

**D MODULES**  
**Fuel Fabrication**



# D Modules

## Fuel Fabrication

### PREFACE TO D MODULES

The introduction to the D-Modules in the 2009 AFC-CBR describes the many in-reactor physical, chemical, and nuclear factors which influence the design and functionality of nuclear fuel. As there are many variations in reactor design; there are even more variations in the design of the fuel which is charged to these reactors. For example, today's commercial LWRs operate on over 20 different "fuel designs", but all contain the same basic ceramic chemical form, either  $\text{UO}_2$  (UOX) or mixed  $\text{UO}_2/\text{PuO}_2$  (MOX) in the fuel "meat." (The colloquial term "fuel meat" is often used to represent part of a fuel rod or assembly containing the main nuclear material constituents whose fissile isotopes undergo fission or undergo other major nuclear transmutation, such as higher isotope production via neutron absorption, inside the reactor). For unirradiated fuel this "fuel meat" is the initial heavy metal (or its chemical compounds) plus any totally blended alloying or matrix constituents. For irradiated fuel the "meat" would include original remaining heavy metal not transmuted plus the mass of any lighter or heavier elements generated by fission or neutron capture transmutation. Because it does not undergo transmutation as a nuclear material the mass of the cladding and other fuel assembly hardware are generally not included in fuel cycle mass balance and economic calculations. The cost estimating figure-of-merit for back end fuel cycle steps is often expressed in dollars per kilogram of initial heavy metal (\$/kgHM). For a particular fuel type the design variation is mainly in the geometric configuration of the fuel rods and the nature of the zirconium metal or other alloy hardware which support them. For example each of the major LWR fuel vendors, such as GE-Hitachi, AREVA, Westinghouse, TVEL, etc. has their own proprietary fuel designs particular to the class (BWR or PWR) and particular models and vintages of reactors they support.

More advanced reactors may have fuels completely different in form and materials than LWRs. For most of these fuels there are presently no large-scale industries or commercial fabrication vendors for their manufacture. Cost information is based on the extrapolation of small scale or pilot plant building and operations costs. The fuel designs are preliminary in nature and may not have undergone the extensive fuel qualification and in-reactor testing (lead test assemblies) required by many national nuclear regulators (such as U.S.NRC) before large-scale irradiation can commence. It should be noted that for all fuels, the fuel fabrication step is basically a service step, in that the cost incurred is for transformation of a nuclear source material, such as high-quality U, Th, or Pu (or mixes thereof) chemical compounds such as oxides, nitrates, oxalates, or fluorides into a finished, completely inspected fuel assembly ready to be charged to a reactor. The cost of the feed nuclear source material is not included in the fabrication cost; however, there may be an included cost for conversion of the pre-fabrication source material to the fuel grade ceramic compound in the "fuel meat", e.g. low-enriched  $\text{UF}_6$  from an enricher to fuel grade  $\text{UO}_2$  powder (LWRs). For LWR fuel the mining, milling,  $\text{U}_3\text{O}_8$  to  $\text{UF}_6$ , and enrichment costs are not part of the fabrication cost, and are covered in Modules A, B, and C. The purchase of non-nuclear fuel assembly components, such as cladding material (e.g., zirconium) or matrix material (such as graphite) and miscellaneous hardware, however, must be included in the fabrication cost. The costs of fuel inspection, certification, and other quality assurance-related activities should also be factored into the cost or price of fuel fabrication. Unit fabrication costs are usually presented in dollars per kilogram of heavy metal (\$/kgHM, \$/kgU, \$/kgTh), even though the actual fuel is in the form of an oxide or other possible chemical compounds. This convention is adopted because of the fact that the nuclear source material (U, Pu, Th, etc.) may change chemical forms several times throughout the overall fuel cycle, and it is simpler to track the elemental heavy metal component material balance over this total fuel cycle.

From the standpoint of cost a major discriminator between fuel types is the nature of the fuel fabrication facility, i.e., whether the in-process fuel can undergo direct or glovebox handling by humans (contact-handling [CH]) or requires non-human or remote handling ([RH] such as by robots) because of the high penetrating radioactivity levels of radionuclides in the fuel meat. The former operations can be handled in a more conventional industrial structure with sufficient security, hardening against natural disasters, and proper ventilation, whereas the latter requires thick, robust radiation shielding of all operations and the use of robots or manipulators for handling in hot cells. The HVAC requirements for the latter are also much more stringent. In this D module contact-handled fuels will be treated in the D1 submodules. (The contact-handling definition will include facilities, such as (Pu, U) O<sub>2</sub> MOX plants, with glovebox operations. In these glovebox-containing facilities the final sealed fuel rod handling and bundling operations allow hands-on direct contact handling). The D2 module will include fuels that are remote-handled in highly-shielded hot cells.

Generally the fuels that can be contact-handled are those directly arising from natural nuclear source materials such as unirradiated uranium or thorium which have never been in a reactor (sometimes called “virgin” materials). Natural and most enriched U fuels are in this category. Fuels containing separated and recovered elements arising from fuel reprocessing can be in this category only if their purity level or radioisotope content excludes or minimizes those isotopes or elements (such as many fission products, higher actinides, or decay daughters) which have associated high penetrating radiation fields. An example would be plutonium and/or reprocessed uranium arising from the aqueous reprocessing of spent LWR fuel. (Aqueous processing allows high decontamination factors for removal of some higher actinides (HAs) such as neptunium, curium, and americium, fission products (FPs), and decay daughters (such as those associated with U-233 production). It should be noted that in many proposed “proliferation-resistant” closed or partially closed fuel cycles complete separation of fission products and higher actinides is neither required nor desired. The intent is to avoid the separation of pure plutonium (or U-233) and make the separated product for fuel refabrication difficult to divert or steal because of its high penetrating radiation fields. These refabricated fuel forms will require remote handling (RH) facilities which will likely have to be immediately adjacent to the reactors or integral to the reprocessing operations. It is important that the reader understand that when products arising from reprocessing of spent fuel are to be fabricated into new fuel, one must know exactly what other radionuclides (FP and HA) will be carried over with the main recovered fuel HM product. As these radionuclides increase the fuel will transition from the CH regime to the RH regime. (This will be true for some of the D1 modules.)

For some reactors we will be dealing with heterogeneous fuel types, where the fissile fuel “driver” may be physically separate in the reactor core from a “blanket” or “target” used for useful nuclear material production (breeding) or waste material destruction (actinide burning). These fuel and target materials are also prepared in facilities with process equipment similar to those for drivers containing the major fissile fuel meat. Fresh blankets containing fertile uranium or fertile thorium for production of plutonium-239 or U-233 are likely to have very low radiation fields and can be contact-handled. Targets containing significant amounts of higher actinides such curium and higher Pu and Np isotopes for “burning/destruction” are likely to require remote handling. This means that for some reactor types using heterogeneous fuel concepts, both remote and contact-handling fabrication facilities will be needed.

As mentioned earlier the cost figure of merit of interest here is the \$ per kilogram of heavy metal required for the fuel fabrication service. “Heavy metal” here includes the nuclear materials in the fuel meat, i.e. uranium, thorium, plutonium, higher actinides, and any residual fission products. Nuclear materials fabricated in contact-handling facilities are likely to be used for once-through or single-pass LWR MOX fuel cycles or the production of start-up fissile drivers (HEUO<sub>2</sub>, high-fissile content MOX, or Pu metal alloy) for a fleet of fast reactors. Remote handling will be required for the spent fuels arising from continuous recycle and re-fabrication of higher-actinide bearing fuel types, especially those involving electrochemical pyrochemical recycle or multiple-pass recycle.

A comparatively high \$/kgHM fuel fabrication cost (or price compared to LWR fuel) does not necessarily mean the fuel will be uneconomical in terms of the fuel cycle component of the levelized cost of electricity (LCOE). A higher \$/kgHM is usually found for higher enrichment (higher percentage of fissile radioisotopes) fuels for which the security, criticality, and accountability requirements are more stringent. The amount of fuel required per kilowatt-hour, however, is likely to be much lower because of the possibility of higher fuel burnup (MWth-days per KgHM). Thus we have a situation with less fuel required per fuel reload at a higher cost per unit of fuel.



**Module Series D1**

**Fabrication of Contact-handled Fuels**



# Module Series D1

## Fabrication of Contact-handled Fuels

### D1. PREFACE AND INTRODUCTION

Nearly all of the world's fuel fabrication facilities operating today are contact-handling (CH) facilities. Contact-handling as here defined can include fuels processed in gloveboxes, but with the final sealed fuel assembly capable of direct human handling if even for a short time. Many of these CH facilities are described in the D1 modules of this 2017 AFC-CBR. Typically a contact-handling facility, including the equipment therein, incurs construction costs in the several hundred to several thousand dollars per square foot of facility including process equipment (Williams 2009). The capacity of the facility depends on the size of the reactor fleet it serves and the expected fabricated fuel usage rate (burnup) during irradiation in these reactors.

The D1 Module for Contact-Handled fuel types is divided into nine sub-modules. The following list indicates the fuel and type of reactor to which it is charged:

- D1-1 Pelletized LWR Uranium Oxide (UOX) Fuel – Used in PWRs and LWRs using low-enriched uranium. A mature fuel fabrication technology. As of 2017 considerable development is underway for “accident tolerant” fuels (Nuclear News 2017) with specialized cladding or pellet matrix modifications to reduce the possibility of rapid fuel failure and melting under accident conditions. Fuel designs allowing higher burnup are also under consideration.
- D1-2 Pelletized LWR Mixed-oxide (MOX) Fuel – Substituted for some or all low-enriched UOX assemblies in LWRs and PWRs, mostly in Europe and Japan. A mature fuel fabrication technology for separated Pu as oxide arising from aqueous reprocessing.
- D1-3 High-temperature reactor particle fuel – Can be used in graphite-moderated, gas-cooled reactors or in molten-salt cooled, graphite moderated reactors. The technology utilizing TRISO (Tristructural-isotropic) particles imbedded in graphite spheres or compacts has been tested at prototype or FOAK (first-of-a-kind) scale in several nations. As of 2017 the fabrication technology is just beginning to reach the maturity required for large-scale, semi-automated plants. This is occurring in China. Most current R&D on TRISO fuels is with uranium; however, the TRISO concept can be utilized for plutonium or thorium.
- D1-4 Ceramic Pelletized Fast Reactor Fuel – Similar to D1-1 in concept but requiring pellet-diameters and rod cladding materials compatible with the liquid sodium coolant for fast reactors. Pilot plants have been built in several nations to provide this fuel for prototype fast reactors. Fuel meat can be MOX or Medium-enriched uranium (MEU) as oxide, carbide, or nitride. Maturity is such that the fabrication process could be readily adapted to large scale production.
- D1-5 Ceramic vibrocompacted Fast Reactor Fuel – Similar to D1-4 except that oxide powders are not pelletized, but rather poured into tubes (rods) and vibrated to compact the powder. The compacted powder self-sinters during irradiation. This technology has been tested mainly in Russia and as of 2017 is not yet mature enough for large scale production.
- D1-6 Metallic or alloyed reactor fuels – Metal fuel has heat transfer advantages in sodium-cooled fast reactors. It has been tested in experimental fast reactors (EBR-II and FFTF) in the U.S. For contact handling the fissile materials therein must be clean and free of fission products or higher actinides capable of producing high radiation fields. The alloying/casting process required has been tested on a pilot scale. This type of fuel is more likely to be used as fast reactor start-up fuel

in conjunction with eventual remote electrochemical fuel recycle as discussed in Module D2. In Russia such U-alloy metal fuel is used for marine reactors. There is some private sector R&D being conducted by the Lightbride Corporation in the U.S. for LWR fuels utilizing metal fuel. This type of fuel would have superior heat transfer characteristics.

- D1-7 Pelletized CANDU Reactor fuels – Similar to D1-1 except that natural assay or slightly-enriched  $\text{UO}_2$  is used and the fuel assemblies are short and loaded into the CANDU reactors horizontally. A mature fuel fabrication technology employing large-scale facilities exists in Canada.
- D1-8 Thorium-based fuels – Thorium oxide has been loaded in pellets and TRISO particles to serve as fertile “blanket” material for the generation of fissile U-233. This concept has been tested in both LWRs and HTRs. Mixed oxide pellets of  $\text{UO}_2$  and  $\text{ThO}_2$  have also been produced. All thorium-related fuel fabrication has been in pilot scale facilities. Thorium salts can also provide the fertile material for use in Molten Salt Breeder Reactors (see Module R7).
- D1-9 Advanced fuels – Much of the recent R&D work on advanced fuels is for the “transmutation fuel” types which would contain higher actinides and even small amount of fission products. These fuels would require remote handling. There is, however, interest in uranium LWR fuels which would be less susceptible to the adverse water-cladding reactions under overheating accident conditions. (These are called “Enhanced Accident Tolerant Fuels.”) Such concepts include alternative claddings, such as silicon carbide, and the use of particles imbedded in a clad matrix material. These fuels could likely be handled in “contact” type facilities.

**NOTE:** *References to all D1-modules are organized by submodules at the end of the entire D1 module chapter.*

For most of the D1 Modules following this Summary Module, 2017 cost updates to the 2009 and 2012 AFC-CBR Modules are now provided along with the original 2009AFC-CBD technology and deployment information. (Future AFC-CBR versions may have more complete technology and deployment status discussions.) Cost summary tables are also provided that update the costs to 2017 dollars using escalation factors.

When considering the nature of Fuel Fabrication facilities and operations, one must remember that fuel fabrication represents the set of chemical, ceramic/metallurgical, and mechanical steps that take a basic chemical form of the fissile material (such as enriched  $\text{UF}_6$  product from an enrichment plant or other fissile chemical forms from a spent fuel reprocessing plant) and convert it to finished fuel assemblies and associated hardware ready for insertion into the reactor as either first cores or reloads. This fuel cycle category would also apply to blanket or target materials that are irradiated in a reactor along with the driver fuel (i.e. a heterogeneous core reactor system).

**The nature of these fuel fabrication facilities and operations is affected by the following factors:**

1. **Type of reactor system** (Module R) into which the fuel will be charged and its associated peak temperatures, fuel heat transfer considerations, reactor moderator/coolant chemistry, fuel fissile enrichment (% U-235, fissile plutonium and other actinide isotopes, or U-233 in the diluent fuel materials), and desired fuel burnup. Fissile isotope enrichment level is important because it defines the batch sizes and equipment sizes that can be accommodated in a fuel fabrication plant that is safe from a nuclear criticality standpoint. The choice of the fuel fissile material also affects the facility design from a safety and environmental standpoint, because some elements, such as plutonium and other higher actinides, present a significant radiotoxicity hazard. As noted below, the nature of the radioactivity of the elements within the fuel will determine whether fuel is “contact-handled” and will be covered in this D1-series of modules or is “remote-handled” and will be covered in the F2/D2 module. The nature of the fuel-handling environment has a very strong effect on fuel fabrication plant

design and ultimately fuel fabrication unit costs. Nonproliferation is another factor that is also becoming increasingly important in assessment of fuel types. The “attractiveness level” to a potential proliferator will depend on the fuel’s radiological and isotopic properties and its physical form. As closed fuel cycles are considered, the compatibility of the fuel form with the associated spent fuel reprocessing scheme (Modules F1 and F2/D2) must also be considered. The fact that new fuel might be refabricated from reprocessing plant “products” is another economic consideration, since “avoided costs” for other fuel cycle steps come into play.

2. **For once-through fuel cycles the fuel form must also be compatible with the method of temporary storage and ultimate geologic disposal.** The fuel cladding or matrix is essentially the first “line of defense” against eventual contact with the environment. Ideally most of the post-irradiation radionuclides will have decayed to negligible levels before the fuel and cladding begin to seriously degrade.

Fabricated fuel assemblies take many different physical forms. Every September, Nuclear Engineering International (Nuclear Engineering International 2011) publishes diagrams and design data for fuel assemblies required by most of the world’s commercial reactors [i.e., pressurized water reactors (PWRs), Voda-Vodyanoi Energetichesky Reaktors (VVERs; Russian pressurized water reactors), boiling water reactors (BWRs), and heavy water reactors (HWRs)].

3. **The regulatory and quality assurance requirements for the fuel as stated in the fuel specification** [i.e., American Society for Testing and Materials (ASTM) International “specs” for enriched uranium oxide (EUO<sub>2</sub>) and light-water reactor (LWR) mixed oxide (MOX) fuel]. These specifications define the morphology, mechanical properties, and allowed impurity levels in the fuel. The intent is to minimize the probability of fuel failure or leakage of fission products into the reactor coolant/moderator. Whatever matrix or containment in which the base fuel form resides, such as a pellet or particle, must be able to confine fission product noble gases and other volatile radionuclides over the duration of irradiation exposure. This means that any fuel types used by electrical utilities must have undergone a rigorous fuel qualification process, which is likely to include the irradiation and postirradiation examination of test fuel ampoules and lead test assemblies.
4. **The fuel form must be capable of safe and secure transport and storage** both as unirradiated fuel before reactor insertion and as spent fuel after discharge. The integrity of the cladding or fuel matrix must be maintained at all times.

**The following assumptions are made for the cost analysis for Module D1:**

1. Nine types of fuel will be considered: (1) ceramic UO<sub>2</sub> LWR fuel in the form of clad pellets (Section D1-1), (2) ceramic MOX (UO<sub>2</sub>/PuO<sub>2</sub>) LWR fuel in the form of clad pellets (Section D1 2), (3) gas-cooled reactor fuel in the form of coated particles in a graphite matrix (Section D1-3), (4) ceramic pellet fuel (and possible pellet blankets) for use in sodium-cooled fast reactors (Section D1-4), (5) ceramic vibrocompacted fuel for use in sodium-cooled fast reactors (Section D1-5), (6) metallic and alloyed fuels for use in sodium-cooled fast reactors (Section D1-6), (7) natural or slightly enriched clad pellet fuels for use in heavy-water moderated Canadian deuterium-uranium (CANDU)-type reactors (Section D1-7), (8) fuels involving the use of thorium as a fertile material, including “seed-blanket” concepts (Section D1-8), and (9) “advanced fuels,” which will include dispersion and inert matrix fuels (Section D1-9). Each of these fuels will be treated in the subsequent writeups as if it were a separate module. The subsection numbering for D1 will subdivide each fuel’s section (D1-x.N) into the same 10 topics (N.1 through N.10; x=1 through 9 depending on fuel type) as if it were a stand-alone module.
2. For this Module D1, all nine fuel types are assumed to be contact-handled. This means that the radioactivity level of the fresh, unirradiated driver fuel or blanket/target fuel is low enough that the rods and bundled fuel assemblies can be safely handled outside of hot cells. (Gloveboxes may be

required, however.) This would mean that the fuel handled is likely to be uranium, plutonium, or plutonium with small amounts of neptunium. This is in contrast with the transmutation fuels discussed in Module F2/D2 that originate from a non-PUREX recycling (reprocessing) process and where major fissile materials are not easily separated to the extent that they can be contact handled. These fuels are likely to contain significant amounts of higher actinides, such as americium and curium, and may also include some unseparated fission products such as elements from the lanthanide series. Some of these remote-handled fuels will need to be refabricated in a hot-cell immediately adjacent to an electrochemical reprocessing step and involve inherently simple metallurgical operations such as direct injection-casting of fuel rods. These Module F2/D2 fuels are likely to be metal alloy fuels such as those envisioned for the General Electric/Materials and Fuels Complex<sup>a</sup> Integrated Fuel Recycle fuel cycle. Fuel materials, such as oxides, arising from an aqueous reprocessing process, such as UREX 1-a, where higher actinides and small amounts of lanthanides are not separated out (i.e., transmutation fuels) also would require remote refabrication. Because of the integral nature of reprocessing and refabrication for this technology, the F2 (reprocessing) and D2 (fabrication) modules are combined.

3. Transportation costs from the fuel fabricator to the reactor are included as part of the fabrication cost. For fuels that can be contact-handled, these costs are generally quite small compared to the manufacturing costs.
4. For enriched uranium fuels, the feed material to the fabrication plant is assumed to be either virgin (never irradiated)  $\text{EUF}_6$  or aqueously reprocessed and converted  $\text{UF}_6$  from enrichment plants or blending facilities. For natural uranium-fueled or thorium-fueled reactors, the feed material is assumed to be a clean “nuclear-grade” oxide from a mill or processor. No fluorine-related steps are required, since there is no enrichment step requiring  $\text{UF}_6$ . For MOX fuels (both LWR and foreign reactor) the feed material is assumed to be clean  $\text{PuO}_2$  or (Pu, Np)  $\text{O}_2$  powder from an aqueous reprocessing plant or from a facility capable of preparing clean  $\text{PuO}_2$  from weapons program feedstocks. “Virgin” uranium or thorium fuel materials are those that are not derived from previous irradiation and reprocessing. Enriched uranium prepared from natural (ore-derived) uranium feed is one such material.
5. The level of technical readiness or deployment varies tremendously by the type of fuel considered. The production of LWR fuels is a highly mature private industry, while other fuel types are still in the bench scale, pilot plant development, or low throughput deployment stage of an overall fuel process qualification program.

A cost summary is provided below for each of the nine types of CH fuel (see Table D1-1). Note that no single reference had up-to-date and “apples-to-apples” comparisons for the costs of fabricating different fuel types. The only documents (Olsen et al. 1979; Judkins and Olsen 1979) found that presented a uniform costing methodology for all fuel types were prepared over 30 years ago by ORNL for the International Nuclear Fuel Cycle Evaluation (INFCE) effort. The data therein may be useful to consider on a comparative basis; merely updating the costs therein for general inflation from 1979 to 2017 would not cover all the cost-affecting changes in the regulatory, security, and financial environment surrounding new nuclear projects in the U.S.

**This table appeared in the 2009 AFC-CBD with all entries in 2008 constant \$. The table did not appear in the preface to the 2012 Update AFC-CBD. It is repeated in this new 2017 version with all entries updated with new technology/cost information gleaned from 2009 to 2012 and for escalation only to 2017\$.**

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

Table D1-1. 2017 Cost summary table.

What-It-Takes (WIT) Table (updated from 2008 constant \$ to 2017 constant \$ and for new data where appropriate)				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Mode Cost)
<b>D1-1 LWR UO<sub>2</sub> Fuel Fab</b>				
NA in 2017	NA	\$230/kgU for PWR \$285/kgU for BWR	\$575 for PWR \$575 for BWR	\$400/kgU for PWR \$400/kgU for BWR, for today's LWR fuel designs
		\$250/kgU for PWR REPU \$315/kgU for BWR REPU	\$635/kgU for PWR REPU \$635/kgU for BWR REPU	\$435/kgU for PWR REPU, \$435/kgU for BWR REPU
<b>D1-2 LWR MOX Fuel Fabrication</b>				
\$1000/KgHM based on European Experience	NA	Unit Cost=\$800/kgHM	Unit Cost = \$1600/kgHM	Unit=\$1000/kgHM
<b>D1-3 Gas-Cooled Reactor particle Fuels</b>				
NA in 2017	NA	\$3300/kgU	\$29,400/kgU	\$10,900/kgU
<b>D1-4 Ceramic Pelletized Fast Reactor Fuel</b>				
NA in 2015	NA	Driver MOX: \$2700/kgHM Blanket UOX: \$270/kgU Driver MEU MOX: \$520/kgU	Driver MOX: \$7600/kgHM Blanket UOX: \$690/kgU Driver MEU MOX: \$1290/kgU	Driver MOX fuel: \$4900/kgHM Blanket UOX: \$500/kgU Driver MEU MOX: \$900/kgU
<b>D1-5 Ceramic Vibrocompacted Fast Reactor Fuel (UOX+MOX)</b>				
NA in 2015	NA	\$720/kgHM	\$1440/kgHM	\$900/kgHM if VIPAC assumed 10% cheaper than pellet fast reactor MOX (D1-2)
<b>D1-6 Metallic or Alloyed Fast Reactor Fuel</b>				
Lightbridge Corp investigating U alloy fuel for LWRs. No cost data available	NA	No data	No data	See Module F2/D2 for remote handled FR metal alloy fuel
<b>D1-7 CANDU Fuel</b>				
NA in 2015	NA	Nat U: \$125/kgU REPU or SEU: \$164/kgU	Nat U: \$327/kgU REPU or SEU: \$425/kgU	Nat U: \$218/kgU REPU or SEU:\$284/kgU
<b>D1-8 Thorium-based Fuels</b>				
(U,Th)O <sub>2</sub> pellet fuel	NA	\$327/kgHM in	\$818/kgHM	\$573/kgHM
ThO <sub>2</sub> blanket fuel	NA	\$273/kgTh	\$687/kgTh	\$490/kgTh
<b>D1-9 "Advanced" Fuels (No cost data available)</b>				
BWR = boiling water reactor EU = enriched uranium HVAC = heating, ventilation, and air conditioning LEU = low-enriched uranium MEU=medium enriched U (actually lower assay HEU 20 to 30%U-235)		LWR = light-water reactor MOX = mixed oxide PWR = pressurized water reactor REPU = reprocessed uranium RTPI = Radkowsky Thorium-Plutonium Incinerator		



**Module D1-1**  
**LWR UO<sub>2</sub> Fuel Fabrication**



# Module D1-1

## LWR UO<sub>2</sub> Pelletized Fuel Fabrication

### D1-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:**
  - Literature review of pricing for this commodity service, which is a totally mature technology for zirconium clad LWR fuel. Late 2012 technical assessment noted that unit costs for PWR and BWR fuel are moving closer together, probably a result of commercial fuel fabricators now making both types.

