Since metal enriched-U-metal only fuels were not part of the NASAP study, interpolation of graphical unit cost data for SFR U-Pu metal and oxide fuels and SFR metal and oxide DU-blanket fuels was required for the establishment of boundaries on U-metal only fuels of various fissile content. Some data from literature sources for HEU fuels were also incorporated in the analyses presented below. It should also be noted that in the NASAP study, the baseline LMFBR incorporated metal blanket pellets that were nearly the same diameter as the U,Pu driver pellets and were also clad with stainless steel. A newer SFR design would probably allow blanket pellets to be larger and to be clad with ferritic steel, which should lower the unit fabrication cost.

D1-6A.8. COST SUMMARIES

The rationale for the new WIT unit cost values for U metal fuels is discussed in this section for the following six contact-handled metal fuel types:

- **NATU- or DU-Blanket Assemblies Produced in High Quantities (Baseline = 520 MTU/yr) in a Category III Facility.** This fuel is assumingly produced by injection casting as per the 1978 NASAP study (Olsen et al. 1979a). The given range should also cover blanket fuel manufactured by the simpler hot-press extrusion method.
- **Low-Assay HALEU-Metal Drivers in the U-235 Enrichment Range 5 to 10% U-235 Prepared from Virgin LEUF6 from Enrichment Plants or the Blending of Clean U Feedstocks.** These can also be produced in a Category III facility but for market reasons likely at lower production rates than LEUOX pellet fuels or U,Pu metal drivers. A baseline production rate of 50 MTU/yr is assumed. This type of fuel might be used in some advanced thermal reactor designs. Injection casting or extrusion fabrication is assumed.
- **Low-Assay HALEU (aka LEU-plus) Metal Drivers in the U-235 Enrichment Range 5 to 10% U-235 Prepared from Reprocessed U (REPU), Therefore Requiring Somewhat More In-plant Personnel Protection Due to U-232 Daughters, Trace Transuranics, and Trace FPs.** These can be produced in a Category III facility but likely at lower production rates than LEUOX fuels for the existing LWR fleet or for U,Pu metal drivers. A baseline production rate of 50 MTU/yr is assumed. This type of refabricated fuel might be used in some advanced thermal reactor designs. Injection casting or extrusion fabrication is assumed as the production technology.
- **Higher-Assay HALEU-Metal Drivers in the U-235 Enrichment Range 10 to 19.95% U-235 Prepared from Virgin or Unreprocessed LEUF6 (Primary Enrichment) or by Blending of Clean U Feedstocks (a Secondary Enrichment Source).** These would be produced in a Category II facility but for market reasons likely at lower production rates than LEUOX fuels or U,Pu metal drivers supporting a fleet of SFRs. A baseline production rate of 50 MTU/yr is assumed. This fuel type would be used to start up a fleet of SFRs and might require sodium bonding. It is also the category for the Lightbridge-type metal LWR fuel. Injection casting and extrusion respectively are the two manufacturing methods assumed. Some microreactor concepts also require metal fuel in this assay range.

- **Higher-Assay HALEU-Metal Drivers in the U-235 Enrichment Range 10 to a19.95% U-235 Prepared from Blended REPU.** These would be produced in a Category II facility but likely at lower production rates than LEUOX fuels or U,Pu metal drivers supporting a fleet of SFRs. The presence of U-232 daughters, trace transuranics, and trace FPs may require special handling in shielded gloveboxes at a slightly higher cost. A baseline production rate of 50 MTU/yr is assumed. This fuel type would be used to start up a fleet of SFRs and would require sodium bonding. It is also the HALEU category for the Lightbridge-type metal LWR fuel. Injection casting and extrusion respectively are the two manufacturing methods assumed. Some microreactor concepts also require fuel in this assay range. Such HALEU is considered a secondary enrichment source, and its quantities may be limited compared to future primary enrichment sources.
- **HEU-Metal or Metal Alloy of 20% U-235 or Higher Enrichment.** This might be needed for smaller-capacity SFR start-up fuel, microreactors, and RRs. It is assumed this fuel is fabricated in Category I facilities from non-REPU.

D1-6A.8.1. U-Metal Blanket Fuel for SFRs

The existing AFC-CBR cost data closest to that for U-metal blanket fuel is for the more complex ceramic DU oxide or natural UOX blanket fuel which has been fabricated for breeder-reactor demonstration projects. For blanket UOX fuel, the unit fabrication cost range and distribution from Module D1-4, Pelletized Ceramic Fuel for SFRs from the 2017 AFC-CBR is as shown in the following Table D1-6A.4 (in FY-17 constant USD). These data are based on historical and literature-based information only and do not include information from the 1978 NASAP study.

Table D1-6A.4. 2017 AFC-CBR WIT unit fabrication cost values for SFR ceramic UOX blanket fuel (not informed by NASAP study).

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2017	270 $/kgU	500 $/kgU	690 $/kgU	487 $/kgU	Triangular
2020 *	284 $/kgU	526 $/kgU	726 $/kgU	512 $/kgU	Triangular
* Escalated to 2020 from 2017 using 5.2%					

Fortunately, U metal blanket fuel was part of the 1977–1978 NASAP study, and using a G4-ECONS type economic model with vetted escalation factors a base unit cost of 362 $/kgU (in 2017 USD) was obtained for a large injection casting facility producing 520 MTU/yr. To produce the same amount of ceramic UOX blanket fuel, the NASAP and G4-ECONS-based spreadsheet model calculates a unit cost of ~422 $/kgU (in 2017 USD) for the somewhat more complex pelletizing-sintering-polishing process flowsheet. (This calculation will be discussed in the new FY 2021 update to Module D1-4.) This latter value is within the 2017 USD range for the table above. This fact gives the authors of this report confidence that the 2017 AFC-CBR UOX blanket ranges and values were reasonable, and by extension, a similar range should exist for U metal blankets. In the table below, the high and low values have been modified to reflect a smaller range, since it was possible with the NASAP algorithms to do a sensitivity study on plant production capacity. The high-low endpoints are now informed by Figure D1-6A.6. If the 354 $/kgU value in 2017 USD is rounded slightly up to 360 $/kgU for the most likely value, the rest of Table D1-6A.5 can be filled in proportionately as follows to obtain 2020 USD:

Table D1-6A.5. 2020 AFC-CBR update WIT unit fabrication cost values for SFR U-metal blanket fuel (NASAP-informed).

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2017	275 $/kgU	362 $/kgU	5,500 $/kgU	396 $/kgU	Triangular
2020**	289 $/kgU	382 $/kgU	579 $/kgU	417 $/kgU	Triangular
** Escalated to 2020 USD from 2017 using 5.2%.					

One might ask why the most likely unit cost value for a fuel using DU is somewhat higher than for UOX fuel using low-enriched U in the range 3 to 5% U-235. The argument could be made that EU should be more expensive to handle that DU (or NATU); however, the answer lies in the design complexity of the fuel itself, the process interfaces such as UF6 deconversion, and the higher annual operation and maintenance (O&M) cost for fuel assembly manufacture. The difference is not in the process building design since both fuels can be produced in a Category III commercial nuclear facility. The higher SFR metal fuel unit cost from the NASAP study is a result of the following:

- The U-metal blanket pellet is about half the size of a sintered EUOX pellet, so there are many more pellets to handle
- The all-metal SFR fuel assembly is smaller than an LWR-UOX fuel assembly, so there are more of these to rods to bundle and inspect
- The thinner U-metal SFR blanket rod would likely require a sodium-bonding step
- The front-end reduction step to produce U-metal from DUF6 or NATUF6 is a more complex batch process compared to the simpler semi-continuous EUF6 to EUO2 step for the LWR ceramic pellet fuel.

D1-6A.8.2. HALEU Fuels

DU- or NATU-metal blanket fuels above and HEU RRs below are the only U metal fuel types for which either detailed cost-modeling or price experienced-based data were available, respectively, the NASAP study for the former and IAEA and other vendor data on the latter. The Lightbridge metal LWR fuel concept also falls in this HALEU category, but no projected manufacturing cost data is available, most likely for proprietary reasons. (Lightbridge makes an economic case for the fuel based on reactor and fuel performance improvements leading to less fuel usage per kwh generated.) To calculate unit cost ranges for HALEU, a graphical interpolation method was used, based on the fact that the unit fabrication cost should increase somewhat exponentially with U-235 content. Criticality concerns associated with increasing U-enrichment assay drive manufacturing processes to smaller batch sizes which are less efficient from a cost standpoint. Probably, the largest effects are the security, safety, accountability, and other nonproliferation regulations associated with higher enrichments and the transition from Category III to Category II or Category I facilities. Figure D1-6A.10 shows a log-log plot of unit costs versus percent U-235 in the overall U fuel meat. The upper right (HEU RR fuel) and lower left (depleted and NATU blankets) quadrants of the plot show regions where unit costs ranges are known. It would make sense that HALEU unit costs would fall in the space between these corners. A straight line drawn on the log-log plot between the two areas would not be realistic, however, since there are some real regulation-based breakpoints between 5% and 10% U-235, 10% U-235 and 20% U-235, and 20% U-235 to 90+% U-235. These are the regulations governing the type of facility physical protection and MPC&A required. These can have a strong effect on both the up-front capital costs and recurring costs which are factored into the unit cost of fabrication. For this reason, the graph has discontinuities or breakpoints at 5%, 10%, and 20% U-235.

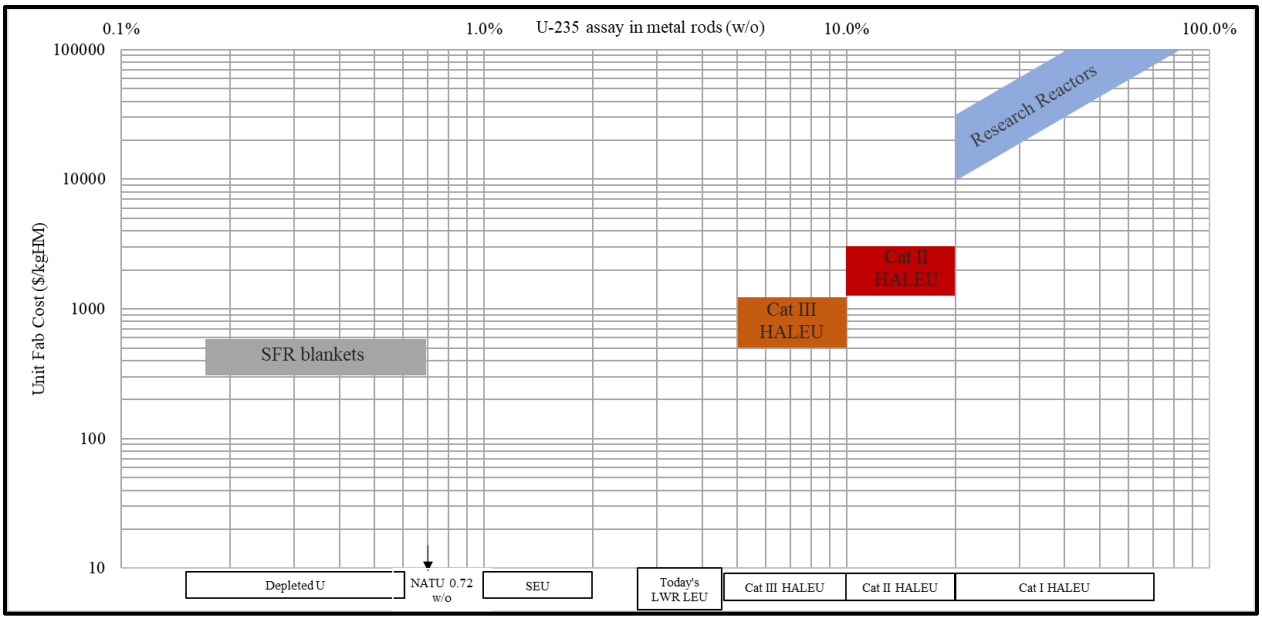


Figure D1-6A.10. Log-log plot of unit fabrication cost in 2019 USD versus U-235 assay or fissile content.

The region from DU up to 10% U-235 is for the least expensive Category III facility; however, no actual high-throughput U metal fabrication plants exists in the range 5–10% U-235 in the United States, new regulations for Category III facilities above 5% (LEU-plus) will soon be needed for some accident tolerant fuels, and these regulations will likely result in somewhat higher fabrication costs. The 10% to 20% U-235 upper HALEU range requires a Category II facility for which regulations have not yet been developed but will certainly be more stringent than for lower Category III HALEU. Assays of 20% and above (HEU) require very high security, and the required Category I facility will experience the highest costs per kgU processed. It is also useful to consider where the projected unit cost for contact-handled U,Pu metal fuel falls on this plot. The highly detailed 1978 NASAP study and its recent FCRD re-analysis (Module D1-6B) calculate a unit cost of 2,087 $/kgHM (in 2017 USD) for this clean (very low percentage of higher actinides and lower percentage of higher Pu isotopes) SFR fuel produced at 50 MTHM/yr in a Category I facility. This U,Pu metal alloy fuel is assumed to have a fissile content of ~15 to 20%, so one would expect HALEU in the 10 to 20% U-235 range to be lower, since direct contact rather than glovebox operations are allowable in most areas of the plant, and Category II instead of Category I regulations would apply.

For Category III HALEU-metal fuel in the 5 to 10% U-235 range (aka LEU-plus), a baseline value was determined by extending the plot line for the 0.15 to 10% X-axis values on Figure D1-6A.10 plot. Assuming the plot line contains most likely or mode values, a rounded-off unit cost of $500/kgU was selected. This Category III HALEU is assumed to be manufactured from blended or virgin U which has been unirradiated, hence has no or only trace amounts of U-236, U-232, transuranics, and FPs. The following Table D1-6A.6 shows the selected range values and uncertainty distribution type for this fuel. The range allows the inclusion of both injection-cast and extruded U-metal fuel types.

Table D1-6A.6. AFC-CBR 2020 update WIT unit fabrication cost values for never-irradiated 5 to 10% U-235 HALEU-metal fuel produced in a Category III facility.

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2019	400 $/kgU	500 $/kgU	1,000 $/kgU	633 $/kgU	Triangular
2020*	404 $/kgU	505 $/kgU	1,010 $/kgU	640 $/kgU	Triangular
* Escalation from 2019 to 2020 is 1%.					

As with LEUOX fuel, HALEU-metal fuel could be reprocessed and the REPU converted, re-enriched, and refabricated to new metal fuel. The trace amounts of U-232 daughters, transuranics, and FPs present would require additional personnel protection measures as it does for contact-handled UOX. As with UOX, an approximate 10% cost penalty is assessed to the unit fabrication cost to cover the additional life cycle expenses. Table D1-6A.7 below shows the selected range and distribution type. All hands-on contact handling in a Category III facility is still assumed.

Table D1-6A.7. AFC-CBR 2020 update WIT unit refabrication cost values for reprocessed and re-enriched 5 to 10% U-235 HALEU-metal fuel produced in a Category III facility (re-enrichment and chemical conversion costs not included in refabrication cost).

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2019	450 $/kgU	550 $/kgU	1,100 $/kgU	697 $/kgU	Triangular
2020**	455 $/kgU	556 $/kgU	1,111 $/kgU	707 $/kgU	Triangular
** Escalation from 2019 to 2020 is 1%.					