It should be noted that Module D1-1 (LWR UO<sub>2</sub> Fuel Fabrication) has not been updated to reflect new market conditions (2017 depressed oversupply market) and the sale, closure, or opening of existing or new facilities. Proposed fuel pricing data for advanced, accident-tolerant LWR UO<sub>2</sub> fuels with innovative cladding are not yet available.

### D1-RH. REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module D1-1. In 2008 AFC-CBR the fabrication costs for LWR fuel made from reprocessed uranium were added.
- **Latest version of module in which new technical data or new market assessments were used to establish unit cost ranges:** 2012 for latest market assessment. Most of the text and historical costs in this version are from the 2009 AFC-CBD.
- **New technical/cost data which has recently become available and will benefit next revision:**
  - There has been considerable progress in the area of Enhanced Accident Tolerant LWR Fuels, (EATF) including some types being readied for insertion as lead test assemblies in commercial reactors. It would be useful if any cost projections for these fuel types are available. Most of the technical enhancements are in the fuel cladding; however, some modifications to the structure and chemistry of the “fuel meat” are being considered. One example of an EATF is the “Chromia” fuel being developed and tested by AREVA-NP.
  - Another is Westinghouse “Encore” Fuel (World Nuclear News 2017).
  - Internet research and perhaps a phone call with TVA’s nuclear fuels manager would be useful to ascertain the effect of the current depressed market on fuel fabrication prices.

### D1-1.1. BASIC INFORMATION

**Fuel Form.** Low-enriched uranium (LEU) light water reactor (LWR) fuel for both pressurized water reactors (PWRs) and boiling water reactors (BWRs) is in the form of ceramic enriched UO<sub>2</sub> (EUO<sub>2</sub>) sintered pellets stacked inside long (up to 14 ft, depending on the reactor size and manufacturer), sealed Zircalloy (or other Zirconium-based alloys such as Zirlo, E-110, M-5, etc.) tubes. A Western fuel assembly consists of a square (n × n) array of these tubes separated by spacers and held in place via clips and springs. Most of the hardware holding the tubes is also made of Zircalloy or a similar zirconium alloy. The upward flowing water [pressurized water reactor (PWR)] or steam/water mixture [boiling water reactor (BWR)] removes the nuclear-generated heat by contacting the outside surface of the Zircalloy tubes enclosing the pellets. Before sealing, the tubes are pressurized to counteract the reactor coolant’s external pressure on the cladding. The tubes are also designed to handle the pressure of any fission product gases generated during fuel irradiation.

## D1-1.2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

**Status of the Industry in 2009.** Production of such LWR fuel assemblies is a highly mature industry and is totally privatized in the U.S. Because of the need to specifically tailor the fuel to the reactor, most of the companies' manufacturing LWR assemblies are also affiliated with the ones that design the nuclear steam supply system for the reactor using the fuel. Table D1-1-1 lists the LWR fuel fabricators in the U.S. and the capacities in terms of MTU/yr for their facilities. This is a highly competitive nuclear business, and because of recent worldwide oversupply (Varley 1999 and 2002) and general consolidation (Kidd 2005) of the nuclear business, the number of fuel fabrication plants in the U.S. has dropped to four. LWR fuel fabrication business is highly international, and there are at least eight countries outside of the U.S. that have LWR fuel fabrication plants. Some of these foreign companies are considering significant expansion of their business (Siebert 2006; Gizitdinov 2007; Rothwell and Braun 2007, Rothwell 2007, Rothwell 2010). Some of these foreign companies sell fuel to U.S. utility customers; however, this requires that the fuel production process and the fuel itself be certified by the U.S. Nuclear Regulatory Commission (NRC) just as it would be for a domestic fabricator. Figure D1-1-1 shows a BWR and a PWR fuel assembly manufactured by Global Nuclear Fuel Americas and AREVA NP, respectively.

Table D1-1-1. LWR fuel fabrication capacity in the U.S. [(2009 Status) To be updated in future versions].

Plant Owner	Location	Capacity in MTU/yr	Fuel Type
AREVA NP	Lynchburg, VA	600	PWR (fuel assembly only, no pellet production)
AREVA NP (formerly Siemens)	Richland, WA	900	Mainly BWR, some PWR
AREVA NP (ref Energy-Business-review.com 2008)	Erwin, TN	small	LEUO <sub>2</sub> powder is produced from blended HEU/NATU nitrate solutions provided by NFS and after conversion to oxide is sent to Richland for pelletization
Global Nuclear Fuel Americas, LLC ( GE Energy, Toshiba, Hitachi)	Wilmington, NC	1,100	Mainly BWR
Westinghouse Nuclear Fuel	West Columbia, SC	1,150	PWR, some Vod-Vodyanoi Energetichesky Reaktor (VVER)

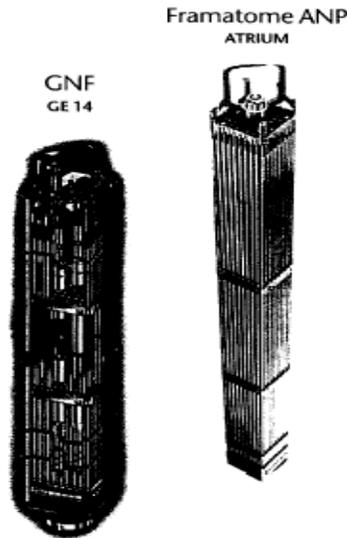


Figure D1-1-1. BWR and PWR fuel assemblies

Fuel fabrication is a highly “campaigned” business (i.e., the production of the  $\text{UO}_2$  powder and subsequent steps are designed to meet the utility customer’s enrichment needs and the utility’s reload schedule). Each campaign may take several weeks, with time required between campaigns to retool for the next utility’s requirements.

**Status of the Industry in 2012.** Little has changed from the *December 2009 Advanced Fuel Cycle Cost Basis Report* in the areas of the basic industrial process, its interfaces to other fuel cycle steps, and the status of LWR fuel fabrication facilities in the U.S.. The following should be noted, however:

- AREVA has closed its commercial reactor fuel fabrication operation at Lynchburg VA and moved its operations to their Richland WA facility (Feb 2011). This facility uses a “dry” process to convert  $\text{LEUF}_6$  to  $\text{LEUO}_2$  for pellet production.
- Westinghouse is adding the capability at its West Columbia SC facility to produce a limited amount of BWR fuel. Sinterable  $\text{LEUO}_2$  powder is produced from  $\text{LEUF}_6$  via an aqueous ADU process.
- Utilities are trying to diversify their fuel fabrication suppliers as much as possible in the hope that the pricing of this service will be more competitive. Foreign sources will be considered if the fuel and production process meet U.S.NRC licensing regulations and standards.
- No U.S. fuel fabrication facilities are presently using feedstock uranium oxide derived from re-enriched reprocessed uranium derived from commercial spent LWR fuel. Unfavorable economics at today’s ore and SWU prices, the lack of a U.S. reprocessing industry, and the need for additional fuel qualification have resulted in minimal interest in this route by U.S. nuclear utilities
- The fuel fabrication industry continues to be dominated by very high quality assurance requirements, especially as utilities move toward the use of “zero-defect” fuel and no fuel failures.
- U.S. fuel fabrication facilities are still limited to the introduction of  $\text{EUF}_6$  (enriched  $\text{UF}_6$ ) feed at a U-235 assay of 5.00% or less. (This is not a formal regulation, but rather an industry understanding) For PWRs to exceed fuel discharge burnups of about 55,000MW (th)-days/MTHM or higher, U-235 assays may have to rise above the 5% level [see MIT, Future of Nuclear Power, p.119 (2003)]. Relicensing actions by the NRC will almost certainly be required, which in turn might require significant modifications to facilities for criticality safety and security. This is a contentious issue in the fuel fabrication industry.
- The trend of some utilities and plant operators to “bundle” all front-end fuel cycle materials and services (including fabrication) into a single price for finished and delivered fuel continues.

### D1-1.3. PICTURES AND DIAGRAMS

**Fuel Fabrication Process.** Figure D1-1-2 shows the basic steps in the generic LWR fuel fabrication process. The process shown is an environmentally preferable and predominant “dry” process in which there are no aqueous steps in the main process. (There may be some aqueous or “wet” steps in the scrap recycle/recovery lines for such plants, however). Most U.S. manufacturers have migrated toward the dry process and have already qualified  $\text{LEUO}_2$  fuel prepared in this way.

The first step in the process is a chemical one, “ $\text{EUF}_6$  to  $\text{EUO}_2$  conversion.” Despite the oxide stoichiometry difference it is basically the same as the  $\text{DUF}_6$  to  $\text{DU}_3\text{O}_8$  process described in Module K1, except in this case the fuel is enriched in U-235, and the typical plant EU throughput quantities (400 to 1,500 MTU/yr) are three to four orders-of-magnitude smaller than those in the proposed plants for converting enrichment plant waste or “tails”  $\text{UF}_6$  depleted in U-235. Because the enrichment levels for  $\text{EUO}_2$  are typically from 2 to 5% U-235, there are some criticality considerations in processing LWR fuel, and batch sizes must be limited. Quality assurance considerations are also important at every step. The  $\text{EUO}_2$  powder from the first step must meet a very high purity and morphology specification (ASTM fuel specification) to be used in LWR fuel. The specified low impurity levels and particle size/flowability

requirements ensure that the  $UO_2$  will not attack the fuel cladding in the reactor and that the  $EUO_2$  powder will sinter into a strong and stable pellet. For this reason, the cost per kgU for this first  $EU_6$  to enriched oxide conversion step is at least an order of magnitude higher than the \$5+/kgU required to convert depleted  $UF_6$  as discussed in Module K1. This conversion or “powder preparation” cost is eventually rolled into the overall fabrication \$/kgU cost/price of the fuel assembly. The second step involves adjustment of the powder U-235 enrichment to meet the customer’s requirement. This is done by blending it with small amount of preexisting enriched blendstock. A binder and flowability enhancer may also be blended with the  $EUO_2$  powder to assist the pellet production steps, which are pressing the “green” pellet; sintering it to a homogeneous, hard ceramic structure; and grinding and finishing it such that it meets dimensional specifications; and loads easily into the Zircalloy tubes. Pellet inspection and loading into tubes is an automated process requiring limited human interaction. Once the tubes are loaded, they are pressurized and welded shut. The washed tubes are then transported to the fuel bundle assembly room where the structural or “skeleton” hardware is added. This operation is semi-automated and requires careful inspection and handling so that the tubes are not damaged and are inserted in the correct array positions. Among the major operations costs involved in the above steps are manufacturing and support personnel and the purchase or onsite manufacturing of Zircalloy tubes and assembly parts. As NRC-licensed fuel cycle facilities under 10 CFR 70, LWR fuel fabrication facilities are also subject to regulatory costs such as inspections. The above recurring operations costs, however, can be partially offset by the sale of hydrogen fluoride (HF) from the  $UF_6$  to  $UO_2$  deconversion step if a buyer of very slightly uranium-contaminated HF can be found. Finished fuel assemblies are hung vertically for storage prior to shipping to light-water nuclear power plants (Module R1).

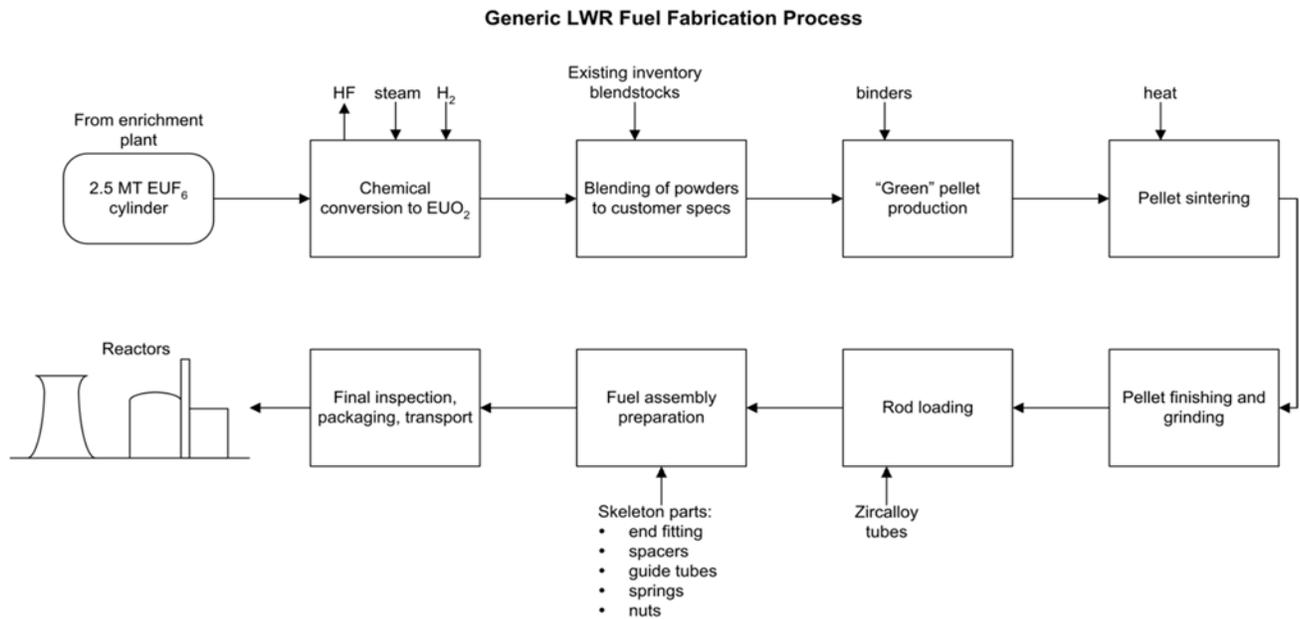


Figure D1-1-2. Generic LWR fuel fabrication process.

## D1-1.4. MODULE INTERFACES

**Front-end interface.** The  $EU_6$  is received from the enrichment plant in 2.5 MTU “30B” type cylinders. These criticality-safe cylinders must be “overpacked” during transportation from the enricher or blender in a certified container. The chemical toxicity hazard associated with fluorine product (gaseous HF) release in a transportation accident is far more serious than the small radioactivity level associated with the uranium product  $UO_2F_2$  (solid particles). (Released  $UF_6$  reacts with the moisture in the air to form HF and  $UO_2F_2$ .)

**Back-end interface.** When ready for transportation, the finished fuel is loaded in special shock-absorbing packages, which are then enclosed in wooden crates. Commercial carriers usually transport these packages on flat bed trucks to the LWR plant sites. The ceramic UO<sub>2</sub> form in sealed tubes is a very safe form for transportation, and the external radiation hazard is very low.

### D1-1.5. SCALING CONSIDERATIONS

Scaling factors are not relevant for this step. Additional LWR fuel fabrication capacity could be added by reopening existing shutdown lines, constructing new additional lines, or by operating existing lines on more than one shift. New capacity would probably be added at an existing site. A recent American Nuclear Society (ANS) paper by Rothwell (Rothwell and Braun 2007) discusses the scaling issue.

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

**2009 AFC-CBR Cost Bases.** Unlike uranium ore, natural U<sub>3</sub>O<sub>8</sub> to UF<sub>6</sub> conversion, and enrichment prices, LEU fabrication prices (and costs) are unpublished and considered proprietary information. This is partly because each fuel fabrication batch is custom-suited to the utility’s core design, and its price is separately negotiated. There are some nuclear consulting firms like NAC International and TradeTech that legally obtain data on such matters from users, which is then made available in “sanitized” report form (NAC Worldwide Consulting 2004) to utilities and other parties at a price too high for this project to use. Its publication in a public document such as this would also be prohibited by non-disclosure agreements. However, it has been possible to calculate approximate LEU fabrication pricing over many initial and reload fuel batches. Table D1-1-2 shows ranges and reference values for four data sources for LWR fuel fabrication.

Table D1-1-2. LEU fuel fabrication prices in \$/kgHM (\$/kgU). (Year \$ assumed to be same as year of study listed on the left column.)

Study/Year	Low Value	Medium or Reference Value	High Value
Energy Resources International (ERI)/2007		207 (PWR in U.S.) 276 (BWR in U.S.)	
Nuclear Energy Cost Data Base (Delene, et al./1988	170	200 <sup>a</sup>	280
OECD NEA/1994	200	275	350
J. James & K. Williams/1999		180 (PWR)	
Harvard (Bunn et al.)/2003	150	250 <sup>b</sup>	350
MIT (Deutch et al.)/2003		275	
MIT (DeRoo & Parsons)/2009		250 (PWR)	
Delene, Williams, et al./2000	200	270	300
<p>a. Higher burnup fuel would add \$20/kgU to this cost.  b. Bunn suggests that the cost (as opposed to price) is on the order of \$200/kgU based on 1999 data of Varley and Collier. Bunn also suggests low, medium, and high penalties of \$5, \$15, and \$25 per kgU, respectively, for handling reprocessed LEU in the fabrication plant.  OECD NEA = Organization for Economic Cooperation and Development-Nuclear Energy Agency  MIT = Massachusetts Institute of Technology  OECD NEA 2001, OECD NEA 2013; and Tolley and Jones 2004 present similar ranges to above (i.e., \$200 to \$300/kgU)  c. ERI (Platts 2007a) reports European prices to be 30% higher than U.S.; East Asian prices 60% higher than U.S.</p>			

The price is expressed in \$/kg heavy metal or \$/kgHM and normally includes the cost of converting the EUF<sub>6</sub> to EUO<sub>2</sub>. Because the only fissile material is uranium, \$/kgHM is the same as \$/kgU in this case. These prices are for unirradiated or “virgin” LEU, and not LEU that arises as product from spent

fuel reprocessing. (A price penalty of 5 to 10% of the unirradiated LEU fuel cost is assessed to cover the additional safety and radiation-related costs of handling reprocessed uranium and its trace fission products and trace higher actinides. This has been done mainly in Europe where reprocessing of spent LWR fuel is commonplace. The use and handling of reprocessed uranium (REPU) is discussed in more detail in Module K2 and at the end of this section). The real (inflation effect removed) prices for LEU fabrication have been decreasing slightly over the last 15 years. This has been due mainly to overcapacity, higher fuel burnup, increased automation, a highly competitive international market, and the use of now fully amortized plants. Because the nuclear fuel market is now beginning to tighten, fuel fabrication costs are likely to rise as proposed NPPs become real construction projects. Other factors that may drive fuel fabrication prices up are:

1. As longer fuel cycles and extended burnup of LEU fuels are required for economic reasons (OECD NEA 1994), the performance requirements for cladding and fuel integrity will become more stringent. The fabricator’s research and development and other costs to allow high burnup will be passed along to the fuel buyer. Perspectives on LWR fuel development are presented in a 1998 article by Gunnar and Junkrans.
2. Higher burnups may require LEU fuels of enrichments greater than the 5% maximum U-235 assay now used as the NRC-licensing basis for LEU fuel fabrication facilities. Retrofitting and relicensing costs will have to be passed along to utility customers. The intent is that higher burnups will eventually result in a lower “mills/kWh” fuel component for the overall electricity generation cost. This reduction will be the result of the fact that less low-enriched uranium (LEU) fuel will be required per kWh generated. Gregg and Worrall (2005) discuss the effect of higher burnup on overall “front-end” UO<sub>2</sub> costs and nuclear design parameters. Gingold and Goldstein (2002) discuss how the choice of higher burnup fuel would affect the fuel steps (modules) downstream of the reactor.

In general, BWR fuel fabrication prices are somewhat higher than PWR prices because of the greater hardware complexity of the former fuel assemblies. Foreign fuel fabrication prices are higher than in the U.S. In 1994, the Organization for Economic Cooperation and Development price range, which in addition to U.S. data contains foreign data, was higher than any of the other ranges in Table D1-1-3. For future U.S. studies and non-reprocessed fuel enrichments less than 5% U-235, the following reference values are suggested by the author: \$220/kgU for PWR assemblies and \$270/kgU for BWR assemblies. For reprocessed LWR UO<sub>2</sub>, a penalty of at least \$20/kgU should be added to the price. It will be seen below, and that reprocessed uranium from higher burnup UO<sub>2</sub> spent fuel is more difficult to recycle, re-enrich, and refabricate.

Table D1-1-3 .2009 AFC-CBD Cost summary table for contact-handled fuel fabrication.

2009 AFC-CBD What-It-Takes (WIT) Table (2007 constant \$)				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
\$240/kgU for PWR \$290/kgU for BWR	N/A	\$200/kgU for PWR \$250/kgU for BWR	\$300 for PWR \$350 for BWR	\$250/kgU for PWR \$300/kgU for BWR
		\$220/kgU for PWR REPU \$275/kgU for BWR REPU	\$400/kgU for PWR REPU \$450/kgU for BWR REPU	\$300/kgU for PWR REPU \$350/kgU for BWR REPU
Only unit fuel costs available, no published capital costs.	Not available	None likely, this mature industry already very competitive	20% or less increase in unit cost if higher enrichment (>5% U-235), higher burnup fuels produced	Based on today’s LWR fuel designs

**2012 AFC-CBD Update Cost Bases.** Several new and recent data sources have been accessed to provide the basis for changing the recommended low, nominal, and high values for the \$/kgU (or \$/kgHM) price of fuel fabrication. (Note that there are no published data on the actual production cost of the fabrication service.) There is no “spot” market for fabrication services, since the supplied fuel assembly product is generally non-fungible and customized to the particular reactor. (Uranium ore, conversion services, and enrichment are “fungible” commodities that can be sold back and forth between utilities and brokers.) This means that there is no published price, since most utility/fabricator contracts are proprietary. Specialty nuclear consulting firms, such as UxC, publish proprietary reports on fuel fabrication and other fuel cycle services which are very expensive (thousands of dollars per copy) and for which use is restricted generally to buyers within a particular utility. Even if this program procured such a report, we would not be allowed to make the fuel cycle unit costs or pricing numbers within it publicly available. This reference (NAC Worldwide Consulting 2004) is one such report.

It should be noted that four prices are discussed here, one set for PWRs and one set for BWRs. The other differentiator is the source of the LEU<sub>6</sub> feed to the fabrication plant. Over 95% of the world’s fabricated LEUO<sub>2</sub> fuel originates as ore and the LEU<sub>6</sub> product fed to the fabrication facility is the result of conventional mining, milling, conversion, and enrichment services. Such material has never been irradiated in a reactor and is often called “virgin” LEU (V-LEU). A much smaller amount of enriched LEU<sub>6</sub> arises from the conversion and re-enrichment of near natural assay or slightly enriched uranium recovered during spent LWR LEUO<sub>2</sub> fuel reprocessing outside of the U.S.. This R-LEU is slightly contaminated with very potent U-232 daughter radionuclides which require special ES&H and handling considerations in the fuel fabrication plant. A pricing penalty is added to the V-LEU price to obtain an R-LEU price which includes the additional costs. There is also a penalty for the U-236 which builds in during irradiation. It is a neutron absorber and forces one to up the required U-235 enrichment slightly in R-LWR fuel. The following Table D1-1 shows fabrication price data from various recent sources:

Table D1-1-4. What-it-takes” (WIT) Prices from Various Sources (Constant 2012\$).

Study or Ref/Year	Low Value (\$/kgU)	Medium or Ref Value (\$/kgU)	High Value (\$/kgU)
<b>WISE Nuclear Fuel Cost Calculator (Europe) (WISE 2009)</b>			
PWR V-LEU	N/A	460	N/A
<b>DEC 2009 AFC-CBR</b>			
PWR V-LEU	200	250	300
BWR V-LEU	250	300	350
PWR R-LEU	220	300	400
BWR R-LEU	275	350	450
<b>EPRI 1020659 (EPRI 2010)</b>			
PWR V-LEU	150	220	250
PWR R-LEU (10% adder)	165	242	275
<b>MIT Future of Nuclear Fuel Cycle (Massachusetts Institute of Technology 2011)</b>			
PWR V-LEU	N/A	250	N/A
PWR R-LEU (7% adder)	N/A	267	N/A
<b>Nuclear Engineering International (Nuclear Engineering International 2011)</b>			
PWR V-LEU	260 (30% adder) <sup>1</sup>	N/A	420 (40% adder) <sup>1</sup>
BWR V-LEU	N/A	360 (20% adder) <sup>1</sup>	N/A
<b>Private Foreign Source</b>			
PWR V-LEU	400	N/A	500
1. To 2009 AFC-CBD value. (% added is suggested by reference source to be added to prevailing 2009 price)			

The most useful public source of new information was the September 2011 issue of Nuclear Engineering International (NEI 2011) which included a review of the entire front-end fuel cycle. The author's market analysis discussed the significant increase in fabrication prices since the 2008-2009 period. The reasons mentioned were the following:

- Higher costs to cover the higher quality requirements for “zero-defect” fuel
- Large increases in the cost of zirconium due to high demand, especially in Asia. The source material for zirconium cladding and hardware is zirconia ( $ZrO_2$ ) derived from the mineral zircon. Recent pricing is as follows in \$ per metric ton of zircon (imported): [U.S. Geological Survey 2012 and UxC Consulting 2011]
  - 2007 872
  - 2008 773
  - 2009 850
  - 2010 1155
  - 2011 2500
  - 2012 2600
  - 2014 1050 (added July 2017)
- Higher labor costs for qualified professionals
- Recovery of increased capital costs for equipment and facility modifications, including facility expansion

Cost factors related to proposed advanced LWR fuels such as “accident tolerant” silicon carbide-clad  $UO_2$  and particle dispersion fuel will be covered in Module D1-9. These Enhanced Accident Tolerant Fuels would allow higher burnup and longer fuel life in addition to having many safety-violated benefits.

It should also be mentioned that European prices are in general higher than U.S. prices. This is likely due to the fact that European and Asian plants are newer than U.S. plants and may still be including capital recovery for plant construction.

## D1-1.7. DATA LIMITATIONS

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

1. The determinable costs of advanced higher burnup fuel research and development must be calculated and amortized over some number of reloads. This includes the ongoing research on new alloys, improved cladding, better process automation, etc.
2. The cost of modifying and relicensing existing fuel fabrication plants to handle the higher enrichments must be determined. These costs must also be recovered in the new, higher price. New enrichment plants will be needed in the U.S. to produce these higher LEU U-235 assays. At least two such new enrichment plants are planned for the U.S., and both are likely to request the production of U-235 assays greater than 5% as part of their licensing basis.
3. No information was available on the costs of constructing or operating new LEU fabrication plants. Such historical information would be proprietary in a highly competitive industry. It is likely that if new U.S. production capacity is needed, it will be added by reopening existing lines, constructing additional process lines, or going to additional shift operations at existing facilities. An educated

guess is that a new fabrication line of 200 to 300 MTHM/yr capacity would cost over \$100 million (2004\$) in an existing building. This value is based on analysis of data in reports that consider the use of LEU fabrication plants for the production of thorium oxide fuel (Hermes et al. 2001a; Hermes et al. 2001b; Lahoda 2004).

**Technical Readiness.** LWR pelletized fuel fabrication falls in the technical readiness category of “viable and fully commercial.” Two variations on pellet LWR fuel that are in the R&D stages are annular fuel (U.S.EC Inc. 2007) and ceramic-clad fuel (Platts 2007b).

### D1-1.8. COST SUMMARIES

The 2009 AFC-CBD module cost information is summarized in the What-It-Takes (WIT) cost summary in Table D1-1-3 above.

For the 2012 AFC-CBD Update the following set of ranges and distributions (Table D1-1-5) were recommended for use in future fuel studies:

Table D1-1-5. Low, Nominal, and High Suggested Fabrication Price Values in \$/kgU (2012 \$)

Type of LWR and Type of Feed to Fabrication Plant	Low (2012 \$)	Nominal (2012 \$)	High (2012 \$)
PWR V-LEU	200	350	500
BWR V-LEU	250	350	500
PWR R-LEU(10% adder to above)	220	385	550
BWR R-LEU(10% adder to above)	275	385	550

The 10% adders for the R-LEU cases cover the additional handling costs related to the presence of U-232 daughter radioisotopes.)The following philosophies were used in price range selection for the 2012 update:

- Low ranges are the same as 2009. This would be a slow nuclear growth scenario where there is less pressure on the zirconium market and fewer capital additions which require amortization.
- PWR costs have increased at a rate higher than for BWRs. It is here assumed that the nominal (most likely long-range constant dollar prices will eventually be the same and will be around 20% higher than the 2009 values. Slowly escalating zirconium costs are likely.
- The high values assume that many new fabrication facilities are constructed and the costs recovered in the price. Zirconium is assumed to remain significantly higher than in the 2007-2009 period. The higher price should be used for output of Asian and European facilities. It remains to be seen whether long term zirconium prices will stabilize and/or even come down as is often the case for commodities. A proprietary report (UxC Consulting 2011) examines some of these issues.
- For uncertainty analyses triangular unit cost distributions should be used

No new data for the period 2012 to 2017 has been collected to inform entirely new values to supersede the 2012 values. For this 2017 Report the 2012 values are escalated by ~9% for Year 2017\$. Table D1-1-6 summarizes the data.

Table D1-1-6. Low, Mode, Mean, and High Suggested Fabrication Price Values in \$/kgU (2017\$).

Type of LWR and Type of Feed to Fabrication Plant	Low (2017 \$)	Mode (2017 \$)	Mean (2017 \$)	High (2017 \$)
PWR V-LEU	230	400	401	575
BWR V-LEU	285	400	420	575
PWR R-LEU(~10% adder to above)	250	435	435	635
BWR R-LEU(~10% adder to above)	315	435	440	635

The triangular distributions based on the costs in the above WIT Table are shown in Figure D1-1-3.

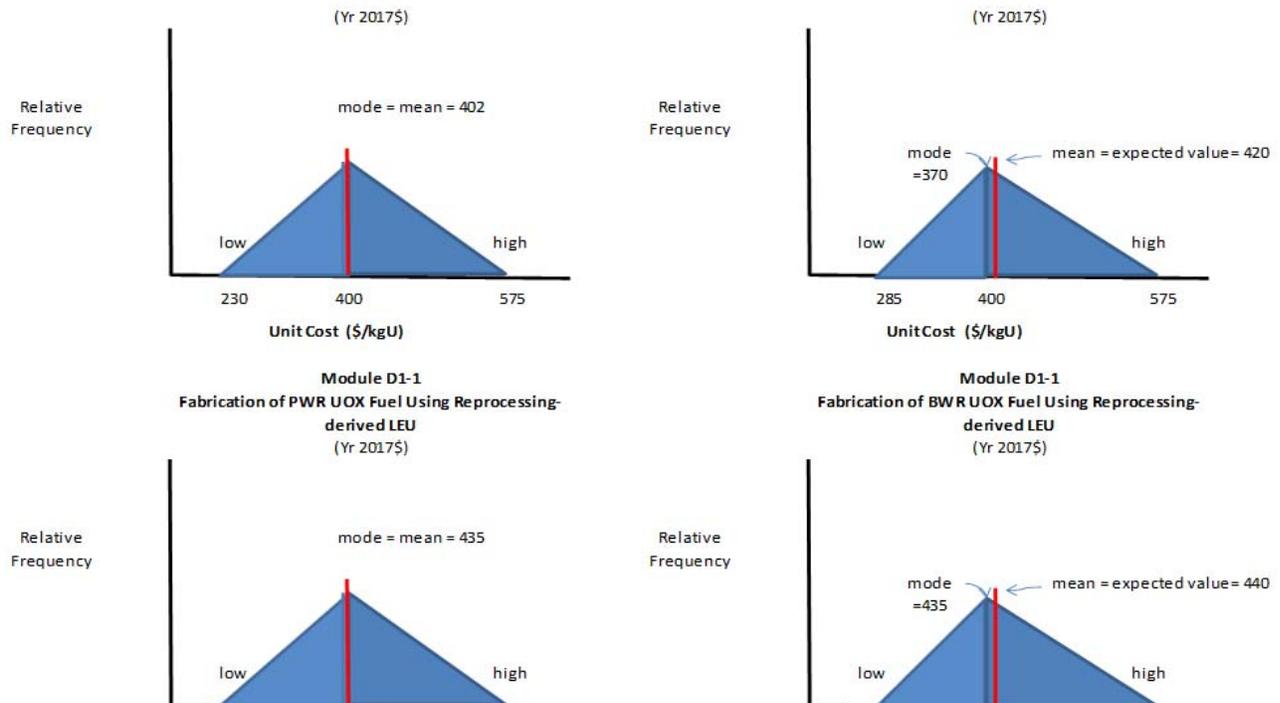


Figure D1-1-3. LWR UO<sub>2</sub> fuel fabrication (PWR & BWR) estimated cost frequency distributions.

## D1-1.9. SENSITIVITY AND UNCERTAINTY ANALYSES

Because of the high readiness level of this fuel fabrication technology, no studies were performed. Fuel fabricators have likely done such studies; however, they are likely to be proprietary.

### D1-1.10. SPECIAL TOPIC: LEUO<sub>2</sub> FABRICATED FROM REPROCESSED URANIUM

(This special section was written for the 2009 AFC-CBD, but is still applicable today). LEU in the form of uranyl nitrate hexahydrate (UNH) is one of the by-products of PUREX or UREX reprocessing of LWR fuels (Module F1) in addition to high-level waste, TRU waste, low-level waste, and separated higher actinides such as plutonium. (It is also possible that UO<sub>3</sub> product could be produced.) Like plutonium, the uranium has some value if it can be reused as reprocessed uranium fuel or REPU. (94%+ of the mass of spent LWR fuel is still in the form of uranium for which the U-235 isotopic content is significantly reduced from that prior to irradiation. Over 50,000 MTU of uranium already exist (2009) in U.S. legacy spent fuel.) If this reprocessed uranium is not reenriched and refabricated, it must be safely stored and dispositioned. Storage and disposition options for reprocessed uranium are covered in Modules K2 and K3, depending whether aqueous or electrochemical technology is used in the reprocessing step. Also like plutonium aqueous solutions from MOX fuel preparation, there are cost-incurring process steps that must be taken on the route from reprocessing plant uranium by-product (UNH) to LWR reprocessed/reenriched/refabricated UO<sub>2</sub> fuel. (The costs of these steps must be assessed against any monetary “credits” for the virgin LEUO<sub>2</sub> assemblies displaced by reprocessed uranium, just as MOX preparation costs are assessed against “credits” for the virgin LEUO<sub>2</sub> assemblies displaced by plutonium-derived MOX.)

The uranium is essentially what is left when the 2–5% U-235 “virgin” unirradiated LEUO<sub>2</sub> pellet fuel has burned down to unfissioned uranium enrichment levels of 0.5–1.2% U-235. This unburned uranium constitutes about 94+% of the heavy metal mass of a spent fuel assembly. (The remaining heavy metal

(HM)-derived masses are fission products and minor actinides such as plutonium, neptunium, americium, and curium.) Unfortunately undesirable uranium isotopes, such as U-236, a neutron absorber, and U-232, an isotope with a very strong gamma-emitting daughter, have been generated in the reprocessed uranium by irradiation, and their percentages increase with reactor fuel burnup. U-232 has the undesirable aspect of producing radioactivity that increases with time. Its decay chain includes the radioisotopes lead-212, bismuth-212, and thallium-208; the latter is especially notable for its 2.615 MeV hard gamma emission. Gamma activity of the freshly separated reprocessed uranium increases for about a decade because of the accumulation of these decay products and then slowly decreases. The associated radiation increases the risks of (and costs of) handling reprocessed uranium vis-à-vis “virgin” uranium in the conversion, reenrichment, and refabrication steps. The natural nonfissile isotope U-234 is also enhanced in reprocessed uranium above its level in virgin LEU fuel by the fact that it does not fission, whereas its adjacent U-235 isotopic species does. U-234 has a short enough half-life (245,000 years) that it becomes a problem for long-term waste disposal somewhat like other actinides. These and other issues are treated in greater detail in Michaels and Welch’s ORNL 1993 report and in a more recent ORNL report (Del Cul 2007).

PUREX-derived reprocessed uranium has been successfully used in commercial reactors; however, steps are needed to prepare it for reactor use. First, the UNH or other stored product form, such as  $U_3O_8$  or  $UO_3$ , must be converted to  $UF_6$ . This is usually done at the reprocessing or enrichment plant site and is anticipated to cost significantly more than the \$5–8/kgU for natural  $U_3O_8$  to  $UF_6$  conversion. The presence of radiotoxic minor isotopes and criticality issues associated with possible higher than natural enrichments probably means that the conversion cost is more on the order of \$11 to \$20/kgU. The second step is reenrichment to a U-235 level capable of use in the same reactor that burns the “virgin”  $LEUO_2$ . Because of the U-236 and U-234 content, a higher U-235 level than for virgin LEU is needed to compensate for the U-236 “poisoning” effect. Because of the difficulty of handling the more radioactive reprocessed  $UF_6$ , the enrichment cost is anticipated to be higher than for virgin  $EU_6$  enrichment plant feed. A 20–30% penalty on the price of separative work unit (SWU) is probably warranted. The last step is fuel fabrication from the  $LEU_6$  enrichment plant product. If not blended with other  $LEU_6$  or passed through an additional enrichment step, the U-232 and U-236 content of this material will be even higher than for the enrichment plant reprocessed  $UF_6$  feed. This is because the gaseous diffusion and centrifuge enrichment processes tend to push these undesirable “lighter” uranium isotopes into the product. The fabrication plant must now minimize personnel radiation exposures and use more automated handling of the process steps. Additional shielding may be required. For these reasons, the cost of reprocessed  $UO_2$  fuel fabrication is expected to be at least several percent higher than for virgin  $LEUO_2$  fuel. In Bunn’s report (2003), penalties of up to \$20/kgU are suggested. Michaels and Welch (1993) indicates that as reactor burnups for LWR fuel increase, the reprocessed uranium derived from reprocessing thereof will have increasingly undesirable isotopic content, thus refabrication costs could go even higher.

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

Reprocessed uranium reconversion, reenrichment, and refabrication for the production of reprocessed  $UO_2$  fuel are now under way in Europe and with the high price of  $U_3O_8$  today (as of 2008) expansion of this REPU capability is planned (Platts 2007c and 2007d). Figure D1-1-5 shows the scheme used in Russia at the Siberian Chemical Combine (Seversk/Tomsk) to take stored French reprocessed uranium (produced at LaHague and stored at Pierrelatte), remove the undesirable daughter products, convert the oxides to  $UF_6$ , and reenrich this clean material to low U-232 enhanced U-235 product in two centrifuge cascades for ultimate refabrication. The processes and economics are described in IBR 2006 and IBR 2008. Russian cost estimates in this reference indicate that this scheme should produce finished

reprocessed  $\text{UO}_2$  fuel at prices competitive with virgin  $\text{LEUO}_2$  fuel, especially as uranium ore ( $\text{U}_3\text{O}_8$ ) prices continue to rise.

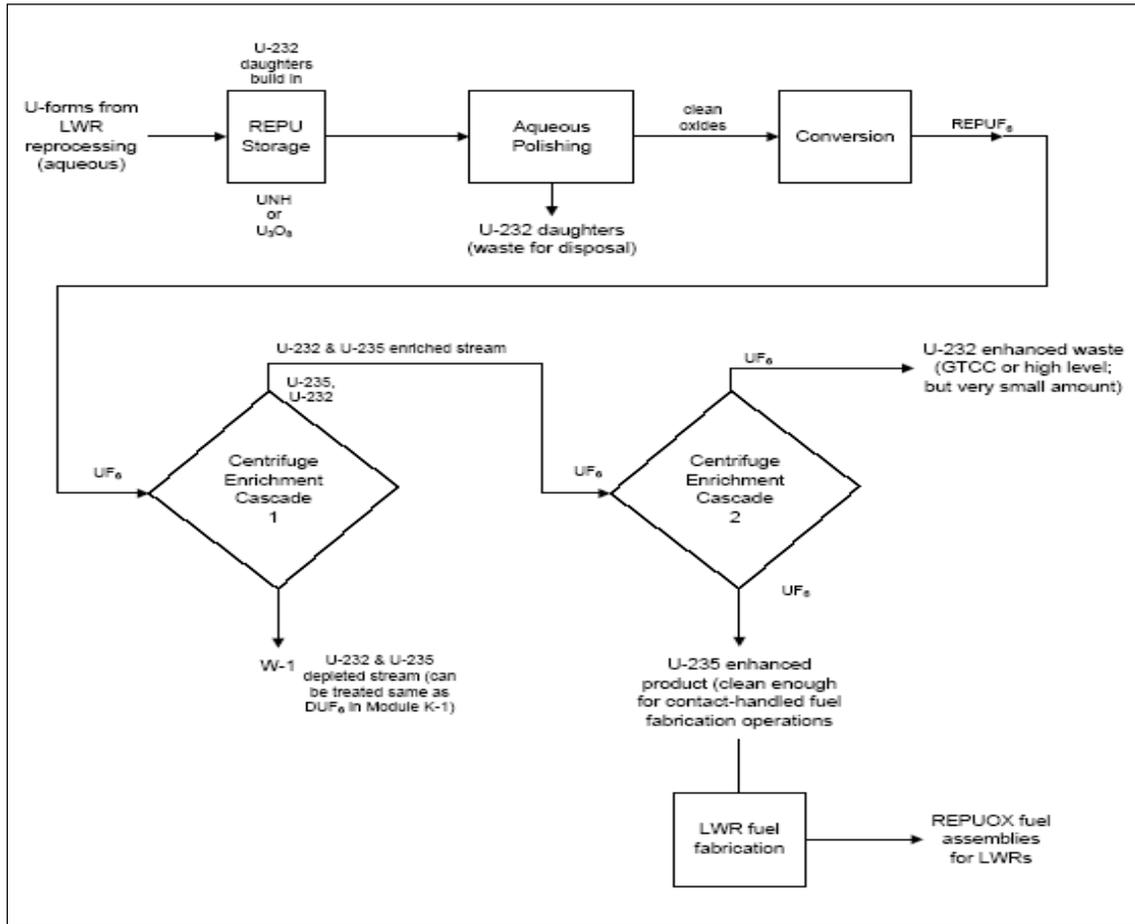


Figure D1-1-5. French-Russian scheme for reprocessed uranium recycle.

AREVA has recently announced plans (Platts 2006) to build their own 1,000-MTU/yr reprocessed uranium oxide to reprocessed  $\text{UF}_6$  conversion plant next to their proposed centrifuge plant at Pierrelatte. This announcement seems to indicate that rising uranium ore costs and large quantities of stored reprocessed  $\text{U}_3\text{O}_8$  are making deployment of this scheme in France economically attractive.

As the U.S. deploys the more versatile centrifuge enrichment technology and reconsiders LWR fuel reprocessing, such a scheme may ultimately prove economical for the even larger amounts of unburned uranium now remaining in the U.S. The U.S. is presently gaining some experience in the use of reprocessed-material fuels via Project BLEU (Tousley 2005 and Nuclear Street 2009). In this program, Tennessee Valley Authority is burning LWR fuels produced by the blending of reprocessed production reactor highly enriched uranium with lower assay blendstocks. The Nuclear Fuel Services Inc. press release on May 30, 2006 (Nuclear Fuel Services 2006) described this U.S. Department of Energy- (DOE) National Nuclear Security Administration (NNSA) supported program in more detail.

**Module D1-2**  
**LWR MOX Fuel Fabrication**



# Module D1-2

## LWR MOX Fuel Fabrication

### D1-2.1 BASIC INFORMATION

#### D1-2.MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Revisit of 2015 WIT values and distribution to remove very deleterious (high cost) effects of SRS MFFF (MOX Fuel Fabrication Facility) construction cost and schedule experience.
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was revised:** Literature review on anticipated new MOX facilities including SRS MFFF project to produce MOX from weapons-grade Pu. This 2017 unit cost assessment depends heavily on the more successful European MOX experience with Pu separated from LWR spent fuel via aqueous reprocessing. The SRS experience is being treated as an outlier, since the SRS MFFF is a very small plant and requires extra facilities and operations to accommodate weapons-grade Pu.
- **MOX technology was successfully implemented in France, Germany, and Belgium. The UK had difficulty with their MOX facility at Sellafield. MOX is a mature technology.**

#### D1-2.RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module D1-2
- **Latest version of module from which new technical data was used to establish unit cost ranges:** 2012
- **New technical/cost data which has recently become available and will benefit next revision:**
  - Progress in Japan on construction of JMOX plant in Rokkasho-mura.
  - UK reports on possibility of new MOX plant to process their large separated Pu stockpile.

#### **Introduction from 2009 AFC-CBR.**

**Fuel Form.** An LWR MOX fuel assembly with its array of pellet-loaded rods appears identical to a LEUO<sub>2</sub> thermal LWR fuel assembly. In fact in the European reactors that burn MOX fuel, the two types of assemblies reside together in the reactor, with 1/3 MOX: 2/3 LEUO<sub>2</sub> being a typical fuel assembly loading ratio. Even the ceramic MOX pellets within the rods appear nearly identical to their ceramic LEUO<sub>2</sub> counterparts. It is because of the radiotoxicity of plutonium; however, that vastly different types of plants are needed to fabricate MOX fuel. This is true even though 90+% of the MOX material flowing through the fabrication plant is the depleted, natural, or slightly enriched U-235 assay UO<sub>2</sub> diluent that is blended with the 10% or less (by mass) of PuO<sub>2</sub> powder to form the MOX pellet. Most of the world's MOX fuel is presently fed to PWRs.

**Status of Industry.** European industries, such as Cogema, Belgonucleaire, and Siemens, have been successfully fabricating MOX, and European utilities in France, Switzerland, and Belgium have been successfully burning it for over a decade. The PuO<sub>2</sub> in all of this European MOX arises from the reprocessing of spent LEUO<sub>2</sub> thermal reactor fuel at facilities such as LaHague in France and formerly THORP in the United Kingdom. The Japanese have begun use of MOX in their reactors as part of their "Pluthermal Fuels" program, and are constructing a MOX facility at Rokkasho-Mura. The UK has

stopped producing MOX, but the SMP (Sellafield MOX Plant) has not yet been decommissioned. (Platts 2007e and World Nuclear News 2011). Up until 1978, the U.S. was on the verge of using MOX as part of a closed LWR fuel cycle. A MOX fabrication plant design had already been submitted for licensing for a MOX plant at Anderson, South Carolina, with PuO<sub>2</sub> to come from a nearly completed fuel reprocessing plant at Barnwell, South Carolina. Construction was never started on the Anderson MOX Facility. This empty concrete shell for the Barnwell Reprocessing Plant still sits near the Savannah River Site in SC. All this was halted by the Presidential edict of Jimmy Carter putting an end to plutonium recycle because of nonproliferation concerns with spent fuel recycling. In 1993, after the end of the Cold War, the U.S. began to start investigating the use of MOX fuel derived from surplus weapons-grade plutonium. Reports by the National Academy of Sciences (National Academy of Sciences 1995) and others (ORNL 1996; Williams 1999) documented the technical and economic feasibility of utilizing existing U.S. utility LWRs to burn partial cores of weapons-derived MOX fuel. In 1996, a Record of Decision (U.S. DOE 1997) was issued by DOE to pursue the MOX reactor option as one of two methods to disposition plutonium. In 1997, a procurement action was started to find a corporate entity willing to design, construct, and operate a government-owned MOX Fuel Fabrication Facility (MFFF) at the Savannah River Site (SRS). In early 1999, the consortium Duke, Cogema, Stone, and Webster (DCS – now Shaw AREVA MOX Services) was chosen for this purpose and was chosen to also burn the MOX fuel at Duke Energy’s two reactor sites, McGuire and Catawba, just north and south, respectively, of Charlotte, North Carolina. (These MOX use contracts have now expired and MOX Services is negotiating with Duke and other potential customers for fuel contracts. These negotiations failed since the SRS-MFFF completion date is too far in the future.) The design of this plant is now complete, NRC construction approval has been received (NTI 2007) and construction is still underway despite NNSA’s decision to proceed with another Pu disposition technology [Construction still is underway due to SC Congressional delegation inserting federal funding. DOE-NNSA never plans to use it and pursuing an alternate method (dilute and dispose) for Pu disposition]. The plant will have processed 70 to 100 MTHM per year for over 10 years. The intent is to disposition 34 MT of weapons-grade plutonium over this campaign and possibly some other less-pure government plutonium scrap. Prior to 2007 (Platts 2007f) a similar “build-to-print” LWR-MOX plant, also based on French MELOX technology, was being designed for a parallel Russian program at Tomsk (Seversk) in Siberia. The MOX was to be burned in VVER-type reactors. Liability, funding technology transfer, and now political concerns have prevented this LWR-MOX project from proceeding any further. It now appears that the Russian Pu-disposition program will utilize weapons-derived fast reactor MOX in BN-type fast reactors for their Pu-disposition program (Platts 2007f). They are operating a small fast reactor MOX fabrication facility at Zhelesnogorsk Mining and Chemical Combine) Figure D1-2-1 shows a flowsheet for a generic reactor-based plutonium disposition programs. [Editor’s note: Russia has now withdrawn from the 2000 Plutonium Management and Disposition Agreement (PMDA; U.S. Dept of State 2000) which it signed with the U.S.]