For Category II HALEU (10 to 20% U-235), the unit cost versus enrichment plot takes a stepwise jump upward due to the many more rigorous CAT-II regulations regarding primarily criticality safety and MPC&A. This fuel is now in the same fissile content range as U,Pu-alloy SFR-MOX or SFR metal fuel. The most likely unit cost value selected for this Category II HALEU case is between the NASAP-derived most likely value for U,Pu-alloy fuel (see Module D1-6B) on the high end and the above (Table D1-6A.7) high 5 to 10% Category III HALEU unit cost value on the low end. The following Table D1-6A.8 shows the selected range and distribution type for unirradiated 10 to 20% HALEU fuel.

Table D1-6A.8. AFC-CBR 2020 update WIT unit fabrication cost values for never-irradiated 10 to 20% U-235 HALEU-metal fuel produced in a Category II facility.

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2019	1,100 $/kgU	1,300 $/kgU	1,500 $/kgU	1,300 $/kgU	Triangular
2020*	1,111 $/kgU	1,313 $/kgU	1,515 $/kgU	1,313 $/kgU	Triangular
* Escalation from 2019 to 2020 is 1%.					

The higher initial enrichment level and likely higher burnup mean any reprocessed and re-enriched U from this U metal fuel type is likely to have even higher U-232, U-236, transuranic, and FP content than lower enrichment HALEU fuel. The unit cost penalty is likely to be greater than 10% since highly shielded gloveboxes may be needed. The penalty delta was chosen by examining the NASAP study unit cost difference (in 2017 USD) for fabricating and refabricating U,Pu metal fuel at a production rate of 50 MTHM/yr, which is approximately $700/MTHM. Applying the same $700/kgHM difference to the range in the Table D1-6A.8 above gives the following unit fabrication cost values for Table D1-6A.9.

Table D1-6A.9. AFC-CBR 2020 update WIT unit refabrication cost values for reprocessed and re-enriched 10 to 20% HALEU-metal fuel produced in a Category II facility.

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2019	1,800 $/kgU	2,100 $/kgU	2,500 $/kgU	2,133 $/kgU	Triangular
2020**	1,818 $/kgU	2,121 $/kgU	2,525 $/kgU	2,155 $/kgU	Triangular
** Escalation from 2019 to 2020 is 1%.					

It should be noted that the 2017 AFC-CBR Update, Module D1-4 (SFR Ceramic Pelletized Fuels) did not differentiate between low-assay medium-enriched U (MEU) (Category II) and higher-assay MEU (Category I) UOX start-up fuel for SFRs. Note with the recent definition of HALEU, the acronym MEU has fallen in disfavor. The 2017 AFC-CBR suggested the following range (Table D1-6A.10) for MEU ceramic UO2.

Table D1-6A.10. 2017 AFC-CBR WIT unit fabrication cost values for unirradiated SFR UOX MEU (10 to 40% U-235) start-up fuel.

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2017	520 $/kgU	900 $/kgU	1,290 $/kgU	903 $/kgU	Triangular
2020***	547 $/kgU	947 $/kgU	1,357 $/kgU	950 $/kgU	Triangular
*** Escalation from 2017 to 2020 is 5.2%.					

The new 2020 values in Tables D1-A.6 through D1-A.9 above now correctly recognize what will likely be significant cost differences in life cycle costs between Category II and Category III facilities, and significant differences between handling unirradiated new fabricated fuel vis-à-vis refabricating reprocessed and re-enriched material. Table D1-6A.10 was provided to supply some historical perspective.

D1-6A.8.3. HEU Fuels

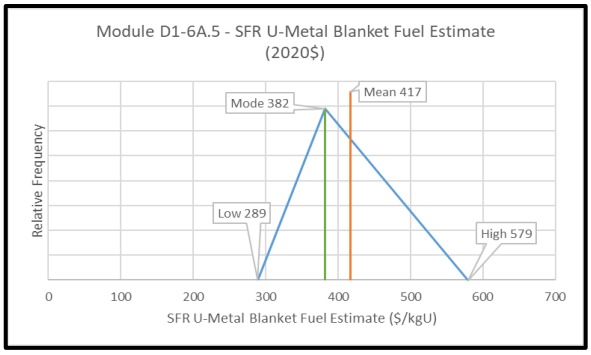
In the United States, the fabrication of HEU fuels (U235 assay 20% or greater) requires a highly secure Category I facility, since material at this assay is considered weapons useable. In addition to higher costs for criticality safety and the inefficiencies of small batch sizes, there are considerable costs for security (i.e., guns, gates, and guards). Despite these fuel-handling difficulties, some reactors may require HEU for reasons of high neutron flux requirement (RRs), very small size for specialized electricity or heat applications (microreactors), or the need for a high power to weight ratio (marine reactors and space reactors). Very small production rates, typically <1 MTU/yr, and often very complex fuel design also result in increased unit costs. RR fuels, such as those manufactured by BWXT in Lynchburg, VA, are essentially custom-made entities. The following Table D1-6A.11 provides the 2019 AFC-CBR update values for this class of U-metal fuels. One might surmise that fuel design, regulatory, safety, and security differences within this category probably overwhelm any differences between metal and ceramic fuels. For this reason, the table below could apply to ceramic fuels such as UO_2, U carbide, U oxycarbide, U silicide, and U nitride. It is assumed these fuels are not reprocessed and re-enriched for possible reasons of providing high-assay REPU for refabrication. (At one time, the U.S. government did reprocess HEU production and naval reactor fuel because of a shortage of U for military applications.)

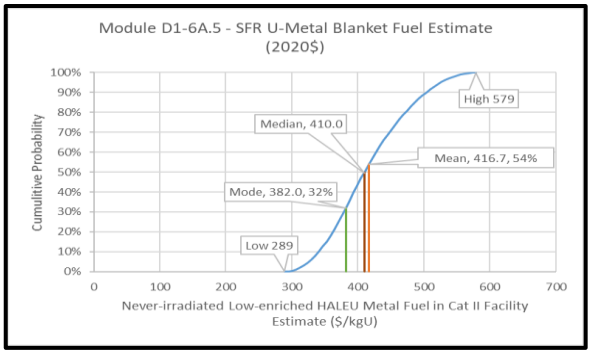
Table D1-6A.11. 2017 AFC-CBR WIT unit fabrication cost values for HEU (> 20% U-235) specialty fuels.

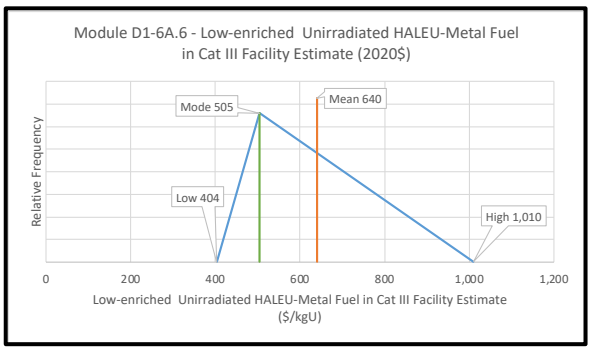
Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2017	10,000 $/kgU	25,000 $/kgU	150,000 $/kgU	61,700 $/kgU	Triangular
2020	11,000	26,000	158,000	65,000	Triangular
Escalation from 2017 to 2020 is 5.2% then rounded to nearest thousand.					

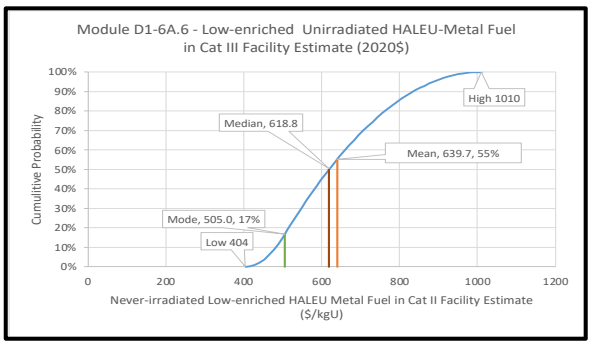
D1-6A.8.4. What-It-Takes Summary

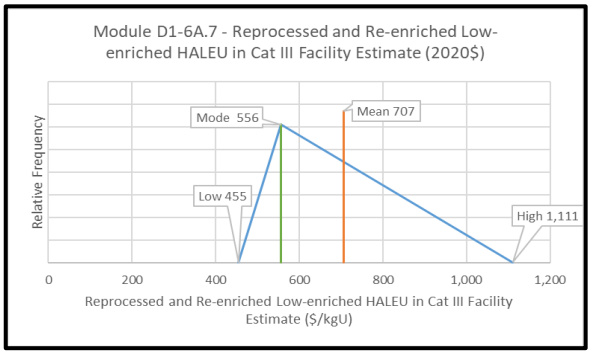
Figure D1-6A.11 below shows the ranges and distribution types for all six uranium metal or metal alloy fuel types considered in this FY-21 update.

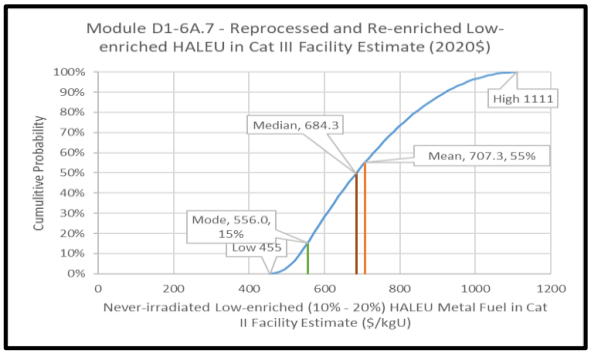

Module D1-6A.5 - SFR U-Metal Blanket Fuel Estimate (2020$)
Mode 382
Mean 417
Low 289
High 579
Relative Frequency
0
100
200
300
400
500
600
700
SFR U-Metal Blanket Fuel Estimate ($/kgU)


Module D1-6A.5 - SFR U-Metal Blanket Fuel Estimate (2020$)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulitive Probability
High 579
Median, 410.0
Mean, 416.7, 54%
Mode, 382.0, 32%
Low 289
0
100
200
300
400
500
600
700
Never-irradiated Low-enriched HALEU Metal Fuel in Cat II Facility Estimate ($/kgU)


Module D1-6A.6 - Low-enriched Unirradiated HALEU-Metal Fuel in Cat III Facility Estimate (2020$)
Mode 505
Mean 640
Low 404
High 1,010
Relative Frequency
0
200
400
600
800
1,000
1,200
Low-enriched Unirradiated HALEU-Metal Fuel in Cat III Facility Estimate ($/kgU)


Module D1-6A.6 - Low-enriched Unirradiated HALEU-Metal Fuel in Cat III Facility Estimate (2020$)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulitive Probability
High 1010
Median, 618.8
Mean, 639.7, 55%
Mode, 505.0, 17%
Low 404
0
200
400
600
800
1000
1200
Never-irradiated Low-enriched HALEU Metal Fuel in Cat II Facility Estimate ($/kgU)


Module D1-6A.7 - Reprocessed and Re-enriched Low-enriched HALEU in Cat III Facility Estimate (2020$)
Mode 556
Mean 707
Low 455
High 1,111
Relative Frequency
0
200
400
600
800
1,000
1,200
Reprocessed and Re-enriched Low-enriched HALEU in Cat III Facility Estimate ($/kgU)


Module D1-6A.7 - Reprocessed and Re-enriched Low-enriched HALEU in Cat III Facility Estimate (2020$)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulitive Probability
High 1111
Median, 684.3
Mean, 707.3, 55%
Mode, 556.0, 15%
Low 455
0
200
400
600
800
1000
1200
Never-irradiated Low-enriched (10% - 20%) HALEU Metal Fuel in Cat II Facility Estimate ($/kgU)

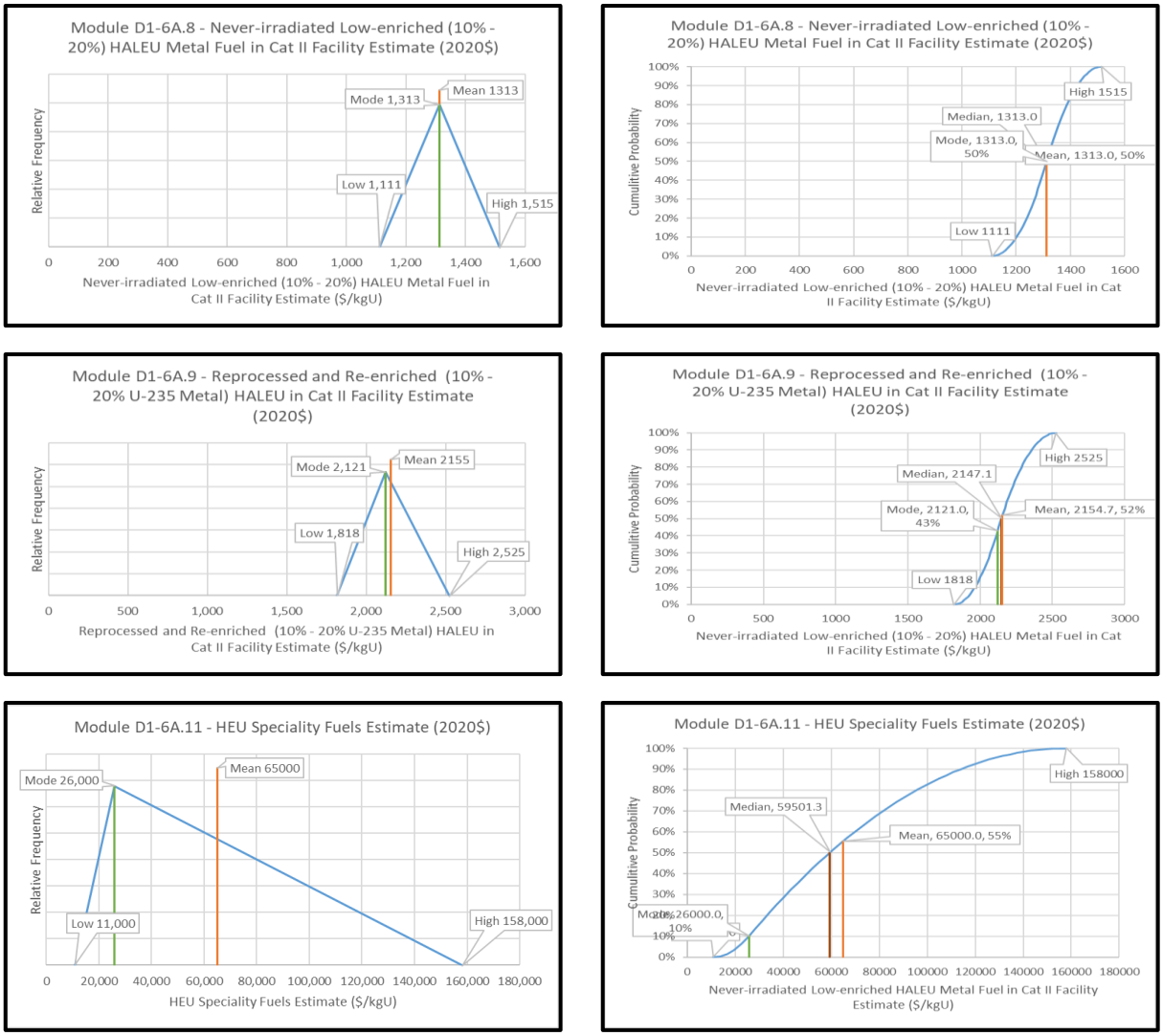


Figure D1-6A.11. What-it-takes unit fabrication costs for all-metal uranium fuels of different enrichment levels.

D1-6A.9. SENSITIVITY AND UNCERTAINTY ANALYSES

Other than unit fabrication cost versus annual production sensitivities for U metal blanket fuel, no other uncertainty analyses were conducted. Since all these fuels are assumed contact-handled for manufacturing operations in centralized plants serving a sizeable reactor fleet, the costs are probably better known than for fuels produced by on-reactor-site remote-handling covered in Module D2/F2.

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Module D1-6B
Contact-Handled U,Pu Metal Alloy Fuel Fabrication

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MODULE D1-6B CONTACT-HANDLED U,PU METAL ALLOY FUEL FABRICATION

MODULE D1-6B: SHORT DESCRIPTION OF METHODOLOGY USED FOR RE-ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant USD ($) Base Year 2020 for this FY-21 Update.**
- **Nature of this FY-21 Module Update from Previous AFC-CBR Versions:** Module D1-6B was created to separate U-Pu metal alloy fuels from those containing U metal only as the source fuel meat nuclear material (Module Dl-6A). This module also contains significantly more technical background, fuel manufacturing and usage history, fabrication process descriptions, cost basis information, and inclusion of unit fabrication cost in the WIT format used for all other AFC-CBR fuel-cycle modules.
- **Estimating Methodology for Latest (2017) Technical Update Which Escalated this FY-21 Update:**
  - No U,Pu-alloy fuel fabrication cost data was presented in the 2017 AFC-CBR version (Dixon et al. 2017), hence no escalation is applied from that document here.
  - The 1978 NASAP life cycle cost data (Olsen et al. 1979) for metal U-Pu driver fuel fabrication has been analyzed and escalated to 2020 USD to support this update. (NASAP data was presented in 1978 USD and was first escalated to 2017 USD for interim unpublished reports.) In this document, the WIT unit fabrication costs are reported in 2020 USD.

D1-6B.1. BASIC INFORMATION

In previous AFC-CBDs and updates Section D1-6.1, “Basic Information,” constituted most (only one page) of the total Module D1-6, since no or little metal fuel cost information of any type was available for further analysis and subsequent discussion. For this expanded. Module D1-6B this introductory section will be used to describe some of the characteristics, advantages, and disadvantages of U-Pu metal alloy fuel.

Characteristics of U,Pu metal as a fuel material. Uranium and plutonium metals are the most dense chemical forms for each of these two actinide elements; and therefore enable a high-fissile density (total grams of fissile isotopes per cm3) of fuel meat (depending of course on the fuel’s fissile enrichment level). This density criterion is advantageous for assuring a critical mass in the smallest possible volume. U-metal has a melting point of 1132 C and Pu metal a MP of 694 C, which is lower than the MPs of the ceramic oxide compounds UO2 (MP of 2865 C) an PuO2 (MP of 2744 C) in MOX fuel. Both are reactive metals which are readily oxidized in air and water, with reaction rates depending on its morphology and temperature.

The advantages of U,Pu metal are: (1) high-thermal conductivity compared to ceramic MOX fuels, allowing a lower fuel rod centerline temperature, (2) the possibility of utilizing standard metallurgical operations such as alloying, extrusion, casting, and forging if such operations can be safely contained in gloveboxes, (3) due to its high-fissile density the capability for high burnup associated with the possibility of higher neutron fluxes (provided issues of fuel swelling, fission gas behavior, and cladding performance can be resolved), and (4) the considerable government and industrial experience over the past 60+ years in U,Pu metal handling and fabrication for small annual production rates. A short U,Pu-metal fuel fabrication and in-reactor usage history will be given below.

Disadvantages include: (1) bare uranium and plutonium oxidize readily in air and water, especially at higher temperatures and high humidity; thereby constituting a serious fire hazard, (2) U,Pu alloys generally require additional alloying with Zr, iron molybdenum, or other non-radioactive metals to reduce corrosion, reduce the fuel rod-deforming stresses of irradiation, and to raise the MP of the alloy above the U-Pu eutectic MP, (3) the need to provide both a rod cladding with a less reactive metal and an interfacing method for readily transferring heat from the fuel meat to the clad, such as the use of sodium bonding as a fabrication process step, (4) compared·to the fabrication of U-only, for which most operations are open air non-glovebox, all U,Pu operations prior to sealed rod bundling must be accomplished in gloveboxes. Some hot, long-rod metallurgical operations such as extrusion may be very difficult in this environment, and (5) because of the presence of Pu-239, a strategic fissile material used for weapons, any U.S. fuel fabrication facilities using Pu are considered by the USNRC to be Category I nuclear facilities, thus requiring more robust building and process design from the standpoint of MPC&A. Protection of workers from airborne alpha contamination is also more difficult than for U,Pu facilities than for U-only facilities.

Factors Affecting Unit Fabrication Cost. Since this document deals with life cycle costs, the multiple factors affecting the unit cost ($/kgHM) for metal U,Pu fuel must be addressed. These are:

- The temperature and neutron flux to which the fuel will be exposed (i.e., the irradiation robustness of the fuel).
- The coolant and moderator to which the hot fuel will be exposed.
- The scale of production (MTHM/yr). In this report, we are interested in the NOAK unit production cost for the production, in a stand-alone facility, of enough fuel to support a fleet of FRs with a particular mature core and fuel design and a mature fabrication process technology.
- The level of initial fissile enrichment percentage of fissile U-235 and fissile Pu isotopes (such as Pu-239) in the fuel. The fuels we will be discussing below are likely to have fissile contents ranging from 15 to 20% for large reactors and 20 to 30% for small compact reactors.
- The hardware complexity of the final fuel assembly product. Both alloying metal and cladding/bundling hardware (purchased and on-site manufactured) costs should be included in the unit fabrication cost.
- The source and form of the U and Pu feeds to the manufacturing facility prior to alloying. Chemical treatment or conversion (i.e., the reduction of oxides or salts to metal) might be required for some feed forms such as UF6, UF4, U3O8, PuO2, PuC14, UF4, UO3, or UO2. The complexity of the non-fuel meat hardware in the rod and fuel assembly is also important.
- The amount of automation implemented in the fabrication process design. Automation can reduce personnel costs and reduce total radiation exposure to the overall workforce.

Potential Markets for Uranium Metal-Based Fuels. The following uses for U-metal or U-metal alloy fuels could provide future markets for this fuel type and/or the continuation of existing markets.

- Future metal-fueled SFR might operate in a plutonium breeding mode, where DU- or NATU-metal blanket rods are required for the radial blankets and for the ends of the higher fissile content driver fuel rods, thereby constituting an axial blanket function. The irradiated blankets and spent U,Pu,Zr alloy driver fuel would be reprocessed to recover fissile plutonium for refabrication into recycle (U,Pu) metal alloy rods for another irradiation pass. The type of SFR-driver fuel required for such a breeding function is the type of fuel discussed in this Module Dl-6B. It is assumed that the Pu utilized for fabrication as part of the U,Pu,Zr alloy is relatively clean (i.e., the percent content of trace FPs and the higher actinides neptunium, curium, and californium are very low). The content of higher Pu isotopes such as Pu-238 and Pu-240 are also assumed lower than for some SFR operating modes such as actinide burners where the initial fissile content and in-core burnup are higher. The designation clean here means that the fuel can be fabricated (and refabricated) by contact handling, which in our definition means gloveboxes, some of which may require heavy personnel shielding. The origin of this clean Pu will be explained in a following Subsection D1-6B.4, “Fuel Cycle Interfaces,” of this module.
- Mostly or all-metal uranium alloy rods are being studied for use in existing and future LWRs (The Lightbridge/EnFission fuel concept described in Module D l-6A would utilize HALEU of around 19.95% U-235.) Advantages of metal fuel in LWRs would include ability to remove heat rapidly with power up rates for existing ceramic fuel cores as a possibility, and higher fuel burn up with less refueling downtime and less fuel usage. A very similar extruded metal rod concept has been proposed for the disposition of clean surplus WG-Pu as U,Pu metal alloy in LWRs. The “Radkowsky Seed-Blanket” (Ref D1-6B) concept was briefly investigated as part of the U.S. Pu-disposition program, and involved twisted U,Pu-metal rod drivers surrounded by fertile thorium dioxide ceramic pellets. Module D1-8 of the 2017 AFC-CBR discusses this concept as a possible application for thorium use as blanket material in LWRs.
- Some advanced FR concepts require metallic contact-handled U,Pu alloy as a fuel source, especially in the early stages of U-Pu-only use before any higher actinides (Np,Cm,Am) are introduced into the unirradiated fuel alloy for burning. A 100 MTHM/yr plant fabricating such fuel could support a fleet of ~10 one-GWe SFRs operating on fuel that is 15 to 20% fissile in a high conversion ratio mode Eventually these reactors might be converted over the burning of multi-actinide (U, Pu, Np, Am. Cm) refabricated metal fuels requiring totally remote refabrication in hot cells or canyons. Small SFRs might require higher fissile content (> 20%) metal alloy fuels to counteract the neutron leakage associated with smaller cores.

History of U,Pu-Metal fuel fabrication. The following historical information is given to provide the reader with the wide international scope of experience in the fabrication of uranium-plutonium metal alloy fuels over the last 70 years:

- **EBR-I Fourth Core.** The 1.1 MWth Experimental Breeder Reactor-I (EBR-I aka CP-4) was commissioned near Idaho Falls ID in 1951, and operated until 1963 (Vam Jaaftem and Turner 1979). The initial three EBR critical masses consisted of 52 kg of U-235 HEU in the form of pins and was about the size of a U.S. football. The total U mass would have been around 100 kgU with an enrichment of over 50% U-235. Uranium metal fuels used in EBR-I consisted of unalloyed HEU (Core 1) and U-Zr alloys (Cores 2 and 3). Cylindrical pin diameters were slightly less than 1 cm for all three uranium cores. (A fourth core using a metallic Pu-Al alloy was introduced toward the end of the EBR-I overall campaign.) The first two cores were clad in stainless steel, and the last two with zircalloy. Zr was found to enhance the radiation resistance of the fuel, resulting in less deformation of the pins. This reactor was the first to demonstrate that plutonium breeding could produce more fissile atoms than are consumed. The fuel pins were fabricated and clad in a small manufacturing facility on the Idaho Falls reservation, which at the time was called ANL-W (now INL's Materials and Fuels Complex [MFC]) in Idaho Falls.
- **Final Cores for EBR-II.** The 62 MWth Experimental Breeder Reactor (EBR-II) was commissioned near Idaho Falls, ID in 1964 and operated until 1994. It was intended to demonstrate the concept of breeding plutonium using a heterogeneous driver/blanket fuel arrangement in the reactor core, and its adjacent support facilities were operated to demonstrate non-aqueous pyrochemical reprocessing of spent fuel and its refabrication (a subject covered in Module D2/F2 and Trybus, Sanecki, and Henslee [1993]). The unirradiated fuel charged consisted of stainless-steel clad U,Pu-containing rods 5 millimeters in diameter and 33 cm (13 in.) long. A typical rod had a mass of 65 to 70 grams of U,Pu alloy. Enriched to 50 to 70% fissile (uranium-235 + plutonium-239) when fresh, the fissile concentration dropped a few percent upon discharge due to fissioning. Most of the metal alloy rods also contained 10% Zr; however, the early cores were charged with 5% fissium [Fs], a non-radioactive group of elements (stable isotopes) meant to act as a surrogate for more radioactive FPs of the same elements. This substitution was done to study cladding-FP interactions under irradiation. Each fuel element was placed inside a thin-walled stainless-steel tube along with a small amount of sodium metal. The tube is welded shut at the top to form a rod unit 73 cm (29 in.) long. The purpose of the sodium bonding is to function as a fuel meat-to-cladding heat-transfer agent. As more and more of the uranium and plutonium undergoes fission, the fuel meat develops fissures, and the molten sodium enters the voids. Excellent production history information is available in References D1- 6A.28 through Dl-6A.32. The enriched uranium and U-Pu-metal fuels were manufactured on the ANL-W Idaho Falls site. The maximum annual U,Pu fabrication rate never exceeded one MTHM/yr. Five EBR-II cores were produced with the following compositions: Mark I: U-5% Fs, Mark II: U-10%Zr and U 5%Fs, Mark III: U- l0%Zr, Mark IV: U-l0%Zr with different clad; and Mark V: 70%U-20%Pu-10%Zr.
- Los Alamos Molten Plutonium Reactor Experiment (LAMPRE-I) operated in the early 1960s and was fueled with molten Pu-iron alloys. Useful plutonium metallurgy data were obtained from this effort.

- The FFTF is a 400 MWth, liquid-sodium-cooled, nuclear test reactor owned by the U.S DOE's (Adams 2017 and Pitner and Baker 1993). It does not generate electricity. It is situated in the 400 Area of the Hanford Reservation in the state of Washington. From April 1982 to April 1992, it operated as a national research facility to test various aspects of commercial FR design and operation, especially relating to breeder reactors; however, the FFTF is not a breeder reactor itself. The reactor at first operated with ceramic oxide fuels but was converted to metal fuel toward the end of its operating life. Over 1000 U-Zr and U-Pu-Zr fuel rods were irradiated at FFTF. Over 800 HT9-clad U-l0Zr fuel elements, 91.4 cm tall, were irradiated at FFTF. This irradiation campaign addressed the concern that longer rods (i.e., those > than the 33 cm in EBR-II) may not behave as well as short ones. Metal fuel for this reactor was provided from ANL-W. Earlier U,Pu-MOX fuel was provided from a NUMEC, Inc. facility in Apollo Township, PA. and a Kerr McGee Corp plant in Cimarron, OK. Fuel production rates for all fuel types were small (i.e., at most a few MTHM/yr).
- The Clinch River Breeder Reactor (CRBRP) was partially constructed in Oak Ridge, TN and was to have been a demonstration of the LWR spent fuel recycling and FR breeding along with commercial electricity generation. The U,Pu-containing fuel for this facility was selected to be ceramic U,Pu-MOX fuel instead of metal fuel. More of this FR-MOX fuel history can be found in Module D1-4. A reprocessing plant to recycle the CRBRP driver and blanket spent fuel was also being planned at the time.
- Other countries showing past or present interest in U,Pu-metal fuels are South Korea, Russia, and India. The French and Japanese have shown a preference for ceramic MOX fuel for their FR programs, with transition from HALEU oxide to U,Pu MOX as the objective.
- The VTR slated for construction at INL will use ~1,800 kgHM annually of a HALEU, Pu,Zr metal-alloy fuel. It is likely to be fabricated in an on-site facility.
- The following conclusions regarding U,Pu-metal fuel production capability and rates can be drawn from the above history:
    - DU or NATU, needed as the fuel meat diluent for the plutonium metal, has been handled in thousands of MTU/yr production rates, and the chemical/metallurgical process technology is mature. Category III facilities for blendable U-metal production (from UF6 or UOXs) could be constructed and operated with minimal security and criticality regulations and with little regulatory ratcheting.
    - Most of the considerable experience with U,Pu-metal fuels was in the late 1950s through the late 1980s. Most of the world's U,Pu fuel experience is now with MOX ceramic fuel rather than U,Pu-metal alloy fuel. Modules Dl-2 and Dl-4 deal with LWR MOX and FR MOX, respectively.
    - Most countries possessing nuclear weapons still have the capability to handle and fabricate metallic Pu and its alloys. Historically, most Pu experience in the United States has been at the now-decommissioned Rocky Flats and Hanford Plutonium Finishing Plants (Golden, CO and Richland, WA, respectively). There are also presently operating NNSA defenses facilities capable of Pu-handling at the SRS (Aiken, SC), the Pantex Plant (Amarillo, TX), and the Los Alamos National Laboratory (Los Alamos, NM). The Radioisotope Engineering and Development Center at ORNL and the Fuel Manufacturing Facility (FMF) at INL can handle Pu and some higher actinides for non-weapons R&D.