For weapons MOX use, the cost savings arise from not requiring perpetual government storage and guarding of plutonium and the fact that other plutonium-disposition methods, such as immobilization, are likely to increase costs and encounter technical difficulties. MOX was essentially to have been made available to the utility at a unit cost somewhat below that for LEUO<sub>2</sub> fuel assemblies in order to provide an incentive to U.S. electric utility participation.

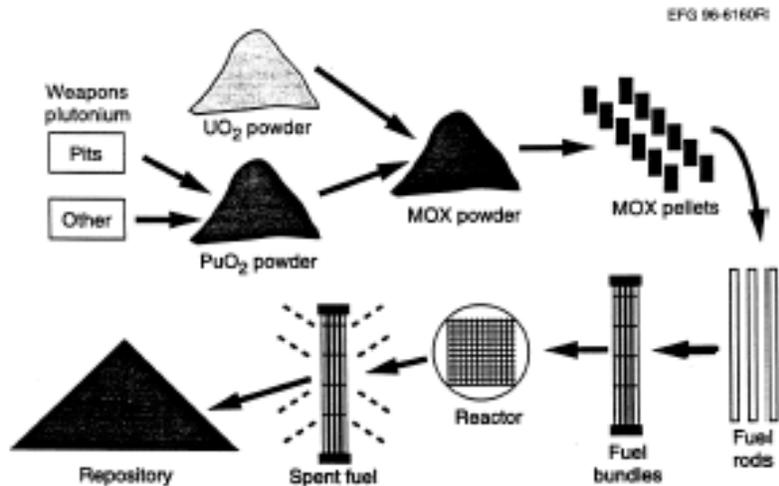


Figure D1-2-1. Generic reactor-based option for weapons plutonium-disposition (ORNL 1999).

Present DOE/National Nuclear Security Administration plans were to have limited the U.S. plant (SRS-MFFF) to weapons plutonium-disposition activities only, even if the plant life was limited to 10 to 12 years of operations. Up until recently (2017), U.S. policy has been to discourage plutonium recycle and the construction of commercial recycling facilities, such as MOX or reprocessing plants. The Trump administration is in the process of reviewing all military and commercial nuclear waste handling policies.

**Introduction from 2012 Update to AFC-CBD.** Again little has changed from the *December 2009 Advanced Fuel Cycle Cost Basis Report* in the areas of the basic industrial process for MOX fabrication and its interfaces to other fuel cycle steps; there have been, however, a few changes in the status of some of the world's MOX fabrication facilities: The Sellafield (United Kingdom) MOX Plant (SMP) is in the process of shutting down and will be slated for eventual decommissioning. Its major customers were Japanese utilities which are now facing the prospect of shuttered reactors after the March 2011 tsunami-induced Fukushima event. The SMP only realized a fraction of its design production rate of 120 MTHM/yr and only operated for a few years. The UK is still considering the burning of MOX fuel in new Generation III+ LWRs as a method of dispositioning its large stockpile of over 110 MT of separated Pu from its commercial and military reactor programs (Nature News and Comment 2011). A new and larger plant would be required that might also be able to produce MOX fuel for fast reactors. (Module D1-4). The UK is considering the fast reactor as part of its future Pu-disposition strategy and is evaluating the GE-Hitachi PRISM fast reactor design.

- The status of the 130 MTHM/yr J-MOX plant at Rokkasho-Mura is unclear. It began construction in 2010; however, the Fukushima event may spell the end of the Japanese “pluthermal” MOX burning program. At the time of drafting this chapter (August 2017) construction of the J-MOX facility continues but at a slow pace.
- The French MELOX facility continues to operate successfully and has a capacity of 195 MTHM/yr.
- The U.S. MOX Fuel Fabrication Facility (MFFF) is still under construction (over 70% complete) at the USDOE Savannah River, South Carolina, Site. It has been beset with rising projected costs and schedule slippage (Augusta Chronicle 2012). This plant is not designed (from a worker protection and non-proliferation policy standpoint) to take as feed separated commercial reactor Pu, which has higher concentrations of Americium and Pu isotopes other than Pu-239. MFFF's feedstock comes from military programs, thus a special “aqueous polishing” front end is needed to remove weapons-related impurities and prepare a pure PuO<sub>2</sub> powder suitable for MOX fabrication. Another predecessor step is required to render the weapons form or “pit” into feed appropriate for the aqueous polishing from end. This stop will also have to be integrated into the MFFF front end and in other

SRS facilities and with additional cost. A waste packaging facility (Waste Solidification Building) was to also have been constructed at SRS to handle the TRU waste, but has been cancelled. Until 2016 the MFFF was anticipated to make MOX fuel for both PWRs and BWRs. Although limited MFFF construction is ongoing, the NNSA today presumes it will never be completed or operated, and that a “dilute and dispose” process involving geologic disposal at the U.S. WIPP (Waste Isolation Pilot Plant) will be utilized for weapons-grade Pu disposition. The U.S. National Academy of Sciences is in the process of reviewing this option.

- As part of the Year 2000 Joint U.S.-Russia Plutonium Management and Disposition Agreement (PMDA) (U.S. Dept of State 2000) both the U.S and Russia had agreed to burn excess weapons Pu in their LWRs. Russia has now decided to burn their Pu in sodium-cooled fast reactors of the BN-800 variety. The type of fuel is likely to be pelletized MOX (Module D1-4) or VIPAC fuel (Module D1-5). The PMDA was modified in 2010 to reflect this new reality. The Russian Federation recently (2016) formally pulled out of the PMDA agreement due to worsening relations with the U.S.; however, they still plan to use WG-Pu in their BN-800 fast reactors. The U.S. has not formally pulled out of the agreement; however, the intent to terminate the MFFF Program essentially negates the PMDA intent to produce (by irradiation in reactors) isotopically altered Pu not suitable for weapons and also self-protecting due to built-in radioisotopes.

Proposed costs for some of these facilities will be discussed below:

## **D1-2.2 FUNCTIONAL AND OPERATIONAL DESCRIPTION**

**MOX Fuel Fabrication Process.** The steps involved in the fabrication of MOX fuel are basically the same as those for LEU fuel assembly production except that most of the front and middle steps must be enclosed in gloveboxes to protect the workers from exposure to radiotoxic plutonium compounds. The radioactivity level in a MOX plant is also somewhat higher than for  $\text{UO}_2$  because of the spontaneous neutrons, beta, and gamma radiation emanating from plutonium isotopes and their daughter radionuclides. Some radiation also comes from (alpha, n) reactions where  $\text{PuO}_2$  is in contact with low atomic weight materials. Fire protection considerations are also important with pyrophoric plutonium compounds, and process areas within the process building must be capable of isolation. There is also a security consideration arising from the fact that MOX has a proliferation or terrorist attractiveness level much higher than for  $\text{LEUO}_2$ . This is because plutonium could be readily chemically separated from the uranium in the MOX and has great value as a fissile material for a nuclear weapon. This fact requires that the stringent Materials, Protection, Control, and Accounting (MPC&A) and safeguards be implemented and that the process building itself be extremely robust and resistant to attack or intrusion. The avoidance of nuclear criticality is also more of a consideration for MOX due to the smaller critical mass of Pu-239 as compared to U-235. All these considerations contribute to the much higher capital and operating costs for MOX as compared to LEU. However, economics must be evaluated on the whole nuclear fuel cycle, where for commercial MOX use, reduced ore, conversion, and SWU costs and waste disposal cost savings due to reprocessing in tandem with MOX use become evident.

## **D1-2.3 PICTURES AND DIAGRAMS**

Figure D1-2-2 shows the generic MOX production process for either commercial (Pu-239 isotopic content less than 94%) or weapons-derived (Pu-239 content 94% or greater) MOX. The feedstocks  $\text{PuO}_2$  and  $\text{DUO}_2$  are blended into a 20 to 30% plutonium “master-mix,” which is then later blended with more  $\text{DUO}_2$  to the desired fissile content of 4 to 9% plutonium in heavy metal. Because of criticality concerns, all early processing operations are in small batches of a few kilograms Pu each. Final blended MOX batches may be 100 kg MOX or more. The pellet pressing, sintering, grinding/finishing, and inspection operations are nearly identical to their LEU counterparts except for the difficulty of handling somewhat smaller batches and the need for glovebox operations. Once the pellets are loaded into the Zircalloy tubes and the tubes are welded and cleaned, the decontaminated rods can be contact handled.

The bundle assembly area is very similar to that of the LEU plant. Because of the higher radiation field arising from decay of the americium-241 plutonium decay daughter, it is necessary to limit worker exposure times to MOX fuel assemblies.

## D1-2.4 MODULE INTERFACES

**Front-end Interfaces.** For commercial MOX as done in Europe, the starting materials are reactor grade  $\text{PuO}_2$  powder arising from aqueous PUREX-type reprocessing such as is done at LaHague or THORP. The reactor-qualified powder so produced is stored in special cans in protected areas at the reprocessing plant. (Costs related to MOX are assumed to start with shipping of this powder in special double-walled cans and special “safe and secure” trucks to the MOX fabrication plant). The diluent natural, depleted, or slightly enriched  $\text{UO}_2$  powder, which is part of the MOX mix, must also be reactor-spec grade and is usually purchased from or manufactured by uranium converters or fuel fabricators with aqueous processing equipment, although some dry-process  $\text{UO}_2$  powder is being qualified for MOX use. (Slightly enriched [ $0.0071 < \text{U-235}$  assay (mass fraction)  $< 0.015$ ] uranium diluent would be likely to be reprocessed uranium oxide, most likely recovered in the same facility as the plutonium oxide. Module K2 discusses issues associated with reprocessed uranium.) This  $\text{UO}_2$  material can be shipped by normal commercial trucks in sealed drums.

The front end steps for the U.S. and Russian plutonium-disposition projects are more complex. The metal plutonium pits and any other weapons-grade legacy plutonium forms from the DOE complex must be converted to clean reactor spec  $\text{PuO}_2$ . For the U.S. program, a Pit Disassembly and Conversion Facility (PDCF) had been planned at SRS to oxidize the impure plutonium metal to impure  $\text{PuO}_2$ . This “pit-derived” impure  $\text{PuO}_2$  plus other legacy impure  $\text{PuO}_2$  is then stripped of its gallium, americium, uranium, halide, and other impurities in an aqueous-polishing front end step: i.e., an MFFF- aqueous polish (AP building) addition to the overall SRS-MFFF MP (MOX Process building). From this AP point onward, the commercial and disposition flowsheets are basically the same, with the back-end of the SRS-MFFF (called the MFFF-MP) being very similar to the French MELOX fuel fabrication plant at Marcoule. As of 2012 the SRS-MFFF had planned to use  $\text{DUO}_2$  as the diluent, thus reducing the U-235 content and maximizing the Pu-239 content of the fissile part of the MOX fuel. This reactor grade  $\text{DUO}_2$  must be manufactured by a conversion plant starting with clean legacy  $\text{DUF}_6$  in cylinders located at one of the former U.S. gaseous diffusion enrichment plant sites. Shaw-AREVA MOX Services, the DOE/National Nuclear Security Administration plutonium disposition contractor, had been responsible for implementing this conversion step and had subcontracted Framatome-ANP to use a specially modified (for DU use) wet conversion line at their Richland, Washington LEU fuel fabrication plant to test the basic process. Shaw-Areva and the DOE Savannah River had been developing a procurement process to obtain the ~1000 MTU of depleted material needed for MFFF operations. The cost of this uranium conversion step was to be included in the SRS-MFFF operations costs and was likely to have cost in the tens of dollars per kgU, with the actual unit cost depending on the batch sizes and quality and morphology of the  $\text{UO}_2$  powder required. Framatome had already prepared cost proposals to Shaw-Areva MOX Services for this operation; however, DOE’s ultimate choice of the  $\text{DUO}_2$  provider will have depended heavily on economics and the response to the procurement request for proposals (RFP). All of the plans described above are now moot due to NNSA’s decision to change WG-Pu disposition options; however, the descriptive material above has been included since the technical and cost issues are germane to any MOX Program.

# Mixed Oxide Fuel Process Flow Diagram

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Rev. 1

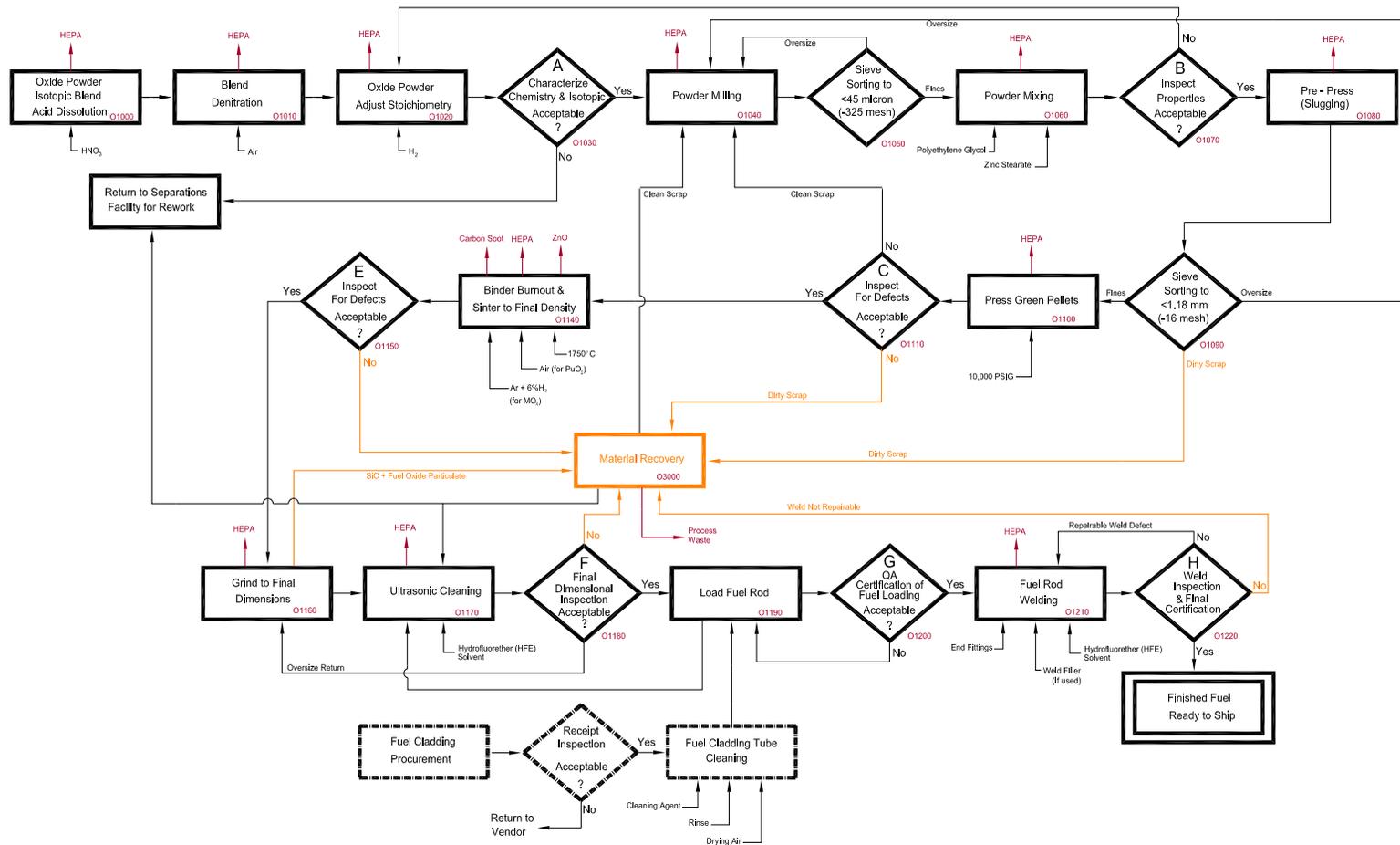


Figure D1-2-2. Generic MOX fuel process flow diagram (DOE-AFCI Fuels Working Group, 2007).

**Back-end Interfaces.** Storage and shipping of the MOX assemblies to the reactor is included in the cost. Special safe and secure transport vehicles are needed for this purpose. For the U.S. plutonium-disposition program the DOE/National Nuclear Security Administration will provide this service.

Transuranic and low-level waste from the MOX fabrication plant must also be handled. For the U.S. disposition program, waste was to have been processed and packaged by modified existing SRS waste facilities plus a new facility, the Waste Solidification Building. Because the plutonium arises from the weapons program, transuranic waste containers can be sent to the DOE/National Nuclear Security Administration's Waste Isolation Pilot Plant (WIPP) geologic disposal site near Carlsbad, New Mexico. For future commercial MOX facilities in the U.S., use of the Waste Isolation Pilot Plant may not be possible. MOX production wastes would have to be jointly considered along with reprocessing wastes and a viable disposal option studied and implemented. Modules J, L, and I discuss some possible waste disposal methods.

### D1-2.5 SCALING CONSIDERATIONS

Scaling rules are similar to those for LWR fuel production, since the fuel manufacturing is performed in parallel process lines. The line size is limited by the fact that many of the process steps are batch operations with batch size limited by criticality concerns. Capacity additions to a plant would likely be realized by adding shifts or adding a new line in an existing building. In fact, from Table D1-2-1 that shows the known capital costs for existing facilities, it is difficult to notice any capital cost scaling relationship. Because the fixed safety, security, and other infrastructure costs associated with both the capital and operating costs are generally high for MOX fabrication facilities, the unit costs climb rapidly as throughput decreases. In fact, according to Stoll (2002), there is such a relationship for unit costs, which include capital and operating components, as shown in Figure D1-2-3. Therefore, in order for MOX to be more competitive, large throughput plants should be built. Rothwell discusses economy-of-scale issues in (Rothwell and Braun 2007).

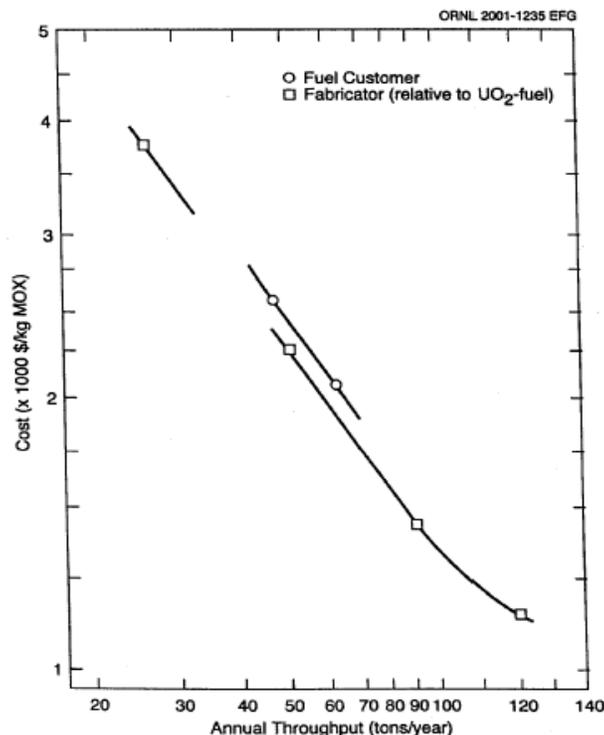


Figure D1-2-3. MOX unit cost as a function of throughput (Stoll 2002).

## D1-2.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES

Most of the MOX fuel fabrication cost data available are for existing facilities in Europe, although no data were found for the French MELOX or the Belgonuclaire facilities. Bunn, et al. 2003 performed a comprehensive survey of life-cycle cost information. Table D1-2-1 summarizes this information along with the Section D1-2 authors' analysis, described below, of the U.S. SRS-MFFF projected life-cycle costs in 2009, when the analysis was performed. [Note: the expected cost of the still-incomplete SRS MOX plant has since ballooned to several times that amount, according to the most recent press information (sup. Ref: Mufson 2017)]. Each of the studies provides the construction costs, (in the form of overnight cost) and occasionally the operation and maintenance costs. In order to generate a unit cost (in \$/kgHM), however, it is necessary to make assumptions on the discount rates and on the facilities' expected lifetimes. A common set of assumptions applied here are described in the bullet list below. (Note: For consistency, the same set of assumptions on discount rates and facility lifetimes are also applied to the analyses performed in module F2/D2).

- **Facility lifetimes of 50 years:** These types of facilities are designed with a high degree of redundancy and reliability, and they could therefore be operated for a long time. However, several MOX facilities in the past were closed after just a few decades of operations, generally for political or commercial reasons, and therefore an expected lifetime based purely on technical factors has not been determined yet. A reasonable analogy could be made with fuel fabrication plants for commercial UOX: For example, the South Columbia Westinghouse fabrication plant was commissioned in 1969, is currently producing without issues and there are no known plans for its shutdown, thus providing a representative example with a proven lifetime of 48 years as of this writing, and probably several more years, if not decades, of expected future operations. Other nuclear facilities, such as reactors, have received U.S. NRC licenses for life extension of up to 60 years, and other types of chemical plants, such as refineries, have been in operations for more than a century. Fifty years was chosen here as representative of a "long lifetime", until more specific data becomes available.
- **Discount rate of 3%:** It was chosen here as representative of a discount rate that would be appropriate for a government project. According to Section 8 of Office of Management and Budget (OMB) Circular A94, which specifies which discount rates should be used for government projects, the treasury borrowing rates (currently about 3%) should be used for discounting if performing "cost-effectiveness analyses". "Cost effectiveness analysis", defined in Section 5, bullet b, of OMB Circular A94, could include various types of reprocessing facilities, under the assumption that the objective is to compare alternative ways to achieve the same benefits to society (such as for example a lower waste heat and volume after reprocessing), and it is impractical to consider the dollar value of those benefits.

In the following, each facility of Table D1-2-1 is analyzed in detail.

The BNFL SMP plant was completed in 1997 but started operations in 2001, and it was later revealed that the planned acquisition of German expertise in MOX fabrication did not materialize as planned, and instead the completion of the plant relied on limited in-house expertise. Eventually it produced only small quantities of usable MOX fuel, about 14 MT in its entire lifetime instead of the planned 120 MT/y (supp. ref: Brady, 2013). The Hanau-2 plant was 95% constructed but never operated (supp. ref: Nuclear Monitor, 1994) so it is difficult to say for sure if the specifications would have been met with the reported costs. However, it is also noted that the Hanau-2 plant was constructed on the same site of a previously operational MOX fabrication facility that operated successfully for several decades, albeit at a much smaller scale. It is conceivable, therefore, that the Hanau-2 facility could build on the experience of Hanau 1, thus reducing the chances of failure. Both Hanau plants have been decommissioned.

Table D1-2-1. Available data on MOX fuel fabrication plants.

Plant	Owner	Location	Capacity (MTHM/yr)	Financing	Capital Cost (2003\$)	Operating Costs (2003\$)	Ref
SMP	BNFL	Sellafield UK	120	Private & Gov't	750M	50M	Bunn et al., 2003
Hanau-2	Siemens	Hanau, Germany	120	Private	750M	Not avail	Bunn et al., 2003
Rokkasho (under constr)	JNC	Rokkasho-mura, Japan	130	Private & Gov't	1,000M	Not avail	Bunn et al., 2003
SRS-MFFF (under constr)	DOE/NNSA	Aiken, So Carolina U.S.	70	Gov't	3.9B not incl aqueous polish (AP)	220M/yr not incl AP	Trade press staffing and TPC scaled for capacity and function
SRS-MFFF (under constr)	DOE/NNSA	Aiken, So. Carolina U.S.	70	Gov't	4,800 incl AP	\$275M/yr	Trade press staffing and TPC

The Total Project Costs of the Savannah River MOX Fuel Fabrication Facility (MFFF) was estimated for the 2009 CBR utilizing the expected cost at the time, and adjusting the costs numbers by (1) by removing duplicated scope for administration and other support buildings and by (2) adjusting to the scope of a MOX fuel fabrication facility that uses all of the products produced by an 800MT/yr LWR reprocessing center. Consequently, an un-adjusted and an adjusted unit costs were provided in the 2009 CBR based on the expected cost of the MFFF facility. However, those estimates are now obsolete and new, substantially increased estimates, have been provided. (Supp. ref: The State, 2016) reports a new revised estimate of \$17B as of September 2016. The original budget in 1999 was \$620 million, with a 2006 starting date: now in 2017 it appears that the project is still about 10 years from the start. (Supp. ref: Mufson 2017)

The total construction cost in 2007 for MFFF was estimated at \$4.8B, adjusted for the factors discussed above in the 2009 CBR to a range of \$4.0B to \$5.1B with levels of contingency ranging from 10% to 40%. O&M costs were calculated in CBR 2009 starting from available staffing levels, and fractions for other O&M costs such as utilities (20%), miscellaneous materials (15%), 3% for insurance and other miscellaneous small projects and \$100M for the specialized fuel fabrication hardware costs. This yielded a point estimate of \$275M/yr. Without aqueous polishing, the staffing was expected to be reduced to about 700 and the annual operating costs drop to \$220/yr. These annual amounts are respectively 6% and 7.5% of the initial capital investment, in line with the range of 4% to 7% reported by (Bunn 2016) for radiochemical facilities.