- The design for the proposed VTR at INL envisions using metallic SFR fuel, most likely an alloy of Pu, ~5% U-235 enriched U, and Zr. It is felt that there will not be sufficient HALEU available for start-up of this test reactor, which will require ~1.8 MTHM of U,Pu,Zr fuel per year (U.S. DOE 2020) DOE's stockpile of surplus WG-Pu would be the technologically best source of Pu metal for alloying; however, considerable processing by NNSA/SRS might be required before any fabrication steps. The *December 2020 Draft VTR Environmental Impact Statement* (DOE/EIS-0542: U.S. DOE 2020) describes the processes and possible sites for fuel manufacture. As with earlier metal alloy fuel projects, injection casting would be the preferred manufacturing process. No cost projections for fuel fabrication are included in the VTR EIS; however, useful fuel design information is available therein.

D1-6B.2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

As with U metal only, U-Pu metal alloy fuel has the advantage of enabling rapid heat removal from the fissioning reactor fuel because of the high-thermal conductivity of metal as opposed to pressed and sintered ceramic powder. The number of steps in a metal-based fuel fabrication process is also smaller than the step count for a process involving ceramic powder blending and handling such as that for U,Pu-MOX fuel. One would surmise that there should be some fabrication life cycle cost advantages (Lineberry 2012) to metal fuel over oxide fuel. Metal fuel is now the preferred fuel type for SFR development in the United States because of its compatibility with dry (non-aqueous) pyrochemical reprocessing flowsheets and the IFR concept. For FRs, U-Pu metal fuel would be used for driver positions in the reactor core after the SFR start-up program, based on HALEU-metal driver fuel, is complete. The timing of this transition would depend upon whenever enough metal Pu from LWR-SNF reactor reprocessing or weapons dismantlement is available for the preparation of U,Pu-alloy drivers. Metal Pu-containing driver fuel has also been suggested for use in LWRs in a seed-blanket concept, but the concept probably could not be further developed and implemented until U metal only drivers are successfully demonstrated in LWRs. Contact-handling fuel fabrication is assumed for all the U-Pu metal alloy fuels discussed in this module. (The non-glovebox fabrication of all-metal U blanket fuel for SFRs is discussed in Module Dl-6A.) In most cases, the majority of the U,Pu fuel-handling steps require gloveboxes. Direct hands-on non-glovebox bundling operations for U,Pu fuels can occur after the fuel rods are welded shut and decontaminated. Most steps in the metal fabrication process will require an inert glovebox atmosphere to prevent metal oxidation and fires.

In the United States, a Category I type facility is required per USNRC regulations for handling multi-kilogram plus fissile materials possessing possible strategic value. There are two basic metallurgical techniques for U-Pu alloy fuel manufacture: casting and extrusion.

- **Casting.** After the U-Pu-Zr alloy blend is prepared in the molten state, a set of evacuated upside-down quartz tubes is inserted into the melt and the molten alloy driven upward into them by a pressure differential (See section Dl-6B - and Figure D1-6B.1 below) After cooling the quartz tubes, which are essentially acting as molds, are broken away; and the resulting U-Pu-Zr-alloy slugs cut to the proper pellet or slug length for cladding with stainless steel. As part of the cladding process a tiny amount of molten sodium is forced into the slug-rod interface to provide a highly conductive metal interface for slug or pellet stack to clad heat transfer. This process is known as sodium bonding. A helical wrap can be added outside of the clad slugs to enhance the heat transfer from the rod to the SFR liquid-sodium coolant. Figure D1-6B.1 and Figure D1-6B.2 in the next subsection illustrate the overall injection casting process. All these steps must be contained in gloveboxes under inert atmosphere.

- **Extrusion.** In this method a U,Pu,Zr-metal billet, and perhaps another jacketing metal are placed in press and die system where the still-solid blended metals are heated until they plastic and can be forced through the custom die. Cladding and Na-bonding steps may be similar to those for cast slugs. Figure D1-6B.5 in Module D1-6A shows an extrusion system used for a metal fuel development project (Lavender et al. 2013) Because of equipment size and long-rod operations, the fitting and operation of extrusion equipment in the gloveboxes required by Pu use may prove to be difficult.

D1-6B.3. PICTURES AND DIAGRAMS

The figures below illustrate the basic U,Pu metal alloy casting process mentioned above.

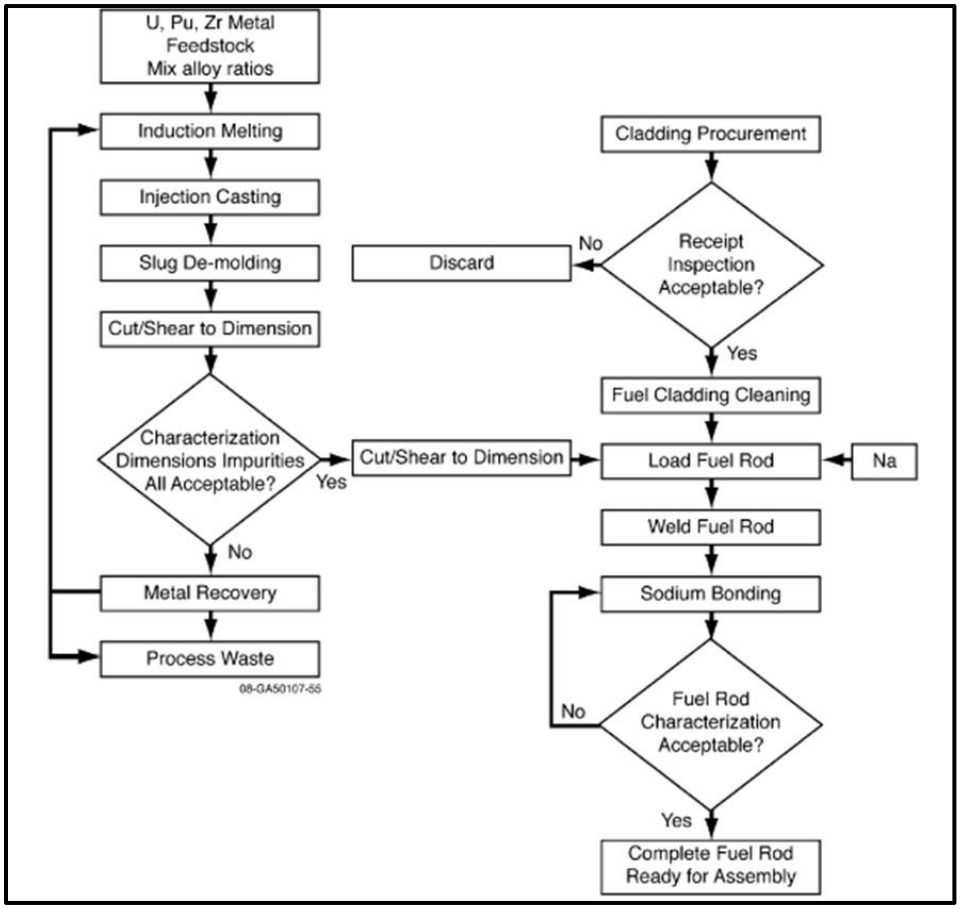


Figure D1-6B.1. Steps in the injection casting method used for the preparation of EBR-II fast reactor fuel (both U,Zr and U,Pu,Zr alloys) from Burkes et al. (2009).

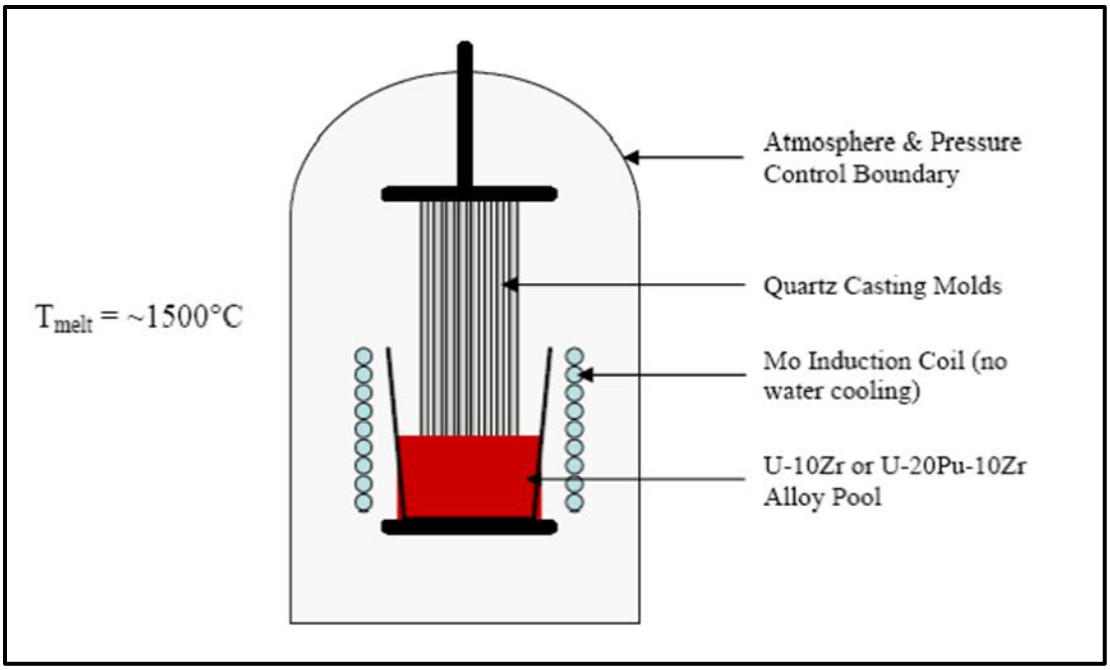


Figure D1-6B.2. Simplified injection casting equipment concept from Hausman (2011).

D1-6B.4. MODULE INTERFACES

For once-through commercial LWR fuel cycles there is a distinct separation between fuel fabrication and the conversion and enrichment fuel cycle functional steps that precede it. Both UF6 to UO2 conversion and uranium enrichment have very large stand-alone facilities that provide these two services to dozens of nuclear powerplants. For more specialized U,Pu-metal fuel fabrication the distinction between predecessor fuel cycle steps and fabrication is less distinct from a cost/pricing standpoint. The nature of the reprocessing steps that recover the Pu fur ultimate fabrication is also an important interface. In these D Modules the intent is to isolate and discuss the true cost of the fabrication and rod bundling service up to the point of transporting the packaged fuel to the reactors that burn it. The unit cost presented should not include the feed cost of the main fuel meat nuclear material containing the major fissile isotopes to the value-added fabrication process. For metal uranium fuels, however, the price would likely include the diluent uranium feedstock DU or NATU, alloying metals such as Zr, and any services required to render a previous Pu chemical form or Pu-metal shapes to the desired metal form or shape, likely to be small metal shards, for blending and alloy preparation. This situation exists because metal fuel fabrication is a relatively small lot size specialty business or government enterprise and the fissile enrichment requirements and conversion needs themselves are diverse. As will be discussed later, much of this nuclear source material has associated sunk costs such as those for surplus weapons plutonium and enrichment plant tails DU hexafluoride. The following describes the likely sources of uranium and plutonium metals as feedstocks for metal fuel fabrication:

- **DU-Metal Diluent (0.15 to 0.6% U-235)**. Huge stockpiles (hundreds of thousands of MTU) of DU exist as enrichment plant tails in the form of UF6 or U308.

- **Defluorination and Reduction Steps to Go from DUF6 to Uranium Metal Are Required.** Defluorination of DUF6 to DUF4 is a continuous process. Reduction is generally a batch process requiring the exothermic reaction of the UF4 with an alkali metal. In this case the total defluorination and reduction costs (5 to 15 $/kgU) would be included as part of the fabrication cost. The DUF6 would likely be provided at no cost from government stockpiles, since it is considered a waste, and any beneficial use is an avoided cost to the government for storage and disposal. If DU3O8 is the starting compound, a direct reduction to metal process might be possible. No cost information on this option is available, however it is likely to be in the same range as that for DUF6 deconversion to metal.
- **NATU Metal Diluent (0.71% U-235).** The yellowcake (Uranium ore concentrate consisting of mostly U308) would be purchased on the open market (see Module A). Reduction (conversion) to metal would be required at a cost similar to that for other DU compounds such as DUF6. The reduction cost would likely be included in the overall fabrication cost.
- **Surplus Weapons-Useable Plutonium.** In a 2000 agreement (Goodson 2018) with Russia, 34 MT of weapons-derived Pu were declared available in each nation for conversion into fuel for nuclear powerplants. The intent was to convert the WG Pu into a spent fuel form with Pu isotopic vectors not suitable for recovery and reconversion of the Pu into weapons-useable material. Additionally, the resulting SNF would have been irradiated long enough to be self-protecting from the standpoint of radiation, thus making diversion for weapons use difficult. In the United States, it was decided to manufacture LWR U,Pu-MOX fuel in a plant (MFFF) formerly under construction at the SRS. The Russians decided to pursue the use of U,Pu-SFR pelletized MOX in their BN-600 and BN-800 series of SFRs. When the U.S.-MFFF project encountered large cost and schedule overruns, the DOE-NNSA began to consider alternative options, such as the construction of one or two high-energy neutron (fast) reactor (PRISM)-type 380 MWth SFRs or the restart of the FFTF at Hanford to burn the surplus Pu as U,Pu,Zr metal fuel. A study (U.S. DOE 2014) was issued in 2014 by NNSA, and the life cycle cost information therein on the fuel fabrication part of these FR options will be discussed in the next subsection of this module.