With an annual capacity of 70 MT/y, a 50 years facility lifetime and 3% discount rates, the adjusted unit cost ranges based on the CBR 2009 estimates are between 2200 \$/kgHM and 2800 \$/kgHM for capital costs, and between 3100 \$/kgHM and 3900 \$/kgHM for O&M. Total unit cost for MFFF, based on the CBR 2009 adjusted costs are therefore between 5300 \$/kgHM and 6700 \$/kgHM. Substantially higher values would be calculated for the 2016-revised capital cost of \$17B.

In conclusion, the MFFF project appears to have been a victim of typical “first-of-a-kind” and “altered scope” problems and also mismanaged, with a construction cost (from Table D1-2-1) several times that of other existing and under construction facilities for MOX fabrication. The reasons for the escalating costs are complex, and will not be discussed here. However, the U.S. DOE-NNSA found in a report released in December 2016 that “The contractor lacked the fiduciary will to plan and execute work to fully benefit the project and taxpayer” (supp. ref: Mufson, 2017). Therefore, this facility appears to not be representative of the cost of a well-executed construction project for MOX fabrication. **For these reasons, the cost estimates of the MFFF will not be included in the expected cost of a MOX fabrication facility as assessed in this module.** The summary costs will instead be based on the other 3 facilities for which cost data are at least partially available: the SMP, the Hanau and the Rokkasho MOX facilities.

Regarding O&M costs, the two values of \$220-\$275 M/y for SRS-MFFF were reported in (the 2009 Cost Basis Repowrt). The operational cost of SMP was reported in (Bunn, 2003), at about \$50 M/y, or 7% of the initial investment costs. No information was found on the O&M costs of the Hanau-2 facility, but it is noted that the SMP data, with O&M costs of 7% of overnight construction costs, may be a reasonable assumption to make also for the identically-sized Hanau-2. It is noted that typical ranges for reprocessing facilities were found in (Bunn 2016) to be between 4% & 7%. The 7% cost was then used for Hanau-2, while.

The O&M cost of Rokkasho was not reported in Table D1-2-1 from (CBR 2009). However, subsequent data found in 2010 (Suzuki 2010) increased the total construction cost for the Rokkasho MOX facility from \$1B to \$2B, and reported a total project cost of \$12.5B. With a facility lifetime of 40 years (Suzuki 2010) and no discounting for the expenditures in different years during the operational life of the plant, the annual O&M costs would be \$263M, or 13.2% of the initial capital investment. This value is substantially higher than the typical range of 4% to 7% for other radiochemical facilities (Bunn 2016). While an explanation for this value was not found, it could be speculated that it could be due to a higher cost of labor in Japan as compared to U.S. and European countries. Alternatively, it could be a conservative overestimation of the actual O&M costs, since the facility is currently almost completed but has not been operated with actual spent fuel.

The unit costs (in \$/kgHM of fabricated fuel) for the fabrication of MOX fuel, based on the costs reported in Table D1-2-1, are shown in Table D1-2-2, for 3 different assumptions about discount rates and facility lifetimes. For the unit costs' "low value" for Rokkasho provided in Table D1-2-2, it was assumed that the O&M cost would be 7% of the construction cost, while for the "high value" the expected 13.2% annual O&M cost from (Suzuki 2010) was utilized. The low, medium and high values for both SMP and Hanau-2 have different assumptions on discount rates and facility lifetimes, from long lifetimes (50 years) with low discount rates for the "low value" to short lifetimes (30 years) and commercial discount rates for the "high value".

Table D1-2-2 Unit cost of MOX fuel fabrication based on the expected cost of various existing (SMP and Hanau-2) and under construction (JNC Rokkasho and SRS MFFF) facilities, for 3 different assumptions about discount rates and facility lifetimes.

Facility	Low cost (3%, 50y) (\$/kgHM)	Higher cost (5%, 40y) (\$/kgHM)	Highest cost (10%, 30y) (\$/kgHM)
SMP (BNFL)	658	778	1074
Hanau-2 Germany (Siemens)	658	778	1074
JNC Rokkasho Mura, Japan <sup>a</sup>	1122	1425	2672

<sup>a</sup> Expected completion in mid-2019 (World Nuclear News 2015)

It is observed from Table D1-2-2 that MOX fabrication unit costs are between 650 \$/kgHM and 1000 \$/kgHM for both SMP and Hanau, under a range of assumptions on discount rates and facility lifetimes. Rokkasho has higher unit costs, but the facility experienced a substantial amount of cost overruns, due to various factors that will not be discussed here. However, because of this, it is observed that this facility, similarly to the MFFF albeit to a lesser degree, is a poor representation of a well-executed construction project for a MOX fabrication facility. Consequently, the costs derived from this facility are likely to overestimate the unit costs that could be expected from a well-executed construction project.

The average of the costs of the 3 facilities are \$813/kgHM, \$993/kgHM, and \$1606/kgHM, approximated as \$800/kgHM, \$1000/kgHM, and \$1600/kgHM. These unit costs are recommended for the triangular distribution of the expected cost of pelletized MOX glove box fabrication for LWR MOX fuel.

#### Unit costs from various literature sources

Table D1-2-4 shows the range of unit production costs for LWR MOX fuel gleaned from the literature. The range is very large and is influenced by market and political factors in addition to pure engineering economics.

Table D1-2-4. Unit fabrication costs for LWR MOX fuels as proposed by various literature sources.

Reference/Date	Fabrication Cost in \$/kgHM ("then year \$") L=Low; M=Medium or Reference; H=High
Bunn et al., 2003	(L/M/H) 700/1,500/2,300
OECD NEA, 1994	(L/M/H) 800/1,100/1,400
Delene et al., 2000	(L/M/H) 2,000/3,200/4,000
CFTC analysis of SRS MOX FFF publicly available data	(L/H) 3,400/ 4,700 (aqueous polish of weapons-derived feed excluded)
NEA 2001	(L/M/H) 1,000/1,250/1,500
MIT Future of Nuclear Fuel Cycle 2003	(M) 1500
MIT Future of Nuclear Fuel Cycle 2009	(M) 2400
MIT Future of Nuclear Fuel Cycle (MIT 2011)	(M) 2400
Red Impact 2006	(M) 1800
WISE Nuclear Fuel Cost Calculator (WISE 2009)	(M) 1840
DEC 2009 AFC-CBR	(L/M/H) 3,000/3,200/5,000
(EPRI 2009)	(L/M/H) 750/1,250/1,750

## D1-2.7 DATA LIMITATIONS

As with LEU fabrication, there is no price list for MOX fabrication. Also, there is no "spot" market for MOX fabrication services, since the product is generally non-fungible and customized to the particular reactor. (Uranium ore, conversion services, and enrichment are "fungible" commodities that can be sold back and forth between utilities and brokers.) This means that there is no published price, since most utility/fabricator contracts are proprietary.

Most of the data presented in this module is instead based on actual plants constructed in Europe and Japan in the 1990s and never operated or operated from a brief period of time. Cost data on facilities that have a substantial operational experience, such as the MELOX plant in France, could not be found. Consequently, there is an intrinsically high uncertainty in the estimates. The large ranges observed for the costs of MOX fabrication found in the literature, reflect the large uncertainty associated with this cost, and several high estimates may incorporate a large degree of conservativeness, mostly due to the high uncertainty. Since the estimates were calculated in the 1990s, better automation and manufacturing technology may have contributed to reduce the costs of these facilities, while an increase in safeguards, security, life safety, and physical protection requirements may have contributed to an increase in the cost of a well-executed MOX fabrication plant.

Fuels that result from proliferation-resistant reprocessing schemes such as UREX will contain higher actinides in the fuel, i.e., actinides such as neptunium, curium, and americium in addition to the plutonium. These additional constituents and their associated higher radioactivity will impose significant safety and operational burdens on a MOX plant (hence the name "dirty" MOX is sometimes applied). The cost effects of these requirements, such as a requirement for remote-handling, are discussed in module F2/D2.

A major variable in the calculation of unit cost is the method of financing and ownership of the MOX facility, as well as the facility's expected lifetime. Most of this difference is attributable to the very large carrying charges or interest associated with construction financing and plant amortization.

In summary, MOX fabrication costs and pricing are very assumption-driven, and have a high degree of uncertainty due to the very limited set of firm data on actual plants. In all cases, MOX fabrication is significantly more expensive than LEU fabrication.

## D1-2.8 COST SUMMARIES

The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table D1-2-6. The summary shows the reference cost basis (constant year \$U.S.), the reference basis cost contingency (if known), the cost analyst’s judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Table D1-2-6. Cost summary table for commercial LWR MOX fuel.

What-It-Takes (WIT) Table (2017 constant \$)			
Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
\$1,000/kgHM as reference cost for “normal” MOX based on European experience.	Unit=\$800/kgHM	Unit=\$1,600/kgHM	Unit=\$1,000/kgHM
	Mature MOX technology in the U.S. for new facilities. Well executed project. 3% discount rate, 50 years lifetime O&M 7% of initial construction costs.	Project with some cost overruns. 10% discount rate, 30 years lifetime O&M 13% of initial construction costs.	Mature MOX technology in the U.S. for new facilities. Well executed project. 5% discount rate, 40 years lifetime O&M 7% of initial construction costs.

The triangular distribution based on the costs in Table D1-2-8 is shown in Figure D1-2-4.

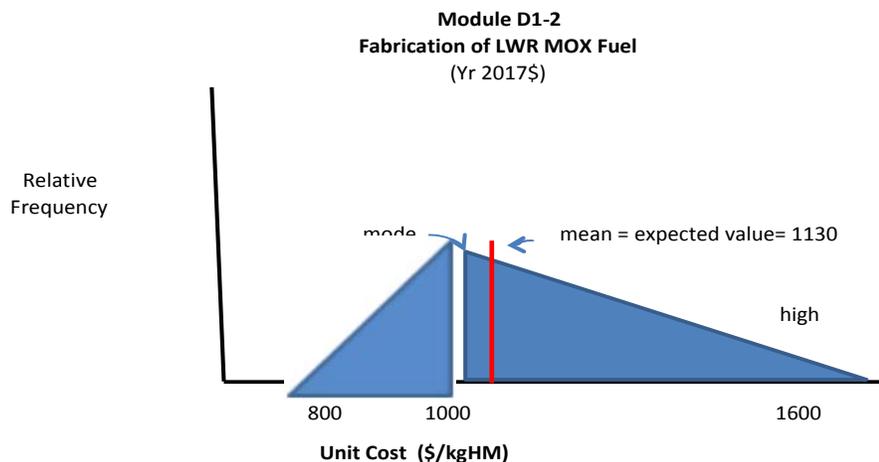


Figure D1-2-4. LWR MOX fuel fabrication estimated cost frequency distribution.

## D1-2.9 SENSITIVITY AND UNCERTAINTY ANALYSES

None provided at this time.

## **D1-2.10 Supplementary References**

### **Added for 2017 revision of module**

Brady 2013, "Revealed: £2bn cost of failed Sellafield plant", Brian Brady, The Independent, 8 June 2013.

Nuclear Monitor 1994, Siemens can continue MOX-fuel plant Hanau, Nuclear Monitor Issue: #417, 02/09/1994

Mufson 2017, "Energy Department issues scathing evaluation of nuclear project", The Washington Post, February 28, 2017

The State 2016, MOX plant at Savannah River Site will cost \$12 billion more than initially thought, By Sammy Fretwell, September 08, 2016.

World Nuclear News 2015, "Major work required at Rokkasho for new regulations", 17 Nov 2015.



**Module D1-3**  
**Gas-Cooled Reactor Fuels**



# Module D1-3

## High Temperature Reactor Fuel Fabrication

### D1-3.MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:**
  - Literature survey and some unit cost calculations for known MHR or GCR fuel projects.

It should be noted that Module D1-3 is based on a fuels technology that has been demonstrated on a pilot plant scale supporting a single reactor, but has not been automated or scaled up to production levels required for a fleet of reactors

### D1-3.RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module D1-3.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2012
- **New technical/cost data which has recently become available and will benefit next revision:**
  - China is building an MHR production facility to support a small fleet of gas-cooled reactors. A search of trade press and international nuclear publications might yield some useful cost data.
  - X-Energy in the U.S. is working on MHR development. They may have done some of their own analyses. A U.S. corporation, CENTRUS Corp, is now partnering with X-Energy on TRISO fuel development (CENTRUS 2017).

## D1-3.1 BASIC INFORMATION

### Basic Information from 2009 AFC-CBD

**Fuel Form.** The high temperatures envisioned for today's gas-cooled reactor (GCR) designs (IAEA 2001) offer the cost advantages of higher power plant thermodynamic efficiency; however, they also put very stringent demands on the fuel. The fact that the moderator, carbon in the form of graphite, is a solid, and the coolant is a gas, helium (or a molten salt), also affects the design of the fuel. The fuel form for GCRs is also supposed to be the first line of "defense in depth" as far as safety is concerned, with the fuel form itself actually described as part of the over all "containment" philosophy. The volatile fission products are contained by the fuel particle design, and the possibility of a "meltdown" in the classical sense is eliminated through inherent safety features.

There are two major fuel forms now envisioned for GCRs:

1. The prismatic concept in which a fuel assembly or "block" is in the shape of a hexagonal cylinder with holes drilled for flow of the gas coolant. These hexagonal blocks are stacked and arrayed inside of a machined graphite core. Each prismatic block has smaller graphite right circular cylinders or "compacts" imbedded in other vertical holes in the block. These compacts contain the fuel particles. This is the concept that has been developed over many years by General Atomics (GA) as the Modular High-Temperature Gas-cooled Reactor (MHTGR) and more recently the direct cycle Gas Turbine-Modular Helium Reactor (GT-MHR).

2. The other fuel “assembly” form is that of a billiard-ball sized graphite sphere or “pebble” with the fuel particles imbedded within. This concept was developed and demonstrated in Germany and is now being vigorously pursued in China and Japan. At one time, South Africa planned to build a demonstration plant called the Pebble Bed Modular Reactor (PBMR). This plant concept was to have been marketed worldwide by South Africa. (ESKOM is the South African utility that ordered the PBMR demo module.) China recently announced plans to deploy the PBMR concept.

#### **Basic Information from 2012 AFC-CBD Update.**

Again little has changed from the *December 2009 Advanced Fuel Cycle Cost Basis Report* in the areas of the basic industrial process for TRISO-based HTR fabrication and its interfaces to other fuel cycle steps; there have been, however, a few changes in the status of some of the world’s planned HTR fabrication facilities. It should be noted that this type of TRISO UO<sub>2</sub> or UCO kernel fuel could also be used with a molten salt coolant, hence the change in the title of this Module from “gas-cooled” to “high temperature”. The Gas-cooled reactor itself is still covered in Module R-3 and a new Reactor Module (R-8) has been added for Solid-fueled Molten-Salt Cooled Reactors, aka Fluoride Salt Reactors (FSRs).

- For economic reasons the utility ESKOM and the South African government have abandoned their ambitious Pebble Bed Modular Reactor (PBMR) program. This happened in 2010 prior to construction of a proposed pilot plant for TRISO fuel production. Design for this pilot plant was already well underway.
- The U.S. DOE has slowed down its NGNP (Next Generation Nuclear Plant) RD&D Program, for which the demonstration plant was to be a gas-cooled HTR. The fuel design/development program originally undertaken with AREVA and GA Technologies has also been slowed down. A small particle-fuels program is still underway at some National Laboratories. There is also a small joint effort with Russia on the use of Pu-loaded TRISO fuels for disposition of plutonium from military programs.

Japan continues its HTR program, with a demonstration reactor at O-Orai near Mito City. The plant is supported by a 400 kgU/yr HTR fuel fabrication line at the Nuclear Fuel Industries Tokai Works. As of March 2012 this facility has produced 300 HTR fuel assemblies (Nuclear Fuel Industries, 2012).

- China is now the most active nation pursuing HTR deployment. A two-module HTR with a single 210 MWe generator is under construction at Shidaowan. To support this FOAK plant a 2100 kgU/yr initial fabrication fuel line is being constructed at Baotou in Inner Mongolia. Each sphere in the HTR pebble bed fuel will contain 7 grams of ~9% U-235 as ceramic TRISO fuel particles. 300,000 such TRISO-loaded graphite spheres, each approximately the size of a billiard ball, per year are required. Available cost information on this facility is analyzed below (World Nuclear Organization 2012).
  - Other nations such as the Netherlands, France, and South Korea are pursuing HTR research under the Generation IV VHTR (Very High Temperature Reactor) program. Most of this analytical work deals with the reactors and process heat applications rather than with the fuel manufacturing process.

### **D1-3.2 UNCTIONAL AND OPERATIONAL DESCRIPTION**

**Two GCR Fuel Concepts.** Both GCR fuel concepts, however, have a common fuel production technology. The fissile material, enriched uranium or plutonium, in the form of an oxide (UO<sub>2</sub> or PuO<sub>2</sub>) or other ceramic forms (e.g., UCO), exists as tiny 200 to >500 micron spheres or “kernels,” which are coated with layers of mechanically tough and highly refractory coatings of porous carbon, silicon carbide, and electrochemical carbon. The resulting sphere, which measures less than 1 mm in diameter, is called a TRISO coated fuel particle and is in essence a tiny pressure vessel. Thousands of these particles are then imbedded in a graphite matrix that forms the “pebble” or the cylindrical “compacts.” The latter are inserted in a prismatic hexagonal block. For both concepts, the fuel enrichments (U-235) are considerably above the 3 to 5% U-235 for today’s LWRs. In fact, early MHTGR designs utilized highly enriched

uranium at >90% U-235. For nonproliferation reasons, all GCR designs have backed off to LEU enrichments in the range 8 to 19.9% U-235. The fuel for these two concepts is often referred to as “particle fuel” as opposed to pellet, vipac, or cast fuel for other reactor concepts. GA includes some “fertile” natural uranium TRISO particles in their design and in the past has incorporated thorium in the form of thoria (ThO<sub>2</sub>) fertile particles.

Figure D1-3-1 shows the basic fuel concept for the GA GT-MHR concept. Figure D1-3-2 shows a similar diagram for the “pebble bed” concept. Figure D1-3-3 shows the makeup of the basic TRISO particle. All GCR concepts discussed for future deployment have some variant of the particle fuel concept.

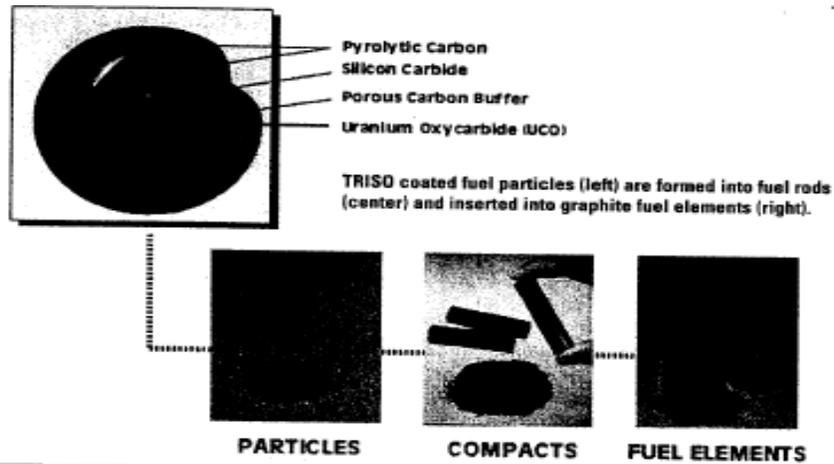


Figure D1-3-1. Prismatic concept utilizing particle fuel (General Atomics concept).

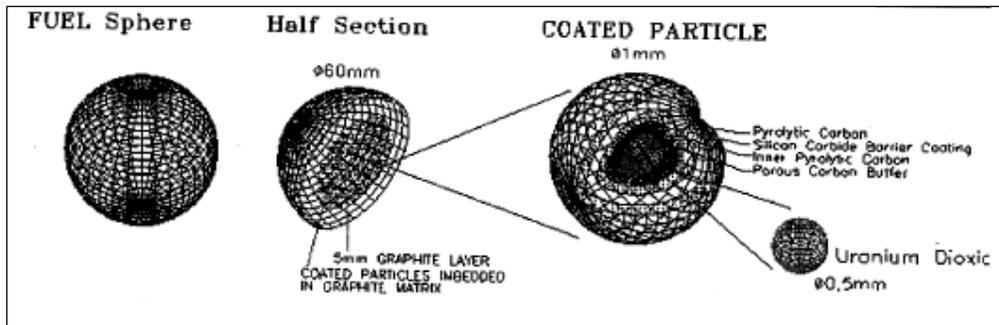


Figure D1-3-2. Pebble concept utilizing particle fuel (UC and OSU 1998).

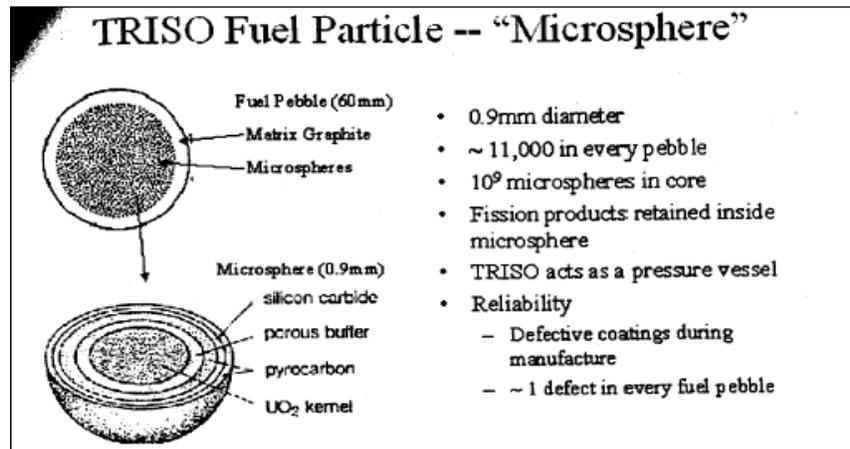


Figure D1-3-3. Illustration of a TRISO fuel particle concept (UC and OSU 1998).

**Status of Industry.** Unlike for LWR fuel, no large-scale GCR fuel manufacturing capability exists in the U.S. (or in the world for that matter). Because there is no fleet of electricity producing GCRs of a current design, this fact is not surprising. (The United Kingdom has an aging fleet of lower-temperature CO<sub>2</sub>-cooled advanced GCRs that are not candidates for further deployment.) All the world's existing high-temperature GCR projects had their fuel produced in pilot scale facilities. A commercial MHTGR was operated for several years at Fort St. Vrain, Colorado. Its fuel was produced in a pilot scale facility operated by GA at Sorrento Valley, California. Pebble bed fuel pilot lines in China and proposed for South Africa at Pelindaba are based on German PBMR technology, which was formerly located at Karlsruhe. Nuclear Fuel Industries in Japan has a 0.4 MTU/yr coated-particle fuel line at Tokai-Mura, which was completed in 1992. NUKEM/HOBEG of Germany had a line at Hanau from 1960–1968 that was capable of manufacturing 200,000 fuel blocks per year. It is now being decommissioned. Cost information on these pilot facilities is either not available or is considered proprietary.

If GCR technology is to be deployed for large-scale electricity generation, a large-scale particle fuel production facility will need to be built to support the fleet of modular reactors. No company has yet initiated such a project and will not until the proposed demonstration GCR modules utilizing pilot-plant-produced fuel prove to be technically and economically viable. [To support a prototype high-temperature GCR, such as the proposed U.S. Next Generation Nuclear Plant (NGNP), a pilot-scale fuel fabrication line will be required.] The U.S. companies Nuclear Fuel Services of Erwin, Tennessee, and BWXT Technologies and AREVA-NP of Lynchburg, Virginia, have all shown some interest in pursuing this technology. GA Technologies of San Diego, California, has decided to pursue only the reactor part of this fuel cycle. X-Energy and CENTRUS are new U.S. cut-outs pursuing this technology.