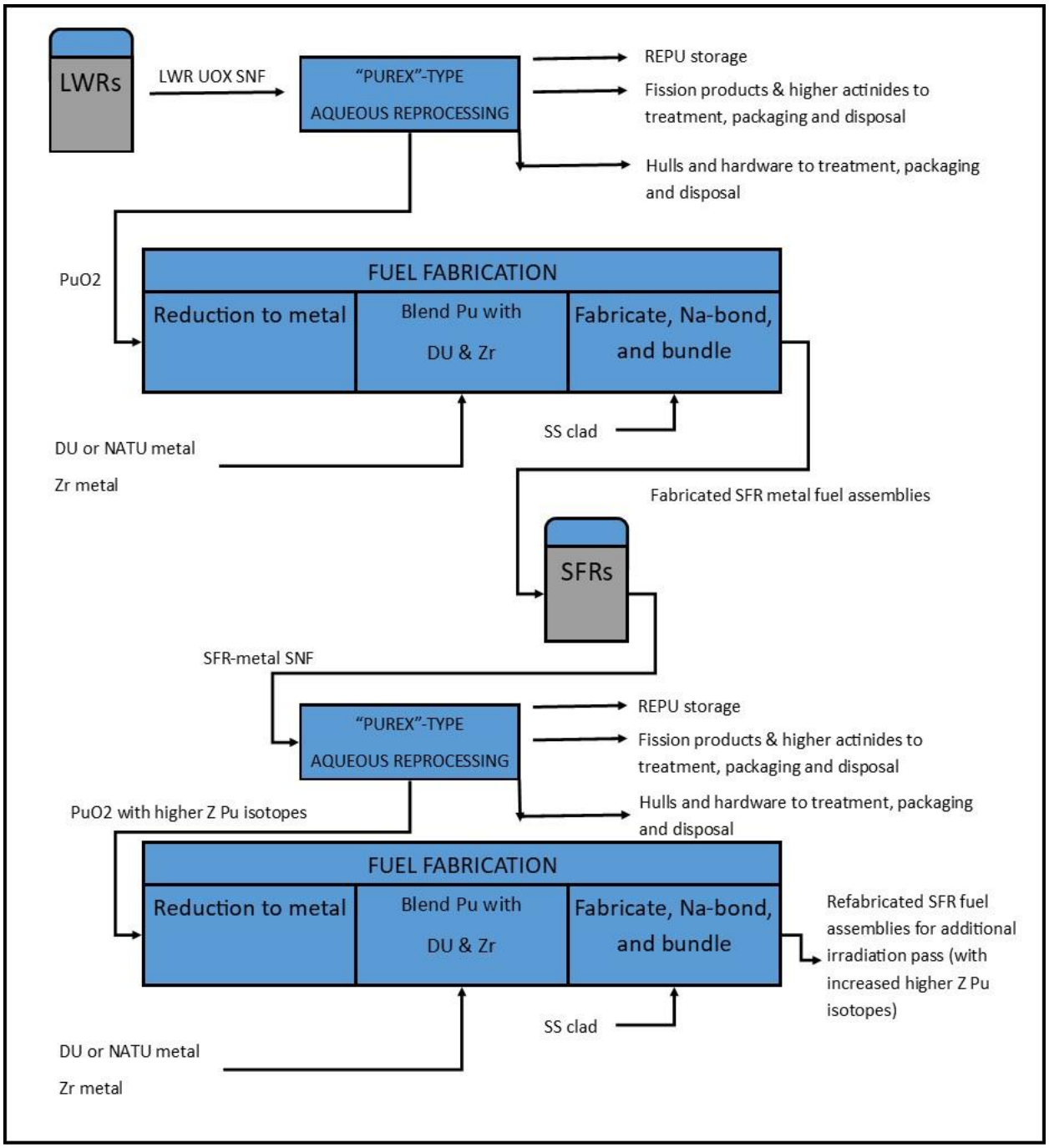
  A few words on the nature of weapons-useable Pu as a FR fuel are in order. This material was produced during the Manhattan Project and the Cold War in production reactors (at Hanford and Savannah River) by the short-period (a few months) irradiation of DU targets with subsequent PUREX-type aqueous recovery of the separated Pu in large reprocessing canyons. This short-cycling produces Pu with lower concentrations of the higher Pu isotopes, mainly Pu-238 and Pu-240, which are undesirable from a weapons design and personnel handling standpoint. The intent in a weapons application is to produce Pu with a fissile Pu-239 content greater than 80%. Higher actinides ($Z > 93$) generated by target irradiation in the production reactors, such as americium (Am), neptunium, and curium, were diverted during reprocessing into the same product stream as the FPs. REPU was separately recovered for re-enrichment. The remaining WG-Pu is referred to as very clean from the standpoint of isotopics, impacting favorably its capability for glovebox-handling. (As the Pu ages, however, the higher actinide, Am-241, is formed from the beta decay of Pu-241. Some alpha and gamma radiation results from Am-241 decay; however, the personnel protection problem is much less serious than the high spontaneous neutron generation problem from the isotopes Pu-238 and Pu-240.)

Table D1-6B.1 shows some of the properties of the various Pu isotopes and Am-241. Most U.S. surplus Pu is 30 to 75 years old and will have around 0.5 to 1% Am-241 in the metal as well as the alloying constituent gallium required for Pu-alloy phase stability in weapons applications. Using this WG clean metal for SFR U,Pu might require removal of gallium and Am to avoid adverse metal-vapor-related problems in the SFR fuel fabrication process; however , from a neutronics standpoint; FR irradiation of fuel with a small amount of gallium and Am should not have adverse reactor performance consequences. In fact, Am-241 is fissionable under fast neutron irradiation and can contribute to power production. The cost of any chemical conversion and purification steps such as aqueous polishing for WG-Pu, however, can add significantly to the overall fabrication cost. There is also a front-end cost for converting the classified Pu-metal disassembled pit shapes into unclassified metal shapes, such as shards, that can be used as blendstock in an unclassified Category I U,Pu metal fuel fabrication facility. The life cycle costs associated with the use of WG-Pu as an SFR fuel are discussed in Section D1-6B.6.

Table D1-6B.1. Properties of the various plutonium radionuclides from OECD 1989.

PLUTONIUM ISOTOPES						
Isotopic Mass	Half Life	Decay Mode (a)(b)	Specific Activity 10^9 Bq/g	Spontaneous fission neutrons n/g.s.	Heat Generation mW/g	Product
236	2.8 y	∝	1.9×10^4	37×10^3	-	U-232
237	45.3 d	β+	-	-	-	Np-237
238	87.7 y	∝	6×10^2	2.6×10^3	560	U-234
239	$2.4 \times 10^{4\ y}$	∝	2	0.03	1.9	U-235
240	$6.5 \times 10^{3\ y}$	∝	8	1.0×10^3	6.8	U-236
241	14.4 y	β	3.7×10^3	-	4.2	AM-241
242	3.8×10^5	∝	0.1	1.7×10^3	0.1	U-238
Am-241	$4.3 \times 10^{2\ y}$	∝, γ	1.2×10^2	1.1	114	–
• 0.002 per cent of Pu-241 decays produce alpha-particles.						
• All the decay processes are accompanied by the emission of some X-rays or gamma-rays.						

Clean Plutonium Derived from the Future PUREX Aqueous Reprocessing of Lower-Burnup LWR-UOX Spent Nuclear Fuel (for Fabrication into Contact-Handled U,Pu,Zr Metal Fuel in Standard Gloveboxes). Most of the world's Pu is not in weapons metal form, but rather as irradiation-formed $Pu0_2$ in the hundreds of thousands of metric tons of pelletized UOX-LWR spent fuel now stored in pools or dry cask storage. Pu content of UOX-SNF is typically around 1% of the total HM mass. Some nations such as the UK, France, Russia, India, and Japan have, are, or plan to reprocess this spent fuel and recover the Pu for use in MOX-fueled LWRs as part of a partially closed fuel cycle. The next likely Pu utilization scenario after LWR-MOX-burning would be to use the Pu recovered from UOX-LWR-SNF reprocessing in SFRs, which from a sustainability standpoint extends the world's U resources. The top half of



- Figure D1-6B.3 below shows a schematic of how LWR spent fuel reprocessing can support a fleet of SFRs.

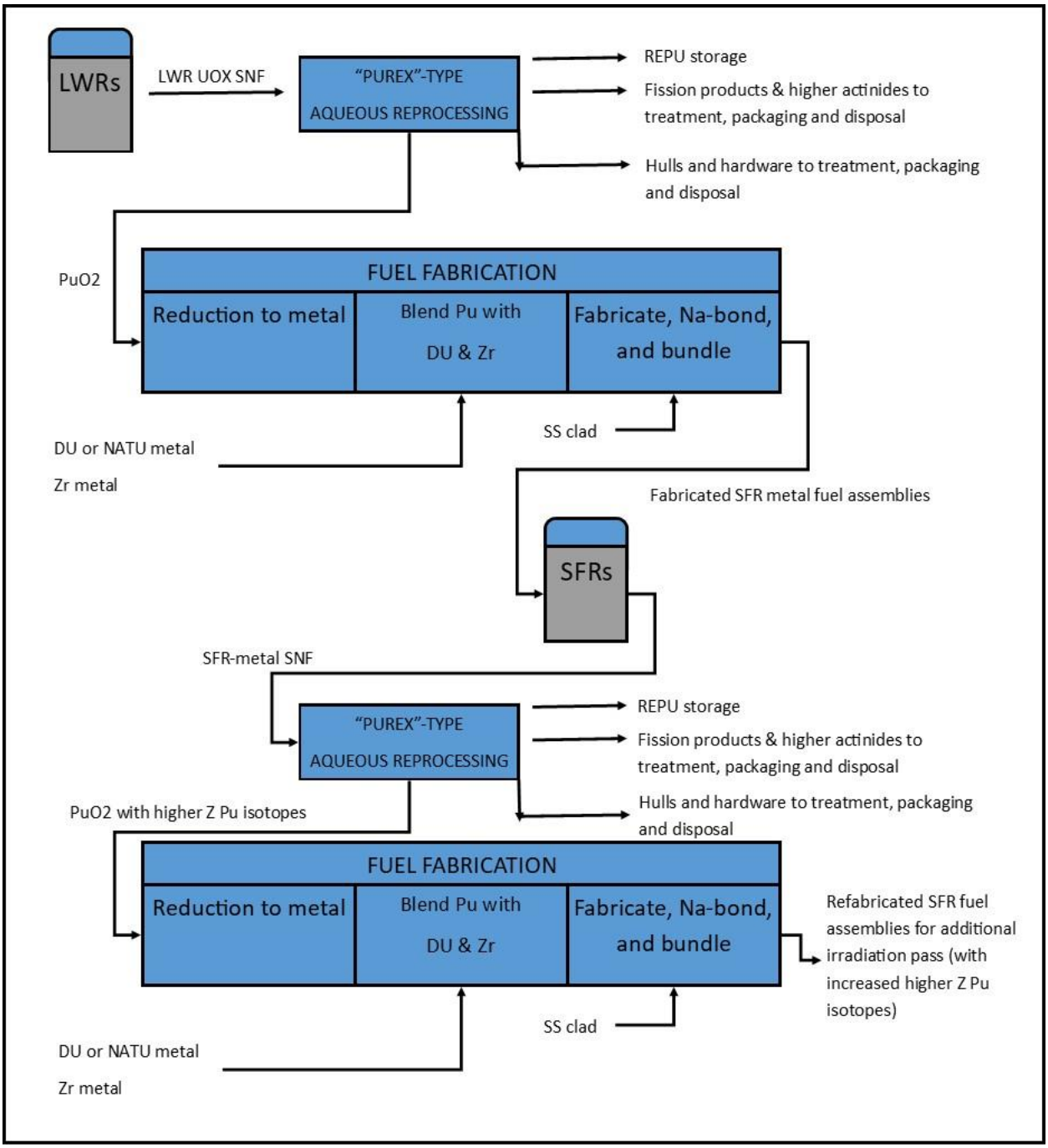


Figure D1-6B.3. Pu sources from both LWR and SFR fuel reprocessing.

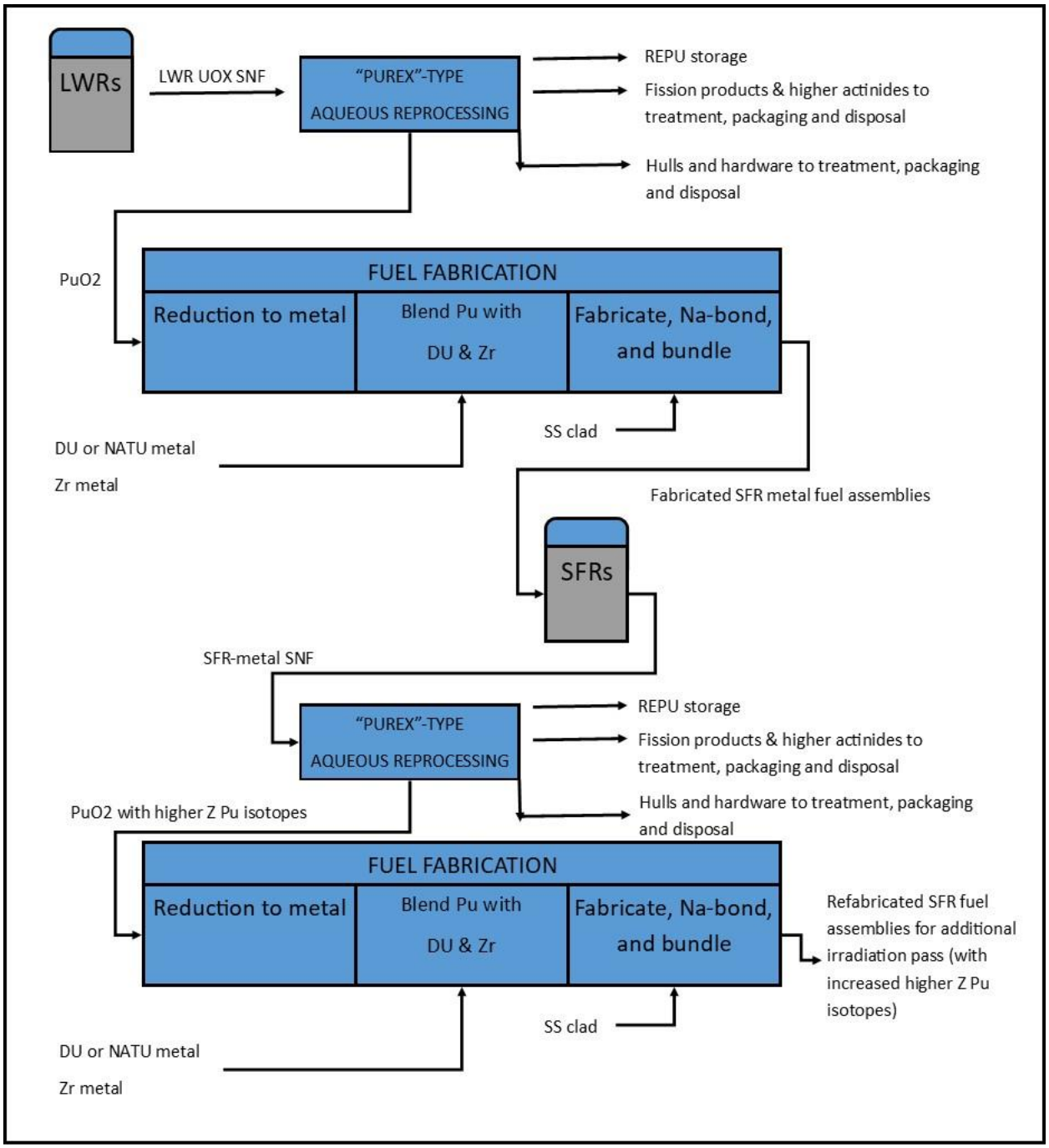
The LWR-UOX-SNF-derived Pu should also be relatively clean as a result of the PUREX-based aqueous reprocessing process effectively separating it from non-fissioned U, the higher actinides (non-Pu HAs), and the FPs. There will, however, be more higher isotopes of Pu in this Pu as compared to WG-Pu as a result of the longer fuel exposure time in a commercial reactor as compared to DU targets in a production reactor. Table D1-6B.2 below shows how fuel exposure time (as represented by fuel burnup) in LWRs affects the distribution of the various isotopes of Pu. It can be seen that lower-burnup UOX LWR SNF is cleaner in the sense that the Pu-239 fraction is higher. In any case, this reactor-grade recovered Pu can be fed to a glovebox contact-handling fuel fabrication process for U,Pu,Zr metal SFR

fuel. Since the aqueous reprocessing plant generally recovers Pu in the form of Pu nitrate crystals or $Pu0_2$, a reduction step will be needed to prepare the metal feed. Removal of gallium will not be a problem in this case, and if the U,Pu,Zr metal SFR fuel is fabricated soon after reprocessing, the buildup of Am-241 should not be a problem. The U diluents for this U,Pu,Zr fuel would likely be DU- or NATU-metal; however, some REPU recovered as uranyl nitrate hexahydrate (UNH) or UO_2 from LWR-SNF reprocessing followed by its reduction to metal could be used.

Table D1-6B.2. Average isotopic composition of plutonium produced in uranium-fueled thermal reactors from OECD 1989.

AVERAGE ISOTOPIC COMPOSITION OF PLUTONIUM PRODUCED IN URANIUM-FUELED THERMAL REACTORS						
Reactor Type	Meanfuel burn up (MWd/t)	Percentage of Pu isotopes at Discharge				
		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
MAGNOX	3,000	0.1	80.0	16.9	2.7	0.3
	5,000	*	68.5	25.0	5.3	1.2
CANDU	7,500	*	66.6	26.6	5.3	1.5
AGR	18,000	0.6	53.7	30.8	9.9	5.0
BWR	27,500	2.6	59.8	23.7	10.6	3.3
	30,400	*	56.8	23.8	14.3	5.1
PWR	33,000	1.3	56.6	23.2	13.9	4.7
	43,000	2.0	52.5	24.1	14.7	6.2
	53,000	2.7	50.4	24.1	15.2	7.1
* Information not available.						

Less-Clean Plutonium Derived from the Future PUREX Reprocessing of Lower-Burnup SFR U,Pu Metal Fuel (for Refabrication into U,Pu,Zr Metal Fuel in Gloveboxes with Additional Shielding and Remote Equipment Maintenance). During SFR irradiation, the U,Pu,Zr metal fuel itself will become SNF from which Pu may be recovered by reprocessing. If aqueous PUREX-type reprocessing is used, the Pu should be sufficiently clean from the standpoint of trace HAs and FPs that contact-handling refabrication is possible with some process containment upgrades. Due to the higher burnups possible in SFRs, the percentages of higher Pu isotopes will be higher for this refabricated U,Pu-metal fuel (the bottom half of Figure D1-6B.3) than for the first-recycle U,Pu-metal fuel derived from LWR-UOX SNF reprocessing (the top half of Figure D1-6B.3).



- Figure D1-6B.3 shows how this first SFR pass spent fuel can be reprocessed in order to provide refabricated U,Pu metal fuel for second-pass SFR use. Additional SFR-passes are possible with aqueous SFR fuel reprocessing capacity; however, each pass results in (1) recovered Pu with higher content of undesirable Pu higher isotopes and (2) the need to bump up the refabricated fuel's fissile content above the 15 to 20% fissile content typical of CRBRP-type SFRs operated in a breeding or high conversion mode. The refabricated SFR-SNF-derived U,Pu-metal FMF will likely require some more stringent design and operational requirements as a result of its higher radioactivity and heat generation during handling. Thicker glovebox windows and remote (robotic) maintenance of the fabrication line may be required to keep the facility remaining as a contact-handling class plant operating under ALARA (as low as reasonably achievable) personnel protection regulations. As will

be seen in the Section D l-6B.6, this aqueous SFR-SNF reprocessing step and refabrication idea was studied in the late 1970s (Carter and Rainey 1980) NASAP program, and fuel fabrication cost estimates for multiple fuel cycles were developed as part of this program.

- **Dirty Plutonium Recovered from Multiple-Pass or Actinide-Burner Fuel Cycles.** Too many passes of recycled Pu result in a fuel that becomes less amenable to aqueous reprocessing (due to solvent radiolysis) and subsequent contact-handling refabrication. Actinide-burning fuel cycles based on reprocessing schemes such as aqueous uranium extraction (UREX) or dry molten-salt-based electrochemistry allow the higher actinides to be recovered along with the Pu so that they can be fissioned in an SFR operating in a low conversion ratio or burner mode. The idea here is to reduce the amount of heat-generating and long-lived radionuclides in a geologic repository. Reprocessing and refabrication in these cases must be performed in a totally remote-handling facility using dry reprocessing technology such as an electrochemical/pyrochemical method. This type of metal-based integrated fuel reprocessing and fabrication is the subject of Modules D2/F2.

  Such electrochemical plants are expected to be small and attached to a set of multiple SFRs on a single site (i.e., the IFR concept). The resulting U, Pu, HA metal fuel that is fabricated will also have trace amounts of some FPs therein. It is sometimes referred to as dirty refabricated fuel.

- **Feedstock Costs**. For government-provided feedstocks such as surplus HEU or Pu, the question arises as to the feed material cost to the fabricator/user. Essentially, the costs of the production and recovery of Pu (production reactors and the reprocessing canyons) are sunk costs to the government, which were spent during the Manhattan Project and the subsequent Cold War. For some government-funded RD&D projects, surplus nuclear source material of this type is provided from the surplus stockpile at little or no cost. Surplus Pu is now in fact considered a waste for which the DOE-NNSA will incur significant costs for storage, surveillance, and eventual geologic disposal in some form. For the now-discontinued U.S. LWR-MOX-based Pu-disposition program, the USDOE had proposed the incentive of offering U,Pu-MOX fuel to a utility (Duke Power) at a unit cost less than that for LEUOX. Unfortunately, the MOX Fuel Fabrication Facility (MFFF) at SRS was never completed and operated. A dilute and dispose program utilizing DOE's SRS and waste isolation pilot plant (WIPP) facilities for surplus U.S. WG-Pu is now underway.

D1-6B.5. SCALING CONSIDERATIONS

The unit cost for the fabrication of a particular design of U-Pu or U,Pu-alloy fuel will be a function of facility size (average MTHM/yr production). As with most manufactured items, there is an economy-of-scale. In the next subsection, a NASAP-derived scaling relationship for the manufacture of two types of SFR U,Pu-metal driver fuels will be presented in graphical form (Figure D1-6B.5 and Figure D1-6B.6). In these cases, life cycle cost data were developed for plants ranging from 50 to 1,000 MTHM annual production capacity.

As the fissile enrichment level of the U,Pu-metal fuel increases, and more precautions must be taken in nuclear material handling, the following cost factors increasingly come into play and result in higher unit cost ($/kgHM):

- Criticality and the need for smaller batch sizes and equipment
- Safeguards, security, and plant physical protection
- Plant construction and operation regulations for Category I nuclear facilities
- Quality assurance and waste management
- Radiation protection for plant workers
- Increased fuel engineering development/testing costs and engineering oversight costs which are amortized into the unit fabrication cost.

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

In order to develop WIT unit cost ranges for various types of U,Pu metal alloy fuels, an extensive literature review was undertaken. Unfortunately, most of the 1950 to 2000 historical information accessed and summarized above did not include cost experience information. Commercial manufacturers, most of them government contractors to national laboratories, usually did not publish such information, and direct government materials production programs, such as those for the U.S. NNSA nuclear defense complex, do not publicize such information because of political and national security considerations. As with other fuel types such as LEUOX (Module D l-1) and LWR-MOX (Module D1-2), and SFR-MOX (Module D1-4), the 1978 ORNL/NASAP studies turned out to be the best source of comparable life cycle cost projections.

D1-6B.6.1. U.S. Government (DOE-NNSA) Studies on Surplus Weapons-Useable Plutonium Disposition

The purpose and history of the U.S. WG Pu-disposition program was explained under Section Dl-6B.4 (Module Interfaces). The possible use of U,Pu,Zr-metal alloy fuel was discussed in detail in a 2014 Pu-disposition options study (U.S. DOE 2014) published by DOE-NNSA. Table D1-6B.4 and Table D1-6B.5 are taken directly from this report and show the life cycle cost data developed for the two PRISM module SFR and FFTF restart options. From these tables, the fuel fabrication-related life cycle costs could be summed, and the total life cycle cost (LCC) divided by the total heavy metal processed to obtain a zero interest or zero financing cost unit fabrication cost ($/kgHM). Table Dl-6B.3 shows this calculation, which results in unit costs in the $24,000/kgHM to $30,000/kgHM range for both the two module PRISM option and the FFTF restart option, respectively. The WG-Pu is assumed to constitute 17% of the required heavy metal (U+Pu) mass in a U,Pu,Zr fuel assembly.

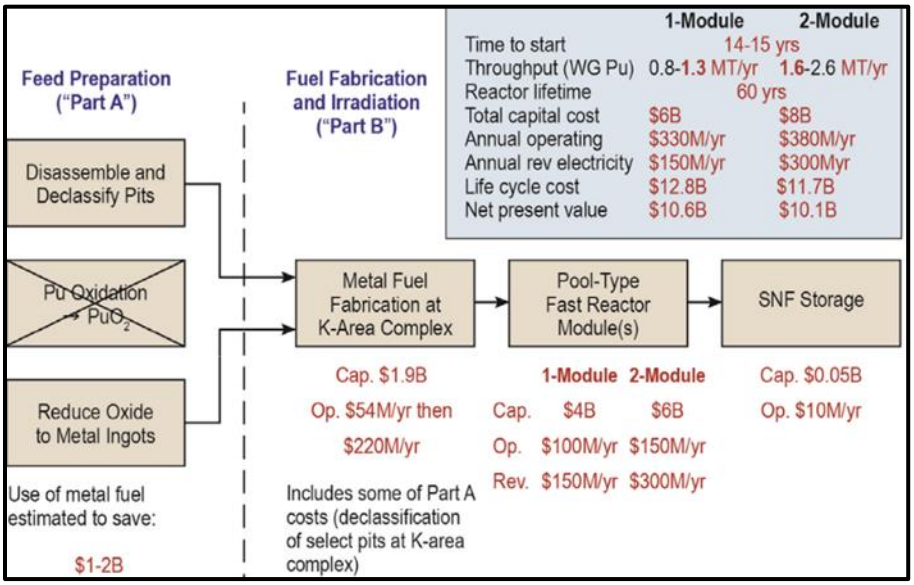


Figure D1-6B.4. Option for dispositioning WG-Pu using new U,Pu-metal-fueled PRISM SFRs from U.S. DOE 2014.

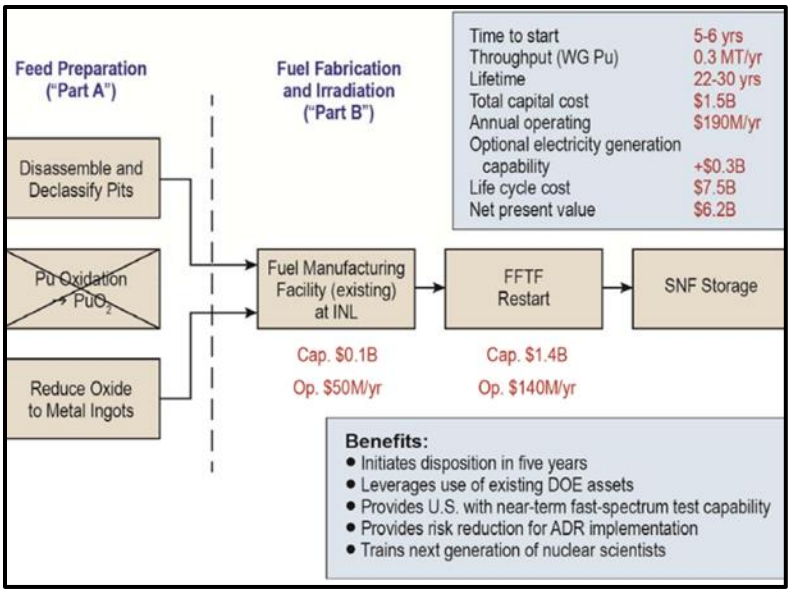


Figure D1-6B.5. Option for dispositioning WG-Pu using restarted U,Pu-metal fueled FFTF from U.S. DOE 2014.

Table D1-6B.3. Derivation of unit fabrication cost for U,Pu,Zr-metal SFR fuel fabricated from surplus weapons-grade plutonium.

Attributes of SFR Fuel Fabrication Facility Only	2 New PRISM SFRs (Fuel Fab in re-purposed SRS K-area)	Restarted FFTF (Fuel fab in INL FCF)
Total WG-Pu to be dispositioned (MT Pu)	34	9
Disposition rate (MT Pu/yr)	2.6	0.3
% Fissile content of U, Pu, Zr metal fuel	17%	17%
Heavy metal consumption rate (MTHM/yr)	15.29	1.76
Years to disposition total (yr)	13.1	30
Capital cost in $M	1,900	100
Start-up cost $M	54	0
Recurring costs and O&M ($M/y)	220	50
Total life cycle cost ($M)	$ 4,831	$ 1,600
Total MTHM fabricated from WG-Pu (MTHM)	200	52.9
Unit cost of fabrication ($/kgHM) (no interest assumed)	$ 24,155	$ 30,222

The high unit costs result for two reasons (1) the throughputs of the fuel fabrication plants are very low (1 to 15 MTHM/yr) compared to the 50 to l00s of HTHM/yr U,Pu-metal fuel fabrication facilities required to service a large fleet of 1 GWe-class SFRs operating in a breeding mode (unit cost-size scaling is important for these type plants), and (2) the fuel fabrication costs would have to pick up the high landlord/overhead costs associated with the SRS K-area and INL FCF facilities doing the fabrication work. At the end of the Pu-disposition campaign, these end-of-life costs could include all SRS K-area facilities decommissioning and waste disposal.

D1-6B.6.2. SFR Uranium-Plutonium Alloy Driver Fuels in Large Production Quantities

For civilian RD&D programs on FR systems, programs on FR systems 1950s, there is considerably more vintage design and cost information available, especially in older U.S. national laboratory technical reports, which fortunately have been archived, scanned, and made available on the Web. These older reports from the late 1970s to the early 1990s are most useful for this Module Dl-6B, since the objective of FR technology development at that time was Pu breeding via the irradiation by high-fissile content U,Pu-SFR drivers DU axial blanket pellets and full radial blanket manufactured fuel assemblies. This type of equilibrium breeding fuel cycle along with a complete annual 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 the fuel design data are shown on Figure D1-6B.6. Today's FR fuel cycle concepts are more oriented toward actinide burning in SFRs and the destruction of higher actinides that would otherwise present long-term problems in a geologic repository. A 2009 report (Shropshire 2009) shows two such equilibrium burner fuel cycles along with complete material balances. Today's U.S. SFR concepts also prescribe the use of on-site integrated SFR fuel recycle using dry pyrochemical reprocessing (Module D2/F2) instead of SFR-SNF aqueous reprocessing.