In terms of heavy metal or uranium throughput, commercial particle fuel production facilities are likely to be smaller than LWR facilities, but this is partially because the U-235 enrichment of this fuel is at least twice that of LWR fuel and less “heavy metal” (combined fertile and fissile) is required per kilowatt of electricity produced. In an LWR fuel assembly, most of the “weight” is UO<sub>2</sub> in the form of pellets. However, for GCR fuel, much of the fuel assembly weight will be machined or formed graphite. The fissile mass is dispersed within defined locations within the graphite.

From 1988–1992, DOE embarked on a program to design and construct tritium production reactors for military purposes. The original Record of Decision was to build eight 350 MWth modules at the Idaho National Laboratory (INL).<sup>b</sup> These steam cycle MHTGR modules were to use 93.5% U-235 weapons-grade highly enriched uranium in its fuel. The fuel design was the TRISO/prismatic block concept. To support this operation, a 3 MTU/yr onsite fuel fabrication plant was proposed, and a preconceptual design was prepared in 1990 by Fluor-Daniel Corporation based on GA process concepts. This plant was to be government (DOE Defense Programs)-owned and financed and operated by the INL prime government contractor. Cost information from this report (DOE/NP-24 1991) will be discussed in a section below.

GA (GA Technologies 1994) has proposed the GT-MHR as a plutonium-dispositioning reactor both in the U.S. and Russia. (The same particle fuel concept can be used with PuO<sub>2</sub> or other plutonium compound ceramic kernels.) GA is engaged in a joint program to eventually construct a plutonium GT-MHR in Russia; however, very limited information on the fuel fabrication facility that would be needed has been presented. The GT-MHR uranium burner is also being NRC-certified for future U.S. deployment; however, no plans or cost information for a supporting fuel fabrication facility have come forth. Some GA cost information can be gleaned from conference papers, and some of this is discussed below.

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b. Beginning February 1, 2005, the name of the Idaho National Engineering and Environmental Laboratory (INEEL) was changed to Idaho National Laboratory (INL).

The South African utility ESKOM had planned a small (maximum 13 MTU/yr) fuel production facility to support their first-of-a-kind demonstration module. This was likely to have been an expansion of the 2.4 MTU/yr pilot plant which was to have been designed and licensed by NECSAs (Nuclear Energy Corporation of South Africa) German contractor Uhde, a division of Thyssen-Krupp. Again, very limited cost information (Platts 2005) on this proposed facility is available.

There is, however, considerable developmental work taking place in the area of TRISO fuels. Two of the International Generation IV (GIF-004-00) reactor concepts involve high temperatures (required for nuclear hydrogen production) and gas-coolants as well as some space reactor concepts. DOE also at one time considered the construction of a NGNP at INL that was to have been a demonstration GCR for hydrogen production. AREVA-NP, BWXT, GA, Nexia (formerly BNFL), and national laboratories such as INL and Oak Ridge National Laboratory all have research and development interests in this type of fuel. Any economic analyses performed on GCR fuel manufacturing, however, have not been made public.

**GCR Fuel Fabrication Process.** There is no single process for all particle fuels, and many of the processes are proprietary. They all have some basic similar element; however, and these will be briefly mentioned. Figure D1-3-4 shows a generic TRISO fuel fabrication process being considered by the Advanced Fuel Cycle Initiative (AFCI) Fuels Working Group. Production of the ceramic  $\text{UO}_2$  or UCO kernel is a crucial step in the process. In order to get uniform spheres, a sol-gel or similar fluidization process must be used to render liquid spheres into hard solid spheres. This means that a liquid solution such as uranyl nitrate hexahydrate (UNH) must be produced from the  $\text{UF}_6$ . This is a relatively simple step, since many of the older LWR fuel “wet” or aqueous fuel fabrication processes required the same step on their front end. Uniform UNH solution drops of the desired size are formed and then contacted with ammonia to form gel-spheres (gel-precipitation process). These gel-spheres are washed with water, dried to a low-density form, calcined to a medium-density form, and then sintered to a high-density microsphere “kernel.” Fission-product-retentive ceramic coatings are applied to the kernel by chemical vapor deposition in a fluidized-bed furnace. The coated particles are mixed with various carbonaceous materials and formed into either cylindrical compacts or spherical pebbles. For the GT-MHR, the compacts are inserted into predrilled hexagonal blocks of graphite. Each pebble or compact will have thousands of such TRISO particles imbedded within. The requirement for quality control and TRISO particles in a reactor core, the defective particle fraction must be kept very low, especially for modern vented confinement reactor designs in order to meet the licensing requirements for low onsite and offsite doses/releases.

Bench and pilot scale work is under way in several nations on variants of this process. The problems of scaleup and automation are just now being seriously considered. The economic viability of this reactor/fuel system will depend heavily on how successful these efforts are.

# D1-3.3 PICTURES AND DIAGRAMS

## TRISO MOX Fuel Process Flow Diagram

9/8/04 Rev. B

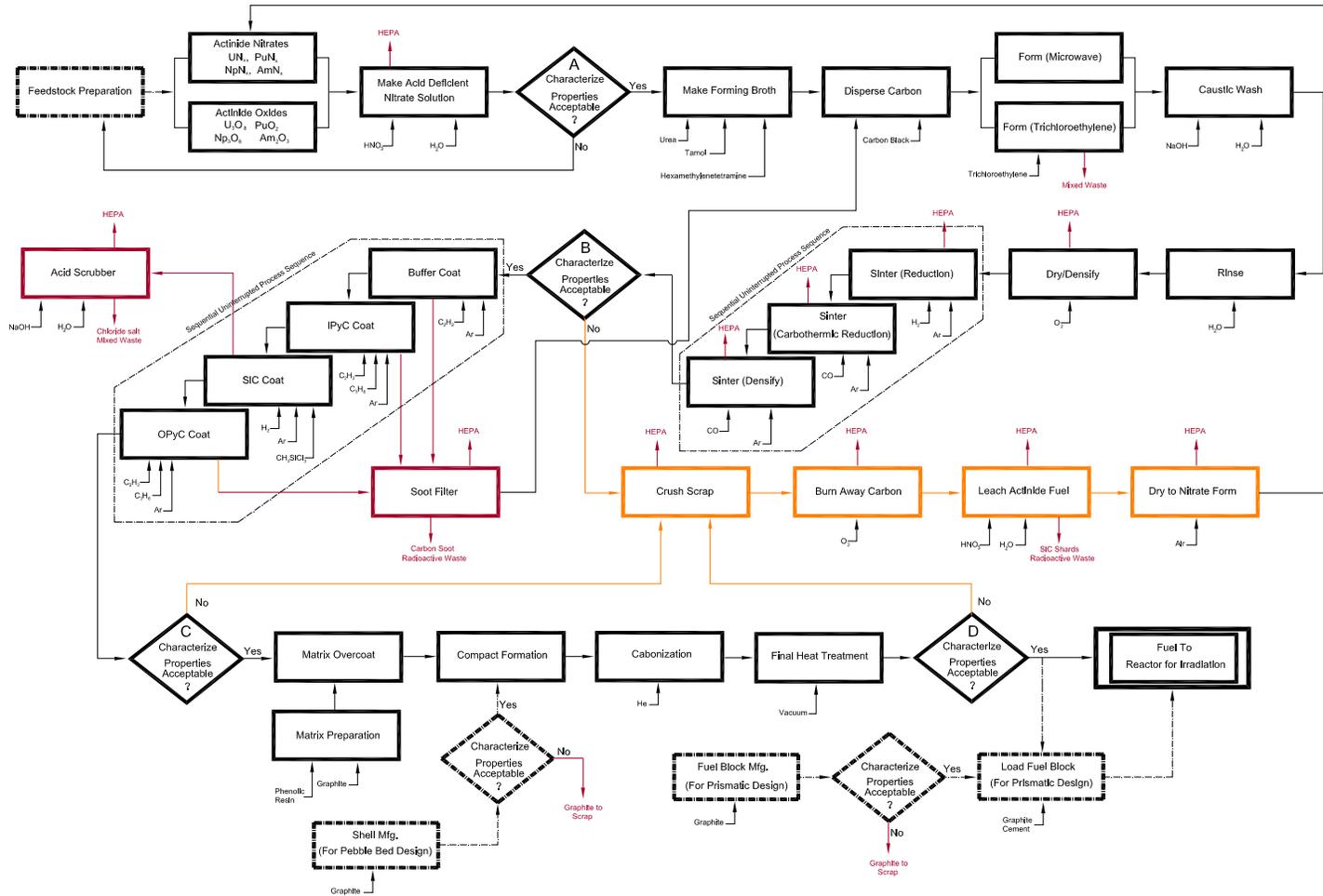


Figure D1-3-4. TRISO MOX fuel process flow diagram (DOE-AFCI Fuels Working Group, 2007).

## D1-3.4 MODULE INTERFACES

**Front-end interface.** Because the fuel enrichment level is 8 to 19.9% U-235, the likely feed material to a fabrication facility will be  $\text{EUF}_6$  coming from a new centrifuge enrichment plant or from blended U.S. or Russian  $\text{EUF}_6$  derived from surplus HEU.

**Back-end interface.** Irradiated blocks and pebbles are the fuel forms that exit a GCR fuel fabrication facility. Special transport packages will need to be designed to safely move and protect this type of fuel. The spent fuel handling and disposal steps are technically different than for LWR fuels. The bibliography includes three publications (Fousberg 2006, Fuls 2004, Owen 1999) dealing with waste characterization and repository issues associated with this fuel type. Most MHR reactor and fuel concepts are designed for open cycles. Reprocessing of this type of fuel presents many processing and waste-related difficulties compared to that for LWR or fast reactor fuels, especially in head-end operations. The Generation IV Roadmap (see Bibliography for reference) for gas-cooled systems discusses research and development issues with reprocessing and other aspects of this technology.

## D1-3.5 SCALING CONSIDERATIONS

No scaling factors or other scaling information was found in the literature. Because batch sizes are limited by criticality concerns, any capacity additions to an already-existing production scale facility (none exists now) will be accomplished by adding new process lines or the use of multiple shifts. The size of an optimal automated TRISO particle fabrication line is still to be determined.

## D1-3.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES

### 2009 AFC-CBD Cost Data.

**Cost and Pricing of GCR Fuel Fabrication.** The fabrication cost of GCR fuel is most useful if it can be expressed in \$/kgU or \$/kgHM and **not include** the ore, natural  $\text{U}_3\text{O}_8$  to  $\text{UF}_6$ , and enrichment components. In the literature, it is hardly ever expressed in this fab-only way, so in the cases below the fab-only unit cost had to be calculated by the author. Four different literature sources are analyzed below.

**Proposed New Production Reactor Fuel Fabrication Facility (DOE/NP-24 and ORNL 1991)** In FY 2003 dollars, this 3 MTU/yr fuel fabrication plant, based on unpublished Fluor-Daniel study, would have cost \$355M and have annual operating costs of \$22.6M/yr. This operations cost does not include the ore, conversion, SWU, or  $\text{UF}_6$  to  $\text{UO}_2$  or UNH conversion needed to supply feed material ( $\text{UO}_2$  or UCO) to the plant. If this New Production Reactor-support plant is amortized over 30 yr at a 4% real discount rate, a unit fabrication cost of nearly \$40,000 per kgU or \$49,000/hexagonal fuel block results. The fabrication of fuel at this price would account for 11 mills/kWh for a steam cycle 135-MWe MHTGR operating on a 1-year cycle at an 80% capacity factor. The proliferation, security, and criticality issues associating with dealing with weapons-grade (> 90% U-235) highly enriched uranium contribute significantly to these high costs. In later commercial designs, such as the GT-MHR, GA designers have reduced the fuel enrichment to below 20% U-235 and increased the fuel burnup, thermodynamic efficiency, and electrical capacity of the reactor, which will drive down the per kWh unit cost.

**GA Study on production of Spherical Targets for Fusion Energy (Goodin et al. 2002).** This report attempts to predict the cost of producing tiny spherical D-T targets for inertial confinement fusion based on past and projected costs of producing TRISO microspheres for GCRs. A graph in this document demonstrates how the cost per particle (fabrication only) for TRISO fuel has decreased from 20 cents/particle for 1960s bench scale fuel to a projected cost of less than 0.001 cents per TRISO particle for future fuel in an automated plant.

Each MHTGR or GT-MHR block (fuel assembly) has over 10 million of these particles. For the more current direct cycle 300 MWe GT-MHR reactor, both 19.8% U-235 and natural uranium particles will be used. Using the above costs per particle (midrange values) the fuel costs are calculated in Table D1-3-1 as

follows, (Note: ore, SWU, graphite, conversion from UF<sub>6</sub>, etc., add \$5,900/kgU to the stand-alone particle fabrication cost):

Table D1-3-1. Fabrication costs as a function of TRISO particle cost (2002\$).

<b>Reference: Particle Cost (US cents)</b>	Fab Cost per Block (particle fab only)	Fab Cost (\$/kgU) (particle fab only)	Fab Cost per Block (incl ore, SWU, conv)	Fab Cost (\$/kgU) (incl ore, SWU, etc.)
<b>20</b>	\$2,540,000	\$573,000	\$2,560,000	\$579,000
<b>1</b>	127,000	28,700	147,000	34,700
<b>0.1</b>	12,700	2,870	33,000	8,850
<b>0.003</b>	382	860	20,700	6,070

Today's cost is likely between the \$33,000 and \$147,000 per block. GA would like to force fabrication costs down to around \$12,000/block (particle preparation and graphite steps, but no ore or SWU cost are in this goal). A block contains around 4 kg of uranium, with over 75% of particles consisting of 19% U-235, and <25% of particles containing natural uranium.

**1993 Gas-Cooled Reactor Associates Commercialization Study (DOE 1993).** This report deals mostly with MHTGR construction costs. However, it does have some fuel cycle information. It states that the goal of the fuel development/qualification program is to get the cost of an MHTGR fuel assembly or "block" down to ~\$12,000 in 1993 dollars. This would be ~\$16,000 per block in today's dollars. It did not state if this includes only fabrication or includes all materials/services such as ore, SWUs, etc. If each block contains ~4 kg of uranium, the goal cost per kgU is therefore around \$4,000/kgU. This means that the Gas-Cooled Reactor Associates goal cost probably does not include ore or SWU, because these combined items alone would likely contribute nearly \$6,000/kgU to the overall fuel cost. If GA can drive the overall cost (\$6,000 + \$4,000) to \$10,000/kg of enriched uranium for a finished fuel assembly, they will meet the target. Realization of the target fuel cost above would result in a fuel cycle component of the power generation cost of around 9 mills/kWh.

**University Design Project Study for Pebble Bed Reactor (UC and OSU 1998).** The concept described is called the Modular Pebble Bed Reactor (MPBR) as opposed to the Eskom/BNFL PBMR. The plant designed and evaluated is a 10-reactor module facility totaling 1,100 MWe. It was developed jointly in 1998 by Massachusetts Institute of Technology (Andy Kadak and students) and INL. It was also part of a University of Cincinnati/Ohio State Design Course for which the documentation was made available on the Internet. The capital cost data are at the two-digit energy economic database code-of-accounts level only. All the costs are in 1992 constant dollars. The data from this study were input by this section's author to the Power Generation Cost model, G4-ECONS, being developed by the Generation IV Economics Working Group. In this model, the costs were all increased by a factor of 1.275 to take them to today's (2008) constant dollars using a construction index similar to the Handy-Whitman Utility Construction Index.

The reactor core for each PMBR module consists of 360,000 round pebbles with 7 g (expressed as uranium) of 8% U-235 enriched UO<sub>2</sub> in each. The UO<sub>2</sub> is encapsulated in 11,000 TRISO-coated microspheres within each billiard-ball-sized pebble. For the Generation IV Economics Working Group model, each pebble is assumed to be a "fuel assembly." An annual reload consists of 120,000 pebbles per module. The design project authors assume each pebble costs \$22 in 1992 dollars including all front-end fuel cycle steps. The author of this section assumes that this has risen to \$28 in today's dollars. This yields a fabrication cost of ~\$1,700/kgHM or per kgU if all other front-end fuel cycle costs (ore, SWUs, etc.) are set at today's values. This cost, in the opinion of the analyst for this report, is unrealistically low given the complexity of GCR fuel fabrication.



around \$2B. This plant could supply fuel for ~6500 MWe of HTR capacity.

## G4-ECONS-FCF Results for Pebble Fab Plant

Page 5		TAB= LUPC and Summary	
G4-ECONS FCF (Fuel Cycle Facility)			
Summary for Process Plant including Levelized Unit Product Cost (LUPC)			
Plant/Facility Name	TRISO Fuel Fabrication facility for MPBR		
Product word description	Kilograms of LEU as fabbed TRISO fuel		
Facility Capacity	50000	kgU	/yr
Capacity factor	80.0%		
Average Annual Throughput	40000.0	kgU	/yr
Overnight Cost	2000	\$M (US)	
Plant Total Capital Cost	2159	\$M (US)	
Discount rate for amortization	5.00%		
Plant life	30		
Fixed Charge Rate for amortization	6.5051%		
Reference year for const \$ costing	2008		
<b>Specific Capital Cost</b>	<b>\$43</b>	<b>\$/kgHM/yr</b>	
Int During Constr as % of Overnt Cost	7.9%		
<b>Levelized &amp; Annualized Cost Components:</b>			
		\$M (US) /yr	\$/kgU
Capital		140.4	3511.12
O&M (Production)		55.0	1375.00
D&D Fund		1.5	37.63
<b>Total</b>		<b>196.9</b>	<b>4923.75</b>
			"LUPC"
Notes: Fab cost only! Ore, conversion, and enrichment to 8% U-235 not included here			

EMWG Training on the use of GIF Economic Modeling Working Group Guidelines and Software G4-ECONS

Slide 52

Figure D1-3-5. Breakdown of unit and capital cost for a TRISO facility.

### 2012 AFC-CBD Update Cost Data.

A review of the literature since 2009 found very limited or very preliminary recent projected unit cost data for TRISO-type HTR fuels. This means that most values used for this module will in part have to be derived by analogy or constructed from other life cycle cost data. Some recently-found older literature sources; however, may shed light on HTR fuels. In 1979, as part of the U.S. NASAP (Non-proliferation Alternatives Systems Assessment Program), ORNL prepared a cost study (Olsen et al. 1979) on the life cycle costs of manufacturing and reprocessing several types of nuclear fuel. The same group of fuels R&D experts, design engineers, and cost estimators prepared pre-conceptual level estimates for the capital, O&M, and decommissioning costs of large (several hundred MTHM/yr) NOAK (Nth-of-kind) fuel fabrication facilities. A cost levelization technique similar to that used in today's G4-ECONS was used to calculate the unit cost of fabrication for each fuel type. An interest rate typical of privately financed nuclear projects was used in the analysis. Given that the life cycle cost estimates were all prepared with level playing field assumptions by the same individuals, the ratio of the more advanced fuel's unit cost to that of typical PWR UO<sub>2</sub> fuel at that time should give a good indication of the technical complexity of manufacturing these fuels even today. Table D1-3.3 shows the unit cost ratios for selected fuels to that for PWR UO<sub>2</sub> fuel, i.e. what this Module's author calls "complexity ratios". It should be noted that in constant 1979 U.S. dollars PWR fuel fabrication was calculated to cost \$110/kgU. Using the Handy-Whitman Power Plant construction index (Miller, n.d.; PJM Inc., n.d.), which is more realistic for nuclear projects than the U.S. Department of Commerce implicit price deflator, the equivalent cost in 2012 constant US\$ would be \$425/kgU, an escalation factor of 3.5. This unit cost falls in the upper range of the PWR fuel unit price distribution for Module D1-1. Since the upper range would represent new plants with full amortization, the escalated (Olsen et al. 1979). PWR fuel fabrication value seems to be valid. Using a unit cost ratio based on the complexity of the fuels technology a value of \$2132/kgU results for fabrication of "HTGR" fuels. Complexity ratios are shown for other fuel types for comparison. For PWR MOX fuel the resulting unit cost is on the low side of the Module D1-2 unit cost distribution.

Because of this observation the author of this module suspects that using “complexity only” ratios for advanced fuels (FR, MOX, and HTR) may be ignoring other cost-affecting factors which have started to more quantitatively dominate fuel fabrication costs for new fuel types since 1979. Most important of these would be regulatory costs such as meeting current nuclear standards, fuel qualification, and very stringent quality assurance requirements for fuel manufacturing. The latter QA factor is especially important to TRISO HTR fuels, since the TRISO coatings are the major “containment” for fission products in the event of a loss of coolant event. This high QA requirement for TRISO particle fuel was mentioned at a recent HTR workshop held at ORNL (Holcomb 2010). The TRISO particle fuel production process together with the “imbedding in graphite” step is very complex when compared to LWR-UOX fuel fabrication. This accounts for much of the high ratio of HTR unit fabrication cost to that of LWR-UOX fuel.

Table D1-3.3. Unit Fuel Fabrication Costs Derived from 1979 ORNL Study (Olsen et al. 1979).

Fuel Type in ORNL/TM-6522	Unit Cost Ratio calculated from Table 18 of ORNL/TM-6522	Module D1-1 "Nominal" Unit Cost for PWR UO <sub>2</sub> fuel from 2012 AFC-CBR Update (\$/kgHM)	Calculated year 2012 \$ unit cost using ratios from ORNL/TM-6522	Remarks on Fuel in Table 18 ORNL/TM-6522
PWR LEUO <sub>2</sub>	1.00	350	350	High capacity plant (1500 MTU/yr); 1979\$ unit cost was 110/kgU or \$/kgHM
PWR (U,Th)O <sub>2</sub>	1.09		382	High capacity plant (1000 kgHM/yr)
PWR MOX (U, Pu)	5.27		1845	MOX plant assumed highly automated with high capacity (1000MTHM/yr); remote ops & maintenance
HWR (nat UO <sub>2</sub> )	0.59		207	High capacity plant (1500 MTU/yr)
HWR (slightly enriched LEUO <sub>2</sub> )	0.60		210	High capacity plant (1500 MTU/yr)
FR MOX (U, Pu)	8.45		2959	High capacity plant (1000 MTHM/yr); remote ops and maintenance
FR metal (U, Pu,Zr)	7.73		2705	High capacity plant (1000 MTHM/yr); remote ops and maintenance
HTGR LEUO <sub>2</sub>	6.09		2132	High capacity plant (500 MTU/yr)
HTGR (MEU,Th)O <sub>2</sub>	5.64		1973	High capacity plant (500 MTU/yr)

The only current HTR fuels projects for which projected cost data are available are the Small scale plant under construction in Baotao, China and the USDOE-NE NGNP project. This Chinese 2.1 MTU per year “graphite pebble” plant is projected to cost 230 million yuan or about \$36 million U.S. It will fuel the two 100MWe FOAK HTRs under construction at Shidoawan, China. No annual operations cost projections are available for this plant. Table D1-3.2 shows an analysis of the Chinese data from (World Nuclear-Organization 2012) and the module D1-3 author’s own analysis of operations costs which are used to project the unit cost of TRISO-based graphite HTR fuel.

Table D1-3.4. Unit HTR Fuel Fabrication costs derived from Analysis of Chinese data.

DATA		
Plant	Baotou, Inner Mongolia, China	Supports 210 Mwe of HTR
Planned Capacity	300000	TRISO-loaded spheres per year
	2100	kgU/yr
U loading per sphere	7	grams U/sphere
Plant Capital Cost	230	million Yuan
	36.4	million US\$
Exchange rate	6.32	Yuan/US\$
Assumed real discount rate	3.00%	
Assumed plant life	20	yrs
Calculated fixed charge rate for capital recovery	6.72%	
Assumed annual operations cost		
low	5	\$M/yr
nominal	10	\$M/yr
high	20	\$M/yr
UNIT COST CALCULATION		
Capital recovery component of unit cost	1165	US\$/kgU
Operations component of unit cost		
low	2381	US\$/kgU
nominal	4762	US\$/kgU
high	9524	US\$/kgU
Total unit cost		
low ops	3546	US\$/kgU
nominal ops	5927	US\$/kgU
high ops	10689	US\$/kgU

The author of this module assumes a low interest rate typical of Far Eastern projects and a 20-year life for the facility. The resulting fixed charge rate is applied against the \$36M capital cost to obtain the capital component of the unit fabrication cost. (This is the method used in G4-ECONS for reactors). Low, nominal, and high annual O&M costs are selected based on the module author's knowledge of small, non-glovebox fuel fabrication facilities. The Table D1-3,4 above shows the calculated O&M components of the unit cost for each. The low, nominal, and high values are derived by adding this O&M value onto the capital component. A range from ~\$3,500 to \$11,000 per kgU results.