In the late 1970s, a prototype FBR, the Clinch River Breeder Reactor [CRBRP], was envisioned to be the prototype for a fleet of FBRs (at that time called LMFBRs) for which an oxide or metal-based fuel cycle was possible. Initial HALEU-based driver fuel (15 to 20% U-235) cores would be quickly transitioned to U,Pu-based cores, for which the U-235 plus Pu-239 fissile content would in the 15 to 19% range. Essentially Zero-source cost blanket DU-metal fuel could have been converted and fabricated from the huge government DUF6 stockpile resulting from decades of uranium enrichment operations, and zero cost plutonium made available from surplus WG-Pu or Pu recovered in government production reactors. A prototype fuel fabrication plant, the SAF-line in the Hanford FMEF: (Stradley et al. 1985) was actually constructed (but never operated) for initial CRBRP fuel fabrication, and an LMFBR fuel reprocessing plant was on the drawing board for recycle of the plutonium recovered from CRBRP driver and target fuels. Only minimal traces of higher actinides, minimal higher Pu isotopes, and traces of FPs in the refabricated fuel feed would allow glovebox contact handling. In the 1970s, optimism for the growth of nuclear power was high, and over 1,000 operating 1,000 MWe-class reactors, including mostly LWRs, some HTGRs, and a few LMFBRs were predicted for the year 2000 .The SFR fuel fabrication plants that were predicted to support the growing LMFBR enterprise were seen to require a deployment level on the order of hundreds of MTHM per yr, with the ~500 MTHM/yr plant as the design baseline. Such a plant would support approximately 50 one-GWe-class LMFBRs. The breeder fuel cycle was seen as the solution to a perceived shortage of uranium ore at that time. Pu-239 in all reactor types would substitute for increasingly less available U-235 as NATU resources were exhausted.

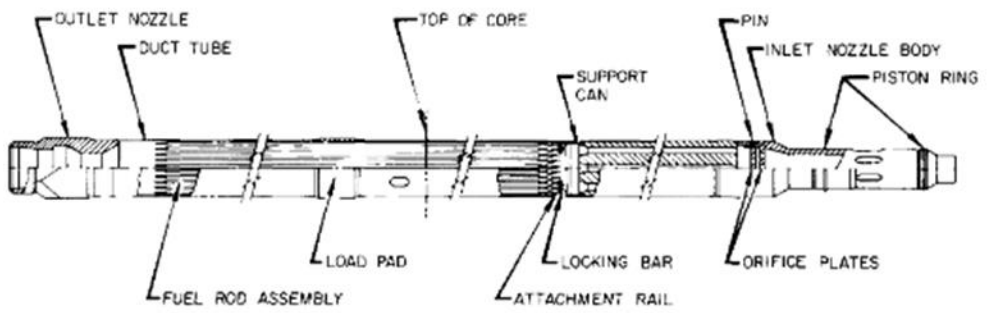


Fig. 4. LMFBR fuel assembly.

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 D1-6B.6. Design details of the SFR (aka LMFBR) driver fuel in the NASAP study (Olsen et al. 1979a.).

After India exploded a nuclear weapon based on Pu separated from power reactor spent fuel, nonproliferation became a huge policy issue for Western governments. The INFCE and NASAP programs were undertaken by the IAEA and 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 from the standpoint of technical feasibility, proliferation resistance, resource requirements, and life cycle costs. These NASAP studies and the reports (Judkins et al.1979a; Judkins et al.1979b; Olsen et al. 1979a; Olsen et al. 1979b) which were generated there from are discussed in more detail in the preface to this set of Fuel Fabrication "D" Modules (Module D1-PR).

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 process complexity and regulatory 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 a levelized unit cost of production for that LWR fuel type was calculated via a revenue-requirements type economic model. For non-UOX cylindrical-clad fuels modifications to the UOX reference fuel design and fuel fabrication facility were made based on fuel design and process complexity, material-handling difficulty, radiation environment, process building safety and security requirements, and recurring resource requirement differences (manpower, purchased materials, and utility usage). All the reference PWR UOX to alternate subject fuel plant changes were embodied in algorithms in a mid-1970s FORTRAN computer code called FABCOST. The computer-generated life cycle costs for each plant type were then tabulated and published in a set of documents (Judkins et al.1979a; Judkins et al.1979b; Olsen et al. 1979a; Olsen et al. 1979b) published by ORNL from 1978–1980. The U-Pu metal driver fuel and DU-metal blanket fuel for a breeder-reactor (LMFBR) 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 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 GWe-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 authors of this 2021 AFC update report confidence that the unit costs generated could be compared, and that 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, general economic and project execution factors, and the regulatory environment. This FCRD-SA&I author's task then became that of adapting 1978 life cycle cost data (for 1978 economic conditions) to the conditions of 2017's economy and regulations. The following paragraphs discuss the procedure and results for the U,Pu,Zr metal alloy LMFBR driver fuel. Module D1-6A (uranium-only metal fuels) describes the same type of analysis for the all-metal uranium blanket fuels which would be manufactured for long-term use in the breeder-reactor fuel-cycle. The manufacture of all-uranium metal HALEU start-up driver fuel was not addressed in the NASAP study, however it is discussed in detail in Module D1-6A of this latest AFC-CBR update.

Once the process differences between PWR-UOX manufacture and U,Pu,Zr metal fuel manufacture were understood and analyzed, equipment lists were prepared by the ORNL engineers working on NASAP, and the resulting equipment laid out on the floor of a single-story process building. Among the process differences identified for going from PWR LEUOX to metal U,Pu,Zr metal SFR 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,Zr SFR drivers (15 to 20%) than for all-U LWR fuel (3 to 5% U-235).
- A more complex batchwise DUF6 to DUF4 to DU-metal front-end deconversion processing flowsheet is needed for the U portion (75 to 80%) of the SFR-driver fuel mass and the DU blankets. This deconversion step is more complex than the semi-continuous LEUF6 to LEUO2 conversion step for LEUOX fuels in today's LWR-UOX fuel fabrication facilities.

- The Pu feedstock to the U,Pu metal blend must be converted from some other chemical form if the Pu is derived from aqueous reprocessing. Such a form might be PuO_2 or Pu nitrate or oxalate crystals.
- The post-conversion metal handling steps (melting, injection casting, and slug shearing) are simpler and fewer than those for LEUOX (powder prep, granulation, pressing, sintering, and pellet finishing) and involve less dust.
- The DU-blanket plant discussed in Module D1-6A produces both complete radial fuel assemblies and additional slugs or pellets to be loaded in the ends of HALEU or U,Pu metal driver assemblies to serve as the axial blanket.
- The U,Pu,Zr fuel meat must be sodium-bonded to the cladding. The loaded fuel pins also require wire wrapping to enhance heat transfer to the liquid-sodium coolant. This step is not required for LWR-MOX or UOX ceramic fuels; however, R&D on non-sodium-containing metal fuel rods may be underway.
- A metal SFR-driver U,Pu,Zr pellet is much smaller and more dense than a finished UOX pellet. (Blanket pellets or slugs can be larger in diameter than those for SFR-driver fuel.)
- More (and shorter) rods are handled for fuel loaded in SFRs.
- The U,Pu,Zr metal driver fabrication plant requires gloveboxes for most operations. For UOX and all-U SFR blanket fuel, hoods and use of inert gases may be required to minimize fire hazards and for personnel protection from airborne dust inhalation.

After the ORNL NASAP engineers laid out the process equipment (including gloveboxes and shielding), the following area requirements (Table D1-6B.4) were calculated for the various process areas of the two single-story plants.

Table D1-6B.4. Comparative process areas required for 2 MTU/day capacity (520 MTIJ/yr) average production-UOX fuel fabrication facility (reference plant) and 480 MTHM/yr average production SFR U,Pu,Zr metal alloy driver fuel fabrication and refabrication facilities (subject plants).

Operation	Hands-on PWR-UOX reference plant: area in square feet per (Judkins and Olsen 1979a)	Glovebox-type SFR-driver fuel fabrication plant: area in square feet	Enhanced shielding glovebox SFR-driver fuel refabrication plant* area in square feet
Feed receipt areas (LEUF6 for UOX, DUF4 for metal)	5,500	4,160	6,240
Milling for UOX; blending & reduction for metal	4,700	11,570	12,610
Powder granulation and pelleting; not applicable for metal	1,900	0	0
Pellet sintering, grinding, and inspection for UOX; slug casting & shearing for U	5,850	19,240	26,870
Fuel rod loading and welding	2,780	14,313	20,618
Fuel rod inspection and storage	7,000	22,750	32,500
Fuel assembly fabrication	3,000	23,504	30,654
Fuel assembly weighing, cleaning, and inspection	3,400	6,630	7,072
Fuel assembly packaging and shipping	4,000	62,400	104,000
Scrap recovery and waste processing	2,000	18,200	26,000
Operational support including hardware fabrication	20,065	91,383	133,237

Operation	Hands-on PWR-UOX reference plant: area in square feet per (Judkins and Olsen 1979a)	Glovebox-type SFR-driver fuel fabrication plant: area in square feet	Enhanced shielding glovebox SFR-driver fuel refabrication plant* area in square feet
Stores (warehouse)	2,000	2,600	2,600
Facility support	9,135	73,107	135,900
Change rooms for contaminated areas	2,005	2,005	2,005
Quality control labs	7,000	9,100	14,359
Maintenance	19,665	91,386	270,000
Total area in ft'	**100,000**	**452,346**	**824,575**

* Refabrication plant requires extra shielding and some hot-cell robotics for remote equipment maintenance.

Equipment and operations adjustments were made by the NASAP engineers to recognize the higher complexity of the fuel itself, using complexity factors that were developed as part of the NASAP analysis. Many of the life cycle cost algorithms in the ORNL NASAP documentation were converted to EXCEL spreadsheets by the FCRD-SA&I author of this module. This allowed a verification that the original, late 1970s, life cycle costs and fabrication unit cost were correctly calculated. The late 1970s costs then had to be escalated to 2017 USD using adequate historical escalation factors for nuclear projects. These escalation factors used for each life cycle cost category (civil, equipment, O&M, and replacements) are listed in Module D1-1 (PWR-UOX). The G4-ECONS economic model was then utilized to calculate the levelized unit cost for a U,Pu,Zr-metal driver fabrication facility with a 50-year life and 3% discount rate (Table D1-6B.5) , as was done for LWR-MOX in Module Dl-2. Two types of driver fuel plants were examined: one with LWR-SNF reprocessing-derived Pu feed called fabrication for first pass SFR fuel, and one with SFR-SNF reprocessing-derived, dirtier Pu feed called refabrication for second-pass SFR fuel.

D1-6B.6.3. Resulting Large U,Pu,Zr Metal Fuel Fabrication and Refabrication Plants

The plants were designed for a nominal 2 MTHM/day production capacity which, including downtime, translates to an average production capacity of 480 MTHM/year. Single-story U,Pu,Zr-metal fabrication process buildings, housing the feed conversion, any alloy blending processes, and all metallurgical and bundling operations, were both found to require footprints of over 452,000 ft^2 and 824,000 ft^2 respectively. Table D1-6B.4 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 for refabrication greatly increase the plant footprint as compared to the reference LWR-UOX facility. There is also the need to fabricate a more complex fuel assembly (with sodium bonding) and the handling of more numerous U,Pu Zr-metal slugs and/or pellets, as well as the need for additional operations staff.

The treatment of the economics and calculation of the unit fabrication cost in the 1978 report (summarized in Table D1-6B.5) reflects prevailing financial conditions and taxation regulations in effect at that time for a privately owned greenfield plant with lower interest, government-guaranteed financing. (Note that in 1978 even the government discount rate was much higher than 2017's.) 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 D1-6B.5 was developed utilizing the O4-ECONS economic analysis tool (Generation IV Nuclear Forum 2007).

Table D1-6B.5. Life cycle cost transitioning from 1978 reference LEUOX fabrication facility to 2017 subject U,Pu-metal driver fabrication and refabrication plants.

Facility and Life Cycle Cost Attributes	PWR LEUOX 1978 USD & 1978 Financial Assumptions (NASAP)	PWR LEUOX 2017 USD & 2017 Financial Assumptions	U,Pu,Zr SFR Metal Alloy Driver Fabrication 1978 USD & 1979 Financial Assumptions (NASAP)	U,Pu,Zr SFR Metal Alloy Driver Fabrication 2017 USD & 2017 Financial Assumptions	U,Pu,Zr SFR Metal Alloy Driver Refabrication 1978 USD & 1978 Financial Assumptions (NASAP)	U,Pu,Zr·SFR Metal Alloy Driver Refabrication 2017 USD & 2017 Financial Assumptions
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	100,000 ft^2	100,000 ft^2	452,346 ft^2	452,346 ft^2	824,575 ft^2	824,575 ft^2
Total Civil Structure Cost (Incl. Indirects & Contingency)	$36.1M	$239M	$448M	$3,008M	$1,111M	$7456M
Total Equipment Cost (Incl. Indirects & Contingency)	$45.1M	$269M	$268M	$1,593M	$311M	$1,851M
Total Facility Overnight Capital Cost Incl. Preoperational Costs	$102M	$629M	$758M	$4,850M	$1,466M	$9,571M
Plant Life	20 yr	50 yr	20 yr	50 yr	20 yr	50 yr
Annual Recurring Costs	$38.1M/yr	$147M/yr	$106M/yr	$418M/yr	$107M/yr	$429M/yr
Financing Basis R = Real Discount Rate	Government-guaranteed loan, private financing, r~ 8.8%	Government financing, r = 3%	Government-guaranteed loan, private financing, r = 8.8%	Government financing, r = 3%	Government-guaranteed loan private financing, r = 8.8%	Government financing, r =3%
Unit Fabrication Cost	~$100/kgHM	$3/kgHM	~$400/kgHM	$1,317/kgHM	~$550/kgHM	$1,773/kgHM

As discussed in Section D1-6B.5 (Scaling Considerations), the unit cost of fabrication is expected to scale with plant annual production capacity. Using cost-scaling exponents from the NASAP reports (Judkins et al.1979b; Olsen et al. 1979a; Olsen et al. 1979b), the following "unit fabrication cost versus average annual production rate" curves were derived:

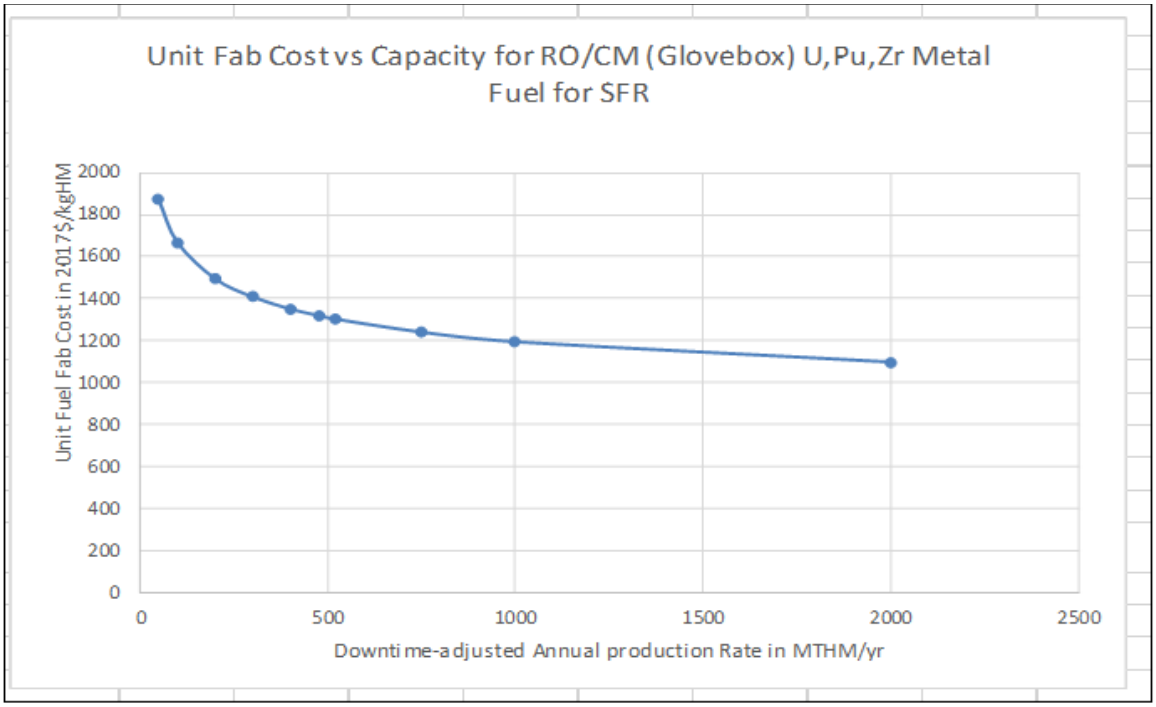


Figure D1-6B.7. Unit fabrication cost scaling with average annual production for U,Pu,Zr-Metal SFR-driver fuel fabrication plant.

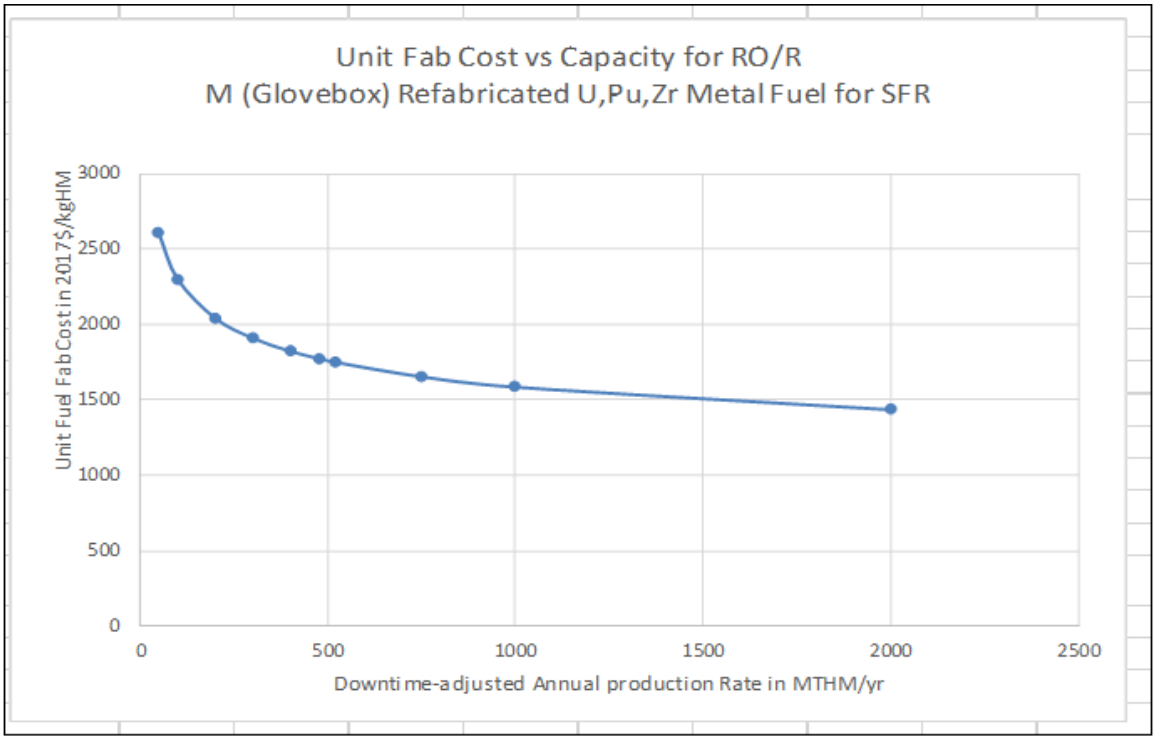


Figure D1-6B.8. Unit fabrication cost scaling with average annual production for U,Pu,Zr- Metal SFR-driver fuel refabrication plant.

D1-6B.6.4. SFR U-Pu-Zr Metal Alloy Driver Fuels in Small Production Quantities in a Government R&D Facility

Some considerable effort was expended in trying to determine the historical life cycle costs associated with the on-site production of EBR-II driver fuel. Most of this fabrication work was done by on-site contactors to ANL-W at the time, and unfortunately these companies and their contracts and financial records are no longer available. ANL and INL staff have tried to develop rough back-of- the-envelope cost data for the low volume (0.3 to 1.5 MTHM/yr) fuel fabrication effort that was being conducted in the 1950s through 1960s. Shown below are some projected calculated unit costs of EBR-II U-Pu-Zr metal driver fuel if it were being produced in the INL FMF today in small quantities and in an FMF operating with additional personnel.

Lineberry (2012)	$6,400/kgHM at a production rate of 1.7 MTHM/yr
Ganda (2017a)	$1,700/kgHM for 1.5 MTHM/yr (low end cost)
Ganda (2017b)	$30,000/kgHM for 1.65 MTHM/yr (high end cost)
	$13,300/kgHM for 100 MTHM/yr (high value scaled for higher capacity)

None of these small-plant numbers have been published in a report or reviewed by multiple FCRD-SA&I program staff.

D1-6B.6.5. Uranium-Plutonium Metal-Based LWR Fuels

Lightbridge Corporation (now EnFission) has been pursuing the use of uranium metal fuel for LWRs for several years. The fuel consists of a co-extruded long rod with a U-metal core and a directly bonded metal jacket or clad. It has a cruciform cross section to allow efficient loading in a fuel assembly, and a twisted rod shape to enhance heat transfer. The same type of rod could be a U,Pu alloy instead of all-HALEU. Glovebox fabrication via hot extrusion of such a long (3+meters) U,Pu alloy could prove to be difficult. No cost information on this option was available. Module Dl-8 discusses a similar concept (Radkowsky 1985) involving a thorium blanket for WG-Pu disposition for which unit fabrication costs were projected to be high.

D1-6B.7. DATA LIMITATIONS

A major limitation is that none of these metal fuel types have been recently produced in the West (U.S. and OECD countries) in large quantities, so no data from fuel users could be obtained. Manufacturing any of these types in production quantities in Category I facilities will require re-establishing dormant fuel fabrication industries under new sets of environmental and MPC&A regulations and financing arrangements. Fortunately, the 1978 USD-based NASAP study provided a basis for at least producing comparable unit cost estimates. based on technical complexity and manufacturing difficulty. Escalation of this data to 2017 constant USD and the application of economic factors typical of today's economy were uniformly applied to all these NASAP cases.

D1-6B.8. COST SUMMARIES

The rationale for the new WIT unit cost values for fabrication of u metal fuels is discussed in this section for the following two glovebox contact-handled U,Pu,Zr metal fuel types:

- Fabricated U,Pu,Zr metal drivers in the fissile enrichment range 15 to 20% prepared from the following reactor-grade Pu recovered from the PUREX-type aqueous reprocessing of LWR-UOX SNF (in the range 55 to 70% Pu-239) and DU-metal recovered from the deconversion of enrichment plant tails DUF6 (of around 0.3% U-235). These SFR drivers would be produced in a USNRC Category I facility and the all-uranium blanket pellets and assemblies in a Category III facility. A baseline production rate of 480 MT U/yr for the drivers is assumed as was the case in the NASAP study. This first SFR pass fuel type would likely be used after a HALEU-fuel campaign to start up a fleet of LMFBR-type SFRs operating in a breeding mode and would require sodium bonding. Injection casting is the manufacturing method assumed.
- Refabricated U,Pu,Zr metal drivers in the fissile enrichment range 17 to 25% prepared from the following: reactor-grade Pu recovered from the aqueous reprocessing of SFR U,Pu,Zr metal SNF (in the range 50 to 65% Pu-239) and DU-metal recovered from the deconversion of enrichment plant tails DUF6 (of around 0.3% U-235). These drivers would be produced in a USNRC Category I facility and the blanket pellets in a Category III facility. A baseline production rate of 480 MTU/yr for the drivers is assumed as was the case in the NASAP study. This fuel type would likely be used after LWR-SNF-derived Pu campaign to continue the operation of a fleet of LMFBR-type SFRs operating in a breeding mode and would require sodium bonding. Injection casting is again the manufacturing method assumed. This fuel is assumed to undergo one additional SFR irradiation campaign (second pass) after refabrication.

D1-6B.8.1. U,Pu,Zr-Metal Driver Fuel for SFRs

Using the baseline unit cost in Column 5 of Table D1-6B.5 and the endpoints of the curve in Figure D1-B.7, the following range (Table D1-6B.6) is suggested for fabricated SFR-driver fuel intended for its first irradiation cycle in an SFR of the LMFBR type and operating mode (in FY 2017 constant USD).

Table D1-6B.6. Year 2017 USD AFC-CBR "what-it-takes" unit fabrication cost values for SFR U,Pu,Zr metal driver fuel (Pu-derived from aqueous reprocessing of LWR-SNF).

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2017	1,097 $/kgHM	1,317 $/kgHM	1,871 $/kgHM	1,428 $/kgHM	Triangular
2020	1,154/$/kgHM	1,385 $/kgHM	1,968 $/kgHM	1,503 $/kgHM	Triangular
Escalation from 2017 to 2020 is 5.2%.					

Using the baseline unit cost in column 7 of Table D1-6B.5 and the endpoints of the curve in Figure Dl-6B.8, the following range (Table D1-6B.7) is suggested for refabricated SFR-driver fuel intended for its first irradiation cycle in an SFR of the LMFBR type and operating mode (in FY 2017 constant USD).

Table D1-6B.7. Year 2020 USD AFC-CBR "what-it-takes" unit refabrication cost values for SFR U,Pu,Zr metal driver fuel (Pu-derived from aqueous reprocessing of SFR-SNF).

Year USD	Low	Mode (Most Likely)	High	Mean (Calculated)	Distribution Type
2017	1,436 $/kgHM	1,773 $/kgHM	2,607 $/kgHM	1,939 $/kgHM	Triangular
2020	1,511 $/kgHM	1,865 $/kgHM	2,743 $/kgHM	2,039 $/kgHM	Triangular
Escalation from 2017 to 2020 is 5.2%.					

For both fuel types, the average production rate is 480 MTHM/yr for the mode or baseline value. Low and high values were pegged off the calculated unit costs for lower (50 MTHM/yr) and higher (2,000 MTHM/yr) production rates. Despite the need for gloveboxes, the unit cost for U,Pu metal fuel fabrication is in the same $/kgHM range for U-only HALEU SFR fuel. Both fuels require non-Category III facilities, which may drive the building and operations costs so high that any equipment differences are not reflected in the unit cost. Unfortunately, there is no breakdown of HALEU-only life cycle costs from which a direct comparison can be made with the NASAP costs for U,Pu-SFR fuel.

D1-6B.8.2. What-It-Takes Summary

Figure D1-6B.9 shows the ranges and distribution types for the two U,Pu,Zr metal alloy fuel types considered in this Module D1-6B 2021 update.

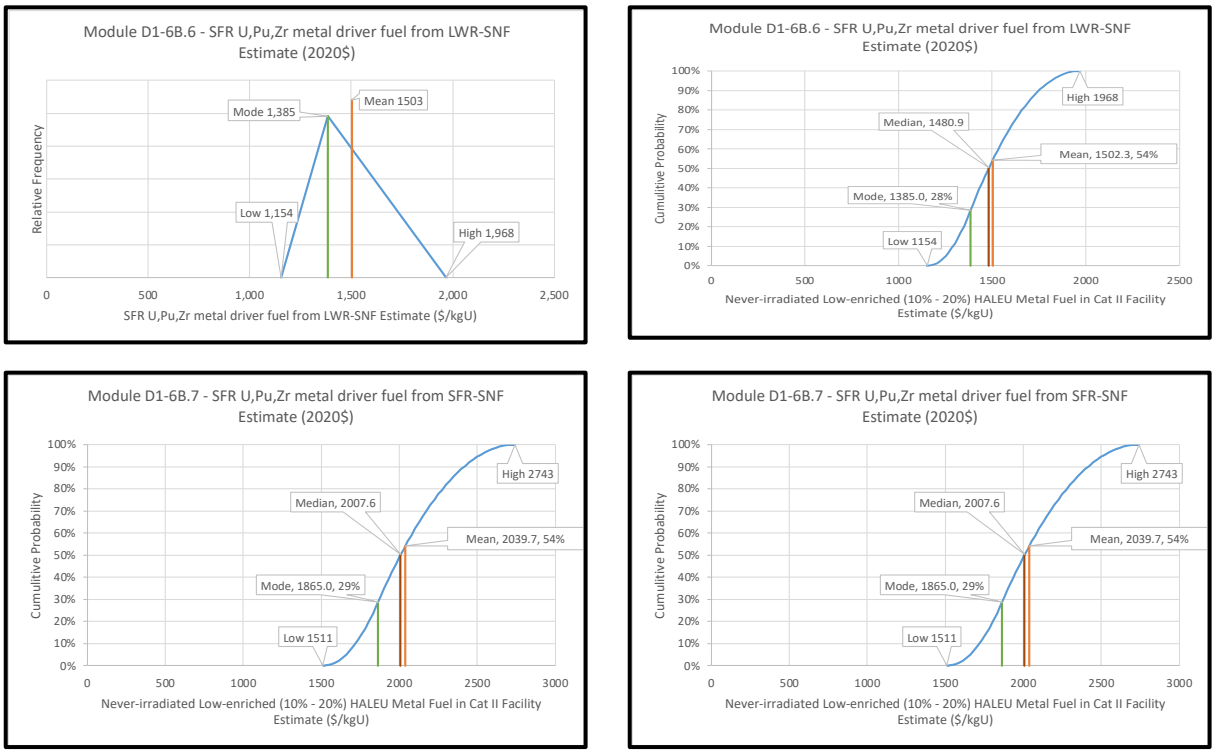


Figure D1-6B.9. WIT unit fabrication and refabrication costs for all-metal U,Pu,Zr fuels.

D1-6B.9. SENSITIVITY AND UNCERTAINTY ANALYSES

Other than unit fabrication cost versus annual production rate sensitivities for U-Pu metal driver fuel, no other uncertainty analyses were conducted. Although all these fuels are assumed contact-handled (in gloveboxes for most of the process flowsheet) for manufacturing operations in centralized plants serving a sizeable reactor fleet, the projected costs are probably only developed at an estimating detail similar to that for newer fabrication cost estimates for SFR fuels produced by IFR-type on-reactor-site remote-handling covered in Modules D2/F2.

D1-6B.10. REFERENCES

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