A recent life cycle cost estimate (INL 2012) for HTGRs was prepared by INL and subcontractors for the NGNP program. It includes both a high and low unit fabrication cost which was used in the fuel cycle cost calculations. The assumed fuel was prismatic and assumed to cost from \$10,600 to \$26,500 per kgU.

The following Table D3-5 summarizes HTR fuel fabrication cost data from the above and other recent sources:

Table D1-3.5. 2012 AFC-CBD Update “What-it-takes” (WIT) HTR fuel fabrication unit costs from Various Sources (Constant 2012 US\$).

Study or Ref /Year	Low Value (\$/kgU)	Medium or Ref Value \$/kgU	High Value (\$/kgU)
DEC 2009 AFC-CBR			
TRISO HTR incl graphite	5,000	10,000	30,000
ORNL/TM-6522 (Olsen et al.) Handy-Whitman escalation only (LEUO <sub>2</sub> kernels from high capacity plant)			
MHTGR TRISO (D1-17)	N/A	2132	N/A
HTR Pebble Fuel with LEUO <sub>2</sub> or UCO Kernels			
Analysis of Chinese data for low-capacity Shidaowan facility (World Nuclear-Organization 2012)	3,550	5,900	10,600
Recent INL Report on HTGR Life Cycle Costs (INL 2012)	10,600	N/A	26,500
Personal communications from un-named fuels experts (range only)	5,000	N/A	20,000

A few recent un-named data sources, both foreign and domestic, have also been accessed to help provide the basis for changing the recommended low, nominal, and high values for the \$/kgU cost of HTR fuel fabrication. (Note that as with UO<sub>2</sub> and MOX pelletized fuel there is no published data on the actual unit production cost. These sources have had access to non-public economic feasibility studies for HTR-related projects, and have been willing to verify that the range of the 2009 AFC-CBR (5,000 to 30,000 \$/kgU) was reasonable for FOAK fuel fabrication facilities.

### D1-3.7 DATA LIMITATIONS

**Identification of Gaps in Cost Information for Future Fuel Cycles.** The gaps in the economic information for this type of fuel are very wide and deep, especially given the fact that PBMRs and GT-MHRs are being seriously considered for deployment as electricity producers and even hydrogen producers. It may be that the private developers of these concepts are keeping such information proprietary. In any case, it would be in DOE’s best interest to initiate a study that would at least consider the economic and cost issues associated with scaleup and automation of at least some of the various TRISO particle fuel flowsheets now under development. It would also be useful to understand the cost issues associated with the radiochemical and radiotoxicity amelioration design fixes required to adapt TRISO fuel production flowsheets to plutonium particle fuel production or actinide burning. The joint U.S./Russian GT-MHR program could also greatly benefit from such an analysis.

**Readiness level.** This fuel fabrication technology reached the pilot plant level of deployment in the U.S. for the production of Fort St. Vrain MHTGR fuel at Sorrento Valley near San Diego, California. Presently, that facility has been shuttered, and any U.S. work in progress is now at the “bench scale.”

### D1-3.8 COST SUMMARY

**2009 AFC-CBD Cost Summary.** The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table D1-3-6. The summary shows the reference cost basis (constant year \$U.S.), the reference basis cost contingency (if known), the cost analyst’s judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to

Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Table D1-3-6. Cost summary table for GCR TRISO fuel (2009 AFC-CBD).

What-It-Takes (WIT) Table				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
Today's 8–19.9% U-235 unit fab cost probably ~\$25,000/kgU	N/A	\$5,000/kgU Low cost assumes that complexity of this fab process is at best comparable to glovebox- handled LWR MOX	\$30,000/kgU	\$10,000/kgU
No highly reliable data on plant capital costs;	Not available	Development of a reliable, highly automated TRISO process in a central large facility	Quality or process development difficulties. Use of PuO <sub>2</sub> kernels	If automated process is successful:

**2012 AFC-CBD Update Cost Summary.** The following set of “what-it-takes” values and a corresponding probability distribution is recommended for use in future fuel cycle studies. A triangular distribution is suggested.

Table D1-3.7. Low, Nominal, and High Suggested HTR Fuel Fabrication Price Values in \$/kgU (2012 \$)

Fuel Type	Low (2012 \$/KgU)	Nominal (2012 \$/KgU)	High (2012 \$/KgU)
HTR	3,000	10,000	27,000

The low end of this range has been lowered from \$5,000 to \$3,000 per kgU. This could reflect a possible future cost from a large capacity, NOAK Far-Eastern facility with low labor costs and high automation. The nominal to high range would be for a Western-style NOAK fabrication facility in a highly regulated environment and in the tens of MTU per year production capacity. Such a facility would also have to be highly automated. The high end cost would likely represent a NOAK facility with less automation and significantly higher personnel costs.

The following Table D1-3.8 merely escalates the 2012 \$ amounts above by 9% to 2017\$ and rounds to nearest \$100/kgHM. No new cost data was gathered in the period 2012 to 2017. The suggested triangular distribution is shown in Figure D1-3-6.

Table D1-3.8. Low, Mode, Mean, and High Suggested HTR Fuel Fabrication Price Values in \$/kgU (2017 \$)

Fuel Type	Low (2017 \$/kgU)	Mode (2017 \$/kgU)	Mean (2017 \$/kgU)	High (2017 \$/kgU)
HTR	3,300	10,900	14500	29400

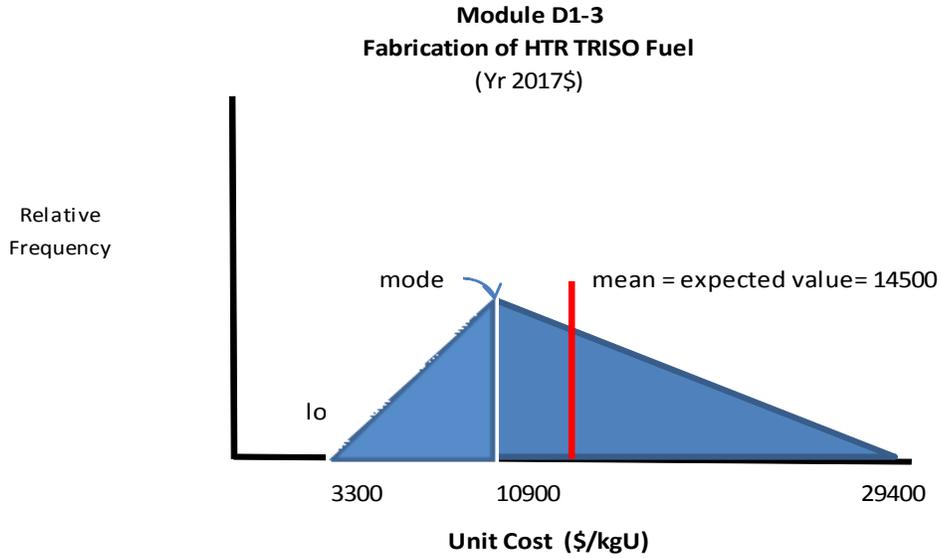


Figure D1-3-6. High-temperature reactor particle fuels estimated cost frequency distribution.

### **D1-3.9 SENSITIVITY AND UNCERTAINTY ANALYSES**

Insufficient base process cost data exist for such studies to begin. Goodin et al. (2002) and DOE (1993) have some limited sensitivity study data.



**Module D1-4**

**Ceramic Pelletized Fast Reactor Fuel**



## Module D1-4

# Ceramic Pelletized Sodium-Cooled Fast Reactor (SFR) Fuel Fabrication

### D1-4.MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only from last time values underwent technical assessment (2012 AFC-CBR)
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:** Review of literature followed by unit cost calculations based on G4-ECONS FC methodology. Analogues based on 1979 fuel fabrication comparative studies were also utilized.

### D1-4.RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module. In the 2012 AFC-CBR costs for the fabrication of higher enrichment UO<sub>2</sub> fast reactor fuels were added to the existing data for MOX-based FR-fuels
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2012
- **New technical/cost data which has recently become available and will benefit next revision.**

## D1-4.1 BASIC INFORMATION

### 2009 AFC-CBD Basic Information.

**Fuel Form.** Ceramic fueled fast reactors can operate on either higher enrichment uranium fuel (such as the BN-600 in Russia) or plutonium-based MOX fuels (such as the French Phenix reactors, the Russian BN reactors, and the cancelled U.S. Clinch River Breeder Reactor). For electricity production “breeder” fast reactors, the ceramic material of choice has been either enriched UO<sub>2</sub> or MOX (Pu, U) O<sub>2</sub>, which can be contact-handled during fabrication if the minor actinide (neptunium, americium, curium) content is sufficiently low. For “burner” fast reactors, where significant amounts of the minor actinides arising from LWR reprocessing or from the fast reactor’s own fuel cycle are to be recycled within the driver fuel, remote-handling during fabrication will be required because of the radiation level associated with mainly americium and curium and any trace fission products carried over from fast reactor fuel reprocessing. These fuel types will be addressed in Module F2/D2, where reprocessing and remote refabrication are considered as integral processes. Because of the use of higher fissile content, typically 15% or higher U-235 or plutonium in heavy metal, the amount of fissile material per unit volume in the driver fuel is a factor of four or more higher than for LWR fuels.<sup>c</sup>

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c. Fast reactors may have as many as three types of fuel rods within the core: drivers, blankets, and targets. Drivers constitute the fissile materials that account for most of the energy production and in which the fissile content falls with continuing irradiation (“burning”). Blanket fuel consists of fertile material, such as DUO<sub>2</sub> or ThO<sub>2</sub>, which will be partially converted via neutron absorption to new fissile material (“breeding”), such as Pu-239 or U-233, which can be recovered by reprocessing and refabricated into new fuel. Targets contain radionuclides, such as higher actinides or fission products, which are converted by neutron irradiation to other nuclides with shorter lives; this “burning” process is sometimes called burnout, transmutation, or destruction. These spent targets can subsequently be more efficiently and safely emplaced in a geologic repository.

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

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

Fuel	Thermal Reactor	Fast Reactor
	UO <sub>2</sub>	(U,Pu)O <sub>1.96</sub>
Fuel Pellet Density (% of theoretical)	92	90
Max. fuel centerline temperature (overpower condition) °C	2450	2800
Cladding	Zircaloy-4	316 Stainless Steel
Max. cladding mid-wall temperature °C	380	660
Coolant temperature, °C	H <sub>2</sub> O, 280-320	Na, 470-650
Maximum rod linear power, W/cm	620	550
Fuel wrapper assembly	Square, 30x30	Hexagonal, 13 cm across flats
# of pins in assembly	200	220
Fuel-rod outside diameter, mm	10.7	6.3
Cladding thickness, mm	0.6	0.4
Initial fuel-cladding radial gap, mm	0.08	0.07
Length of fueled portion, cm	365	90

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

Ceramic fuels other than oxides have also been considered, with uranium or plutonium nitrides and carbides receiving the most research and development attention in the U.S.

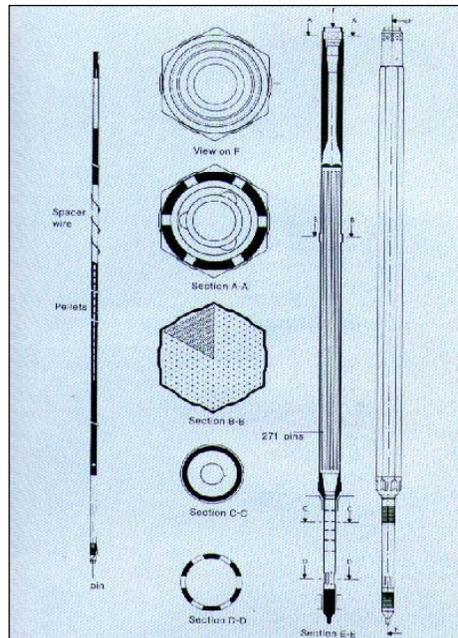


Figure D1-4-1. Superphenix fuel assembly diagram (CEA, 1985).

## 2012 AFC-CBD Update Basic Information.

Again little has changed from the *December 2009 Advanced Fuel Cycle Cost Basis Report* in the areas of the basic industrial process for FR ceramic pelletized fabrication and its interfaces to other fuel cycle steps. The only fabrication process that has been conducted on a near-industrial scale for FR ceramic fuel is basically the same process that is used to prepare LWR MOX fuel. The main differences are the following, however:

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

It is most important to realize that the fuel we are discussing in this module can be contact handled in gloveboxes as powder/pellets (if it contains plutonium) and outside gloveboxes in sealed pin form (for MOX or enriched UOX). If the fuel is enriched uranium (typically 13 to 25% U-235) in some ceramic form such as UO<sub>2</sub>, powder and pellets can be handled outside a glovebox environment. For this reason the fuel must be largely free of fission products, higher Pu or Np-isotopes, or higher actinides such as curium and americium which pose radiation hazards to workers as well as heat-generation problems from the decay of these isotopes. (Such “transmutation” or “actinide burning” fuels or targets are considered in Module D2 which deals with remote-handled fuel. “Proliferation resistant” fast reactor fuels which carry over some FP and HAs would require remote refabrication.) The fuels described here would probably be used as start-up fuels for fast reactor systems or in fast reactor systems for which fuel recycle is not yet established. A good example would be the BN series of fast reactors in Russia. The BN-600 reactor has run mainly on medium-enriched UO<sub>2</sub> (MEUO<sub>2</sub>) fuel with some (U, Pu) MOX assemblies undergoing lead testing. Russia is now constructing BN-800 sodium-cooled fast reactors which will use MOX fuel with Pu content (in heavy metal with U diluent) in the 15 to 25% range. This fuel will be contact-handled. A small and now shuttered glovebox pilot line “PAKET” at Mayak has been used to fabricate BN-600 test assemblies. The MOX Pu processed and burned in the first BN-800 fast reactors will be weapons-capable material arising from Russian military programs. This material is being fabricated at a small MOX plant inside a mountain at Zheleznogorsk.

### D1-4.2 FUNCTIONAL AND OPERATIONAL DESCRIPTION

**Similarity to LWR MOX.** The functions and operations in a fast reactor fuel plant based on pellet technology are similar to those in an LWR MOX plant. The higher fissile content (typically >15%) of fast reactor fuel, however, requires more stringent security and criticality avoidance measures. The previous existence of a developing fast reactor industry in Europe, Japan, and Russia shows that such facilities are technologically viable.

**Status Update from 2009 AFC-CBD: Status of Industry.** Slowdowns or cancellations of fast reactor programs have put production of ceramic fast reactor fuel worldwide at a near standstill. Belgium, the UK, France, Germany, and Japan all have fabrication plants that are now shutdown or inactive. Russia still produces mostly highly enriched uranium (HEU) and some (U, Pu) O<sub>2</sub> MOX fuel for their BN-600 Reactor located at Beloyarsk. When the U.S. was about to construct the Clinch River Breeder Reactor, plans were being drawn up to construct a U.S. fast fuel fabrication facility. The ceramic fast reactor fuel production that has taken place in the U.S. has been on a small scale in national laboratory or reactor vendor development facilities, and most of this was in the 1960s and 1970s. Unless interest is revived in closed fuel cycles and particularly one that uses ceramic rather than metallic fast reactor fuel (Module F2/D2), near-term prospects are dim for the deployment of such fast reactor fabrication capacity in the

U.S. As the Generation IV and AFCI programs progress, however, interest may be revived. (AFCI “burner” fast reactor concepts are more likely to require the types of remote-handled, higher-actinide laden fuels discussed in Module F2/D2; however, the first cores are likely to be U, Pu only.)

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

### **Status Update from 2012 Update AFC-CBD.**

It is of interest to explore the status the world’s existing or planned fabrication facilities.

- United Kingdom: The UK is still considering the burning of MOX fuel in new Generation III+ LWRs and/or in Sodium-cooled Fast Reactors as a method of dispositioning its large stockpile of over 110 MT of separated Pu from its commercial and military reactor programs (Nature News and Comment 2011). A new MOX plant would be required that might be able to produce MOX fuel for fast reactors in addition to LWRs. The UK is considering the fast reactor as part of its future Pu disposition strategy and is evaluating the GE-Hitachi PRISM fast reactor design, which can be customized for ceramic or metal fast reactor fuels. The hypothetical UK MOX plant is discussed from a cost standpoint in Module D1-2.
- Japan: Japan’s Tokai works has the capacity to produce 20 MTHM of fast reactor MOX fuel per year. The capacity is in two 10MT/yr lines, and the facility has made fuel for test reactors. (WNO 2012).
- Russia: As part of the Year 2000 Joint U.S.-Russia PMDA (Plutonium Management and Disposition Agreement) both the U.S and Russia had agreed to burn excess weapons Pu in their LWRs. Russia has now decided to burn their Pu in sodium-cooled fast reactors of the BN-800 variety rather than in VVER water reactors. The type of fuel is likely to be pelletized MOX (Module D1-4) or VIPAC fuel (Module D1-5) or both. The PMDA was modified in 2010 to reflect this new reality. At Mayak there is a small, now shut down, FR MOX pilot line called PAKET which has manufactured pellet fuel for lead test assemblies for irradiation in BN-600. The U.S. formerly was to technical and financial assistance to Russia for the eventual construction of a larger FR MOX plant to supply military-derived Pu fuel for the BN-800 reactors. The Pu in the MOX will have the high Pu-239 content typical of weapons Pu. No credible cost estimates are yet available for this proposed facility, which is to be located at Zheleznogorsk.
- U.S.: An industrial scale ceramic fuel fabrication line for Pu-containing FR fuel has never been operated in the U.S., although such a line was constructed at Hanford [the Secure Automated Fabrication (SAF) line] to support the cancelled Clinch River Breeder Reactor Project. The >\$100M SAF line was never operated. There is a B&W plant in Lynchburg VA that has the capability to produce enriched U fuels above 5% U-235, and it does this for mainly Government customers (naval fuel, research reactors, etc.) The site security and safety envelope for this site would very likely be adaptable to the production of medium to high-enriched uranium oxide ceramic fuel that might be used for startup of a sodium-cooled fast reactor. A smaller plant operated by Nuclear Fuel Services (NFS) at Erwin, Tennessee can also handle enriched uranium forms greater than 5% U-235.
- China: To support their 1000 MWe China Demonstration Fast Reactor (CDFR), which will start-up in 2017 and will ultimately burn ceramic (U, Pu) MOX fuel, a 40 MTHM/yr FR ceramic MOX plant is planned at Sanming. No cost information is available on this facility.

- India: India's nearly complete 500 MWe Prototype Fast Breeder Reactor (PFBR) will ultimately use (U, Pu) MOX fuel produced in a proposed Fast Reactor Fuel Cycle Facility (FRFCF) located adjacent to the PFBR at Kalpakkam. Fuel rods will be 21 and 28% fissile Pu (SME Times 2010). The FRFCF will also reprocess oxide fuel and handle waste management. Its cost has been estimated at 5000 Crore (U.S.\$ 898M).

### D1-4.3 PICTURES AND DIAGRAMS

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

**Fast Reactor Pellet Fuel Fabrication Process.** For medium enriched uranium (>10% U-235 or <20% U-235 or highly enriched uranium), ceramic fuel the process would be much the same as for LEU fuel production. Because of the security and criticality concerns, batch sizes would be very limited in size. For MOX ceramic fast reactor fuel, the process is much the same as for thermal MOX (Section D1-2). Again, the batch sizes handled would have to be much smaller. Both plants would likely have to purchase or fabricate their own stainless steel fuel assembly hardware such as grids and spacers.

### D1-4.4 MODULE INTERFACES

For the fast reactor MOX plant the starting material for driver fuel would likely be clean, reactor-grade PuO<sub>2</sub> powder from the reprocessing plant or PuO<sub>2</sub> storage. (For contact handling some neptunium and/or very small amounts of americium can be present with the plutonium.) For the EUO<sub>2</sub> driver fabrication plant, the starting material is likely to be EUF<sub>6</sub>. Blanket UO<sub>2</sub> fuel could be produced in a conventional industrial facility with very low security and radiation protection requirements, i.e., no gloveboxes or criticality alarms. Transportation of finished fast reactor MOX driver fuel will, of course, need special casks for added security and radiochemical safety reasons. Other interfaces are similar to those for LWR MOX.

MOX driver fuel and DUO<sub>2</sub> blanket fuel are best matched to aqueous reprocessing at the back end of the fast reactor closed fuel cycle. The Japanese have already begun planning such a plant to reprocess spent fuel and blankets from their Japanese Sodium-cooled Fast Reactor (1,500 MWe; JSFR) concept. Note that spent fast reactor fuel is likely to require development of a new type of storage/shipping cask.

# Mixed Nitride Fuel Process Flow Diagram

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Rev. 1

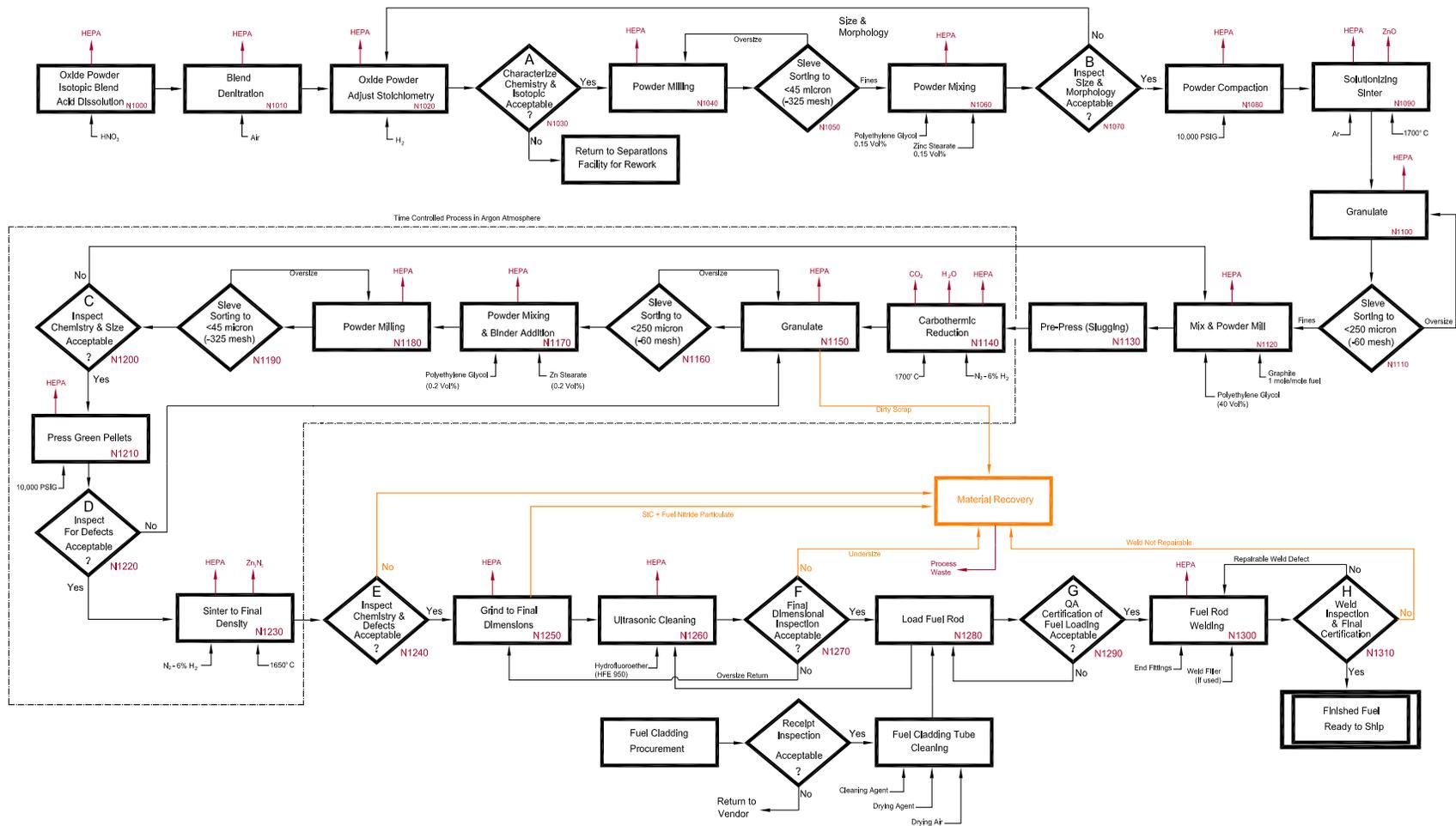


Figure D1-4-2. Fabrication process for mixed nitride fuels (DOE-AFCI Fuels Working Group, 2007)

## D1-4.5 SCALING CONSIDERATIONS

The same considerations apply in this area as for LWR MOX fuel (see Subsection D1-2.4). In terms of heavy metal throughput, the reference fast reactor MOX plant will be much smaller for the same amount of fissile nuclide (plutonium) processed.

## D1-4.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES

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

The sizing of ceramic fast reactor fuel fabrication plants is uncertain, because it is not known how many fast reactors utilizing pellet fuel might eventually be used. The only scaling data found were from the 1988 Oak Ridge National Laboratory Nuclear Energy Cost Data Base (NECDB 1988) which references data from the late 1970s Nonproliferation Alternative Systems Assessment Program (NASAP) that looked at many fuel cycles. A table from the Nuclear Energy Cost Data Base (NECDB 1988) is reproduced here (Table D1-4-3) to show some plant capacity and capital cost data. All costs are in 1987 dollars. A multiplication factor of 1.9 would bring them to 2009 dollars.

Table D1-4-2. Unit fabrication costs for various fast reactor fuels.

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

Table D1-4-3. Fast Reactor (LMR) recycle costs from 1988 Oak Ridge National Laboratory NECDB 1988 study.

Table D1-4-3. Recycle facility costs (1987 dollars)						
Capitalization, fraction						
	Debt					0.3
	Equity					0.7
	Interest on debt, %/year					9.7
	Return on equity, %/year					17
	Tax depreciation life, years					15
	Decommissioning cost, <sup>a</sup> % initial investment					10
	Plant life, years					30
	Design and construction lead time, years					8
Process	Fuel	Plant size (10 <sup>3</sup> kg/yr)	Capital cost <sup>b</sup> (\$10 <sup>6</sup> )	Capitalized cost <sup>c</sup> (\$10 <sup>6</sup> )	Operating cost <sup>d</sup> (\$10 <sup>6</sup> /yr)	Unit cost (\$/kg HM)
Fabrication	LWR-MOX	100	365	530	40	1200
		480	960	1390	140	730
	LMR core	100 <sup>e</sup>	615	890	90	2250
	LMR blanket <sup>f</sup>	270 <sup>e</sup>	1335	1930	220	1900
		100	55	80	30	430
Reprocessing	LWR	400	1030	1490	60	710
		1500	1850	2680	100	340
	LMR <sup>g</sup>	750	1850	2680	100	680
Integral <sup>h</sup>	LMR metal	20	135	175	30	2800
	LMR oxide	20	260	330	25	3700 <sup>i</sup>
<sup>a</sup> 10% of capital investment (including AFUDC) in constant 1987 dollars (escalates with inflation in nominal dollars) accumulated in an annuity at 7.0%/year nominal interest rate. <sup>b</sup> 1987 overnight cost. Includes all preoperational costs except AFUDC. <sup>c</sup> Total capitalized cost in 1987 dollars including AFUDC. <sup>d</sup> Includes equipment replacement. <sup>e</sup> Throughput of active core material only. Unit cost applied to active core throughput only and includes axial blanket costs. <sup>f</sup> Radial and internal blanket fuel. <sup>g</sup> Core and blanket fuel throughput combined. <sup>h</sup> Five-year design and construction time. <sup>i</sup> Estimated unit cost for 35 × 10 <sup>3</sup> kg/year oxide fuel facility = \$2700/kg HM.						

The Japan Atomic Energy Agency (JAEA) (G4-EMWG 2006) has projected a capital cost of approximately \$750 million for a 200-MTHM/yr pellet MOX fabrication facility needed to support JSFRs. The updated unit cost of \$1,675/kgHM in G4-EMWG 2005 data of Table D1-4-2 is calculated based on amortization of this capital cost and the addition of operations and maintenance and decommissioning levelized costs. 2012 AFC-CBD Update Cost Bases.

**2012 AFC-CBD Cost Data Sources.** A few recent data sources have been accessed to provide the basis for changing the recommended low, nominal, and high values for the \$/kgHM cost of ceramic MOX and MEUO<sub>2</sub>/HEUO<sub>2</sub> fast reactor fuel fabrication. (Note that as with UO<sub>2</sub> pelletized LWR fuel there is no published data on the actual production cost or pricing of material from an operating fabrication facility.) Most fuels of this type are produced (or have been produced) in quantities very small compared to LWR MOX fabrication. The following Table D1-4-4 shows some ceramic pelletized FR fabrication cost data from various sources. Some of the numbers required escalation to bring them to 2012 dollars. Most of the data are for (U, Pu) type MOX fast reactor fuels; however, the cost numbers might be comparable for large scale production of nitride or carbide pelletized FR fuels. Note that enriched U fast reactor fuel has been added since the 2009 AFC-CBR, since this material would likely be used to start-up fast reactors until enough Pu-based fuel became available. The fissile content (Pu or U-235) for all of these fuels would be in the 13% to 25% range. The cost of uranium ore, conversion, and enrichment are not included in the unit fab cost for MEU or HEU FR fuel.

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

Study or Ref/Year	Low Value (\$/kgHM)	Medium or Ref Value (\$/kgHM)	High Value (\$/kgHM)
<b>DRIVER FUEL (U, Pu)</b>			
DEC 2009 AFC-CBR (2009 \$)			
Pelletized (U, Pu) O <sub>2</sub> Ceramic	3200	4000	6000
(EPRI 2010) (2010 \$)			
FR MOX (U, Pu) O <sub>2</sub>	750	1500	2100
MIT Economics of Nuclear Fuel Cycle (MIT 2009) (2010 \$)			
FR MOX (U, Pu) O <sub>2</sub>	N/A	2400	N/A
Escalated unit cost from ORNL/TM-6522 (Olsen) (U, Pu) MOX FR fuel (Complexity factor=8.45 against LEUO <sub>2</sub> fuel)	N/A	2950	N/A
<b>BLANKET FUEL (NATU or Depleted U)</b>			
Escalated from 2003\$ (in parentheses) to 2012 \$ (Bunn et al. 2003)	175 (150)	300 (250)	425(350)
ORNL 6522 (Olsen) using complexity ratio	N/A	450	N/A
<b>MEU/HEU DRIVER FUEL</b>			
ORNL 6522 (Olsen) using complexity factor	N/A	825	N/A

The most recent reports which include unit costs for the fast reactor fuels category are the EPRI “Multi-recycling” economic study (EPRI 2010) and the MIT “Economics of the Nuclear Fuel Cycle” (MIT 2009) reports. The unit costs are for a hypothetical, mature fuel fabrication industry supporting multiple fast reactors. These values fall in the lower range of the LWR MOX (Module D1-2) range, which leads the author of this module to believe that more credible unit costs will be significantly higher, especially since the higher fissile enrichment fast reactor ceramic fuel will encounter the same manufacturing difficulties, plus some, as LWR MOX fuel. As with HTR fuel in Module D1-3, one can look at old estimates for multiple fuel types prepared by ORNL staff in 1979 (Olsen 1979) to gauge the level of technical complexity of FR ceramic fuel (Driver (U, Pu) MOX in this case) fabrication vis a vis that for LWR UO<sub>2</sub> fuel. If escalation is considered, a unit cost of \$2950/kgHM is obtained for a nominal case. The same “complexity factor” approach can also be used to assign a unit cost to the UO<sub>2</sub> “blanket”

fuel required by some fast reactor designs. A nominal value of \$450/kgU is obtained for this material, which would be natural or depleted UO<sub>2</sub> that can be contact handled without criticality or security concerns, and with minimal HS&E difficulties. A 2003 cost report on the fuel cycle (Bunn et al. 2003, EPRI 2010) suggested blanket fabrication unit cost values that were the same as for LWR UO<sub>2</sub> fuel. No actual cost data was found on enriched U (15 to 25% U-235 range) ceramic fast reactor driver fuels. The “complexity factor” approach using 1979 ORNL cost studies was again used to obtain a nominal unit fabrication cost of ~ \$825/kgU. This fuel would not need glovebox handling; however, criticality and security concerns could be much beyond those for LEUO<sub>2</sub> fuel. The higher projected unit cost is therefore appropriate.

## D1-4.7 DATA LIMITATIONS

**Technology Readiness Level.** Fast reactor MOX or enriched uranium pellet fuel production technology in the U.S. could reasonably progress quickly to the pilot plant stage; however, changing requirements would link FR MOX progress to that for LWR MOX. Considerable fuel qualification would be required before industrial scale implementation in the U.S.

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

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

To increase the proliferation resistance of closed fuel cycles, the idea of not separating plutonium from other transuranic actinides (“grouped” actinides) in the aqueous reprocessing plant has been advanced. The UREX 1a reprocessing concept is one such process. This means that the fast reactor fuel that would be refabricated from this material would contain neptunium, americium, and perhaps other actinide (curium and trace californium) oxides in the MOX. Sometimes referred to as “dirty” MOX, this material would impose special and more stringent requirements on the fuel fabrication facility from the standpoints of personnel radiation exposure, heat management, criticality, and materials accountability. The resulting plants would more appropriately fall under Module F2/D2 (remote handling). These additional costs of more automated or remote handling are not known; however, if a “dirty MOX” economic study is done for thermal reactor fuel, such as (Pu,Np)O<sub>2</sub> or for higher actinide LWR targets, the results will have similar impacts on fast reactor MOX plants.

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

## D1-4.8 COST SUMMARIES

**2009 AFC-CBD Cost Summary.** The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table D1-4-5. The summary shows the reference cost basis (constant year \$U.S.), the reference basis cost contingency (if known), the cost analyst’s judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Table D1-4-5. Cost summary table for Fast Reactor Pelletized Ceramic fuels.

What-It-Takes (WIT) Table (2007 constant \$)			
Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
\$2,400/kgHM from centralized, private 50-MT/yr facility with loan and market guarantee	\$3,200/kgHM  Blanket: \$350/kgU	\$6,000/kgHM  Many of same factors affecting SRS-MFFF would affect this cost. (see Module D1-1)  Blanket: \$700/kgU	Core: \$4,000/kgHM  Blanket: \$500/kgU
No reliable and validated data on plant capital costs	Same as for LWR MOX; use of enriched uranium in 15 to 25% U-235 range would be cheaper (fabrication cost) than plutonium use.	25% higher than for LWR MOX nominal cost	20% higher than for LWR MOX nominal cost

**2012 AFC-CBD Update Cost Summary.** The following set (Table D1-4-6) of “what-it-takes” year 2012 values and a corresponding probability distribution is recommended for use in future fuel cycle studies:

Table D1-4-6. Low, Nominal, and High Suggested Fabrication Cost (2012 AFC-CBD Update)

Fuel Type	Low (2012 \$/kgHM)	Nominal (2012 \$/kgHM)	High (2012 \$/kgHM)
FR (high-end LEU to low-end MEU U-235 content) Pelletized Ceramic Driver Fuel	475	825	1180
FR Pelletized Ceramic (U, Pu) Driver Fuel such as MOX	2500	4500	7000
FR Pelletized Ceramic NATUO <sub>2</sub> or DUO <sub>2</sub> Blanket Fuel	250	450	630

For uncertainty analyses triangular distributions should be used with each row’s the values in the table above. The first row of Table D1-4.6 above provides suggested fabrication costs for the enriched, stainless-steel clad ceramic UO<sub>2</sub> fuel that might be used for the startup of the first fast reactors in a fleet. Enrichment costs, which would be significant for the 15 to 25% U-235 levels required, are not included in this cost. The complexity factor approach based on 1979 ORNL data (Olsen 1979) was also used to assign the low and high values, in addition to the nominal value as was explained above.

Assignment of costs for the (U, Pu) driver fast reactor ceramic fuel required more subjective judgment and comparison to other fuel types, especially LWR MOX fuel because of the fabrication process similarity. The LWR MOX values in Module D1-2 were based on better life cycle cost estimates, and it is assumed by the author of this module that fast reactor MOX fuel will not be any cheaper to manufacture than LWR MOX. The unit costs in the second row reflect this thinking and are also somewhat higher than the 2009 AFC-CBR values due to inflation in O&M costs and commodities.

Projected costs for ceramic blanket fuel have been added to this 2012 AFC-CBR and are shown in the third row of the table. The “complexity factor” method was again used to assign the low, nominal, and high values.

Table D1.4-7 shows the year 2012 values escalated to 2017\$, There is a 9% increase from 2012 to 2017.

Table D1-4-7. Year 2017\$: Low, Mode, Mean, and High Suggested Fabrication Cost

Fuel Type	Low (2017 \$/kgHM)	Mode (2017 \$/kgHMN)	Mean (2017 \$/kgHM)	High (2017 \$/kgHM)
FR (high-end LEU to low-end MEU U-235 content) Pelletized Ceramic Driver Fuel	520	900	900	1290
FR Pelletized Ceramic (U, Pu) Driver Fuel such as MOX	2700	4900	5060	7600
FR Pelletized Ceramic NATUO <sub>2</sub> or DUO <sub>2</sub> Blanket Fuel	270	500	485	690

The triangular distribution based on the costs in Table D1-4-7 is shown in Figure D1-4-3. The distribution is skewed toward the low cost because there is European and Japanese industrial experience, although at a small scale, with this type of fuel.

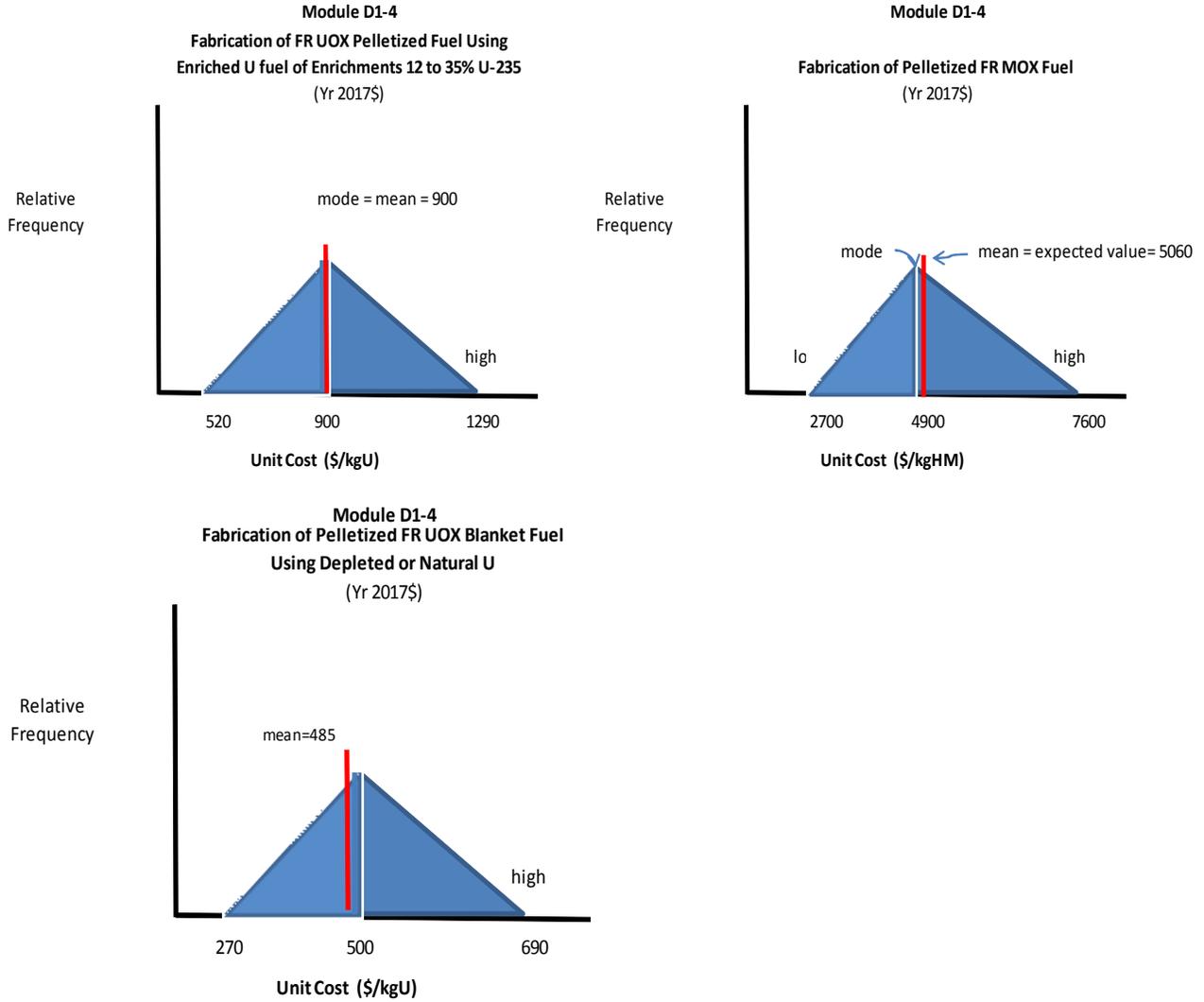


Figure D1-4-3. Ceramic pellet fast reactor fuel estimated cost frequency distributions.

### D1-4.9 SENSITIVITY AND UNCERTAINTY STUDIES

No such studies were found in the literature or were performed by the author for this fuel type.



## **Module D1-5**

# **Ceramic Vibrocompacted Fast Reactor Fuel**



## Module D1-5

### Ceramic Vibrocompacted Fast Reactor Fuel Fabrication

#### D1-5.MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:** Because of simple process VIPAC fuel unit costs assumed to be 10% lower than ceramic fast reactor fuel costs in Module D1-4. VIPAC fuel is at the pilot plant stage of development. Unit costs given are for a hypothetical NOAK VIPAC facility in a structure and under regulatory regime similar to current European pelletized MOX plants.

#### D1-5.RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module D1-4
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2012
- **New technical/cost data which has recently become available and will benefit next revision:**
  - Russia continues to develop this technology. A new literature review might yield some cost information.

### D1-5.1 BASIC INFORMATION

**2009 AFC-CBR Status.** A vibrocompacted or VIPAC fast reactor fuel assembly appears identical to a pelletized ceramic fuel assembly on the outside. The fuel rods, however, initially contain vibrationally compacted, dense ceramic granulate instead of stacked pellets. (Some metallic powder may be added to the oxide mix to improve the fuel performance characteristics.) As the VIPAC fuel is irradiated, the reactor heat sinters the granulate into what is essentially a long pellet. The technical and cost advantage of this type of fuel is elimination of the costly pressing, sintering, and pellet grinding/finishing steps in the usual MOX fuel fabrication process. This process was investigated on a bench scale in the U.S. several decades ago, and some fuel was irradiated in the Saxton (Pennsylvania) test reactor. There is still considerable interest in this process for fast reactor MOX in Russia and in Japan. The Japanese have funded some Russian MOX vibro-fabrication work at RIAR (or NIIAR) in Dimitrovgrad, and some test rods have been irradiated in the BN-600 at Beloyarsk (Mayorshin, Skiba, et al. 2000). Figure D1-5-1 describes the purported advantages of vibropack technology as presented by RIAR. This technology is presently slated to play a role in the joint U.S./R.F. plutonium disposition program.

There are several variations of VIPAC technology. Early techniques focused on granulate produced by crushing sintered ceramic pellets. More recent work outside Russia has focused on use of sintered gel-spheres, and the associated technology is known as Sphere-Pac in reference to the resulting spherical feed. The East German–Russian variant promoted vigorously by NIIAR uses a crushed glassy granulate resulting from electrochemical deposition of  $UO_2$  or  $(U, Pu)O_2$  out of the molten salt solution.

VIPAC fuel fabrication is often paired with electrochemical fuel reprocessing (Module F2/D2 type process, but with ceramic rather than cast-metal fuel) in proposed fuel cycles because of the nature of the processes as explained below. One such fuel cycle is for the STAR-H2 reactor (The Secure Transportable Autonomous Reactor for Hydrogen [Electricity and Potable Water] Production). This is one of the

metal-cooled reactor concepts being studied under the Generation IV program by Argonne National Laboratory (Wade 2005) and would use a U, Pu-nitride fuel.

**2012 AFC-CBR Status.** In this case nothing has changed from the *December 2009 Advanced Fuel Cycle Cost Basis Report* in the areas of the basic industrial process under development for FR vibrocompacted (VIPAC) fuel fabrication and its interfaces to other fuel cycle steps. The method is still under consideration for the production of (Pu,U) O<sub>2</sub> driver fuel for the BN-800 series of fast reactors being constructed in Russia. As part of a joint U.S./Russia Pu disposition agreement the U.S. was to have made funds (~\$400M) available to Russia for this non-proliferation program. Some of these funds were likely to have been used for design and construction of some kind of contact-handling fuel fabrication facility for BN-800 fast reactor mixed oxide fuel. The Russian Federation has not yet decided whether the facility will produce ceramic pellet fuel, VIPAC fuel, or even both types. (Pellet fuel is more likely to be selected due to more experience with this method.)

## D1-5.2 FUNCTIONAL AND OPERATIONAL DESCRIPTION

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

## D1-5.3 PICTURES AND DIAGRAMS

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

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

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

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

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

Fuel column is a mechanical mixture of (U, Pu) O<sub>2</sub> granulate and uranium powder, having a function of getter and is added to a fuel weighted portion at the stage of agitation before pouring. Getter addition for regulation of the fuel oxygen potential and elimination of process impurities effect allowed for complete solution of the problem of chemical interaction of vibropack oxide fuel and cladding. The process provides for a 100% fuel column quality control including distribution of plutonium and density along the fuel column length. The uniform getter distribution is ensured by the technology.

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

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

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

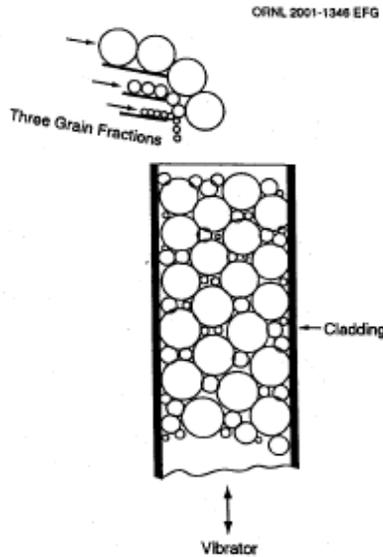


Figure D1-5-2. Conceptualized view of VIPAC as envisioned by ORNL researchers.

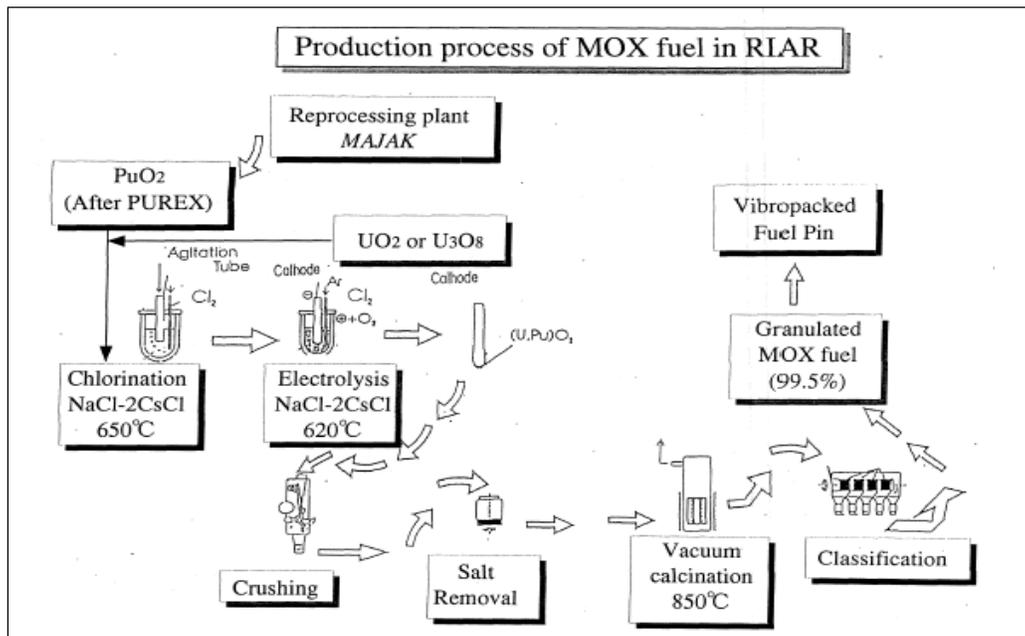


Figure D1-5-3. The VIPAC process and its relation to pyrochemical reprocessing technology as envisioned by the Scientific Research Institute of Atomic Reactors, Dimitrovgrad, Russia (RIAR).

### D1-5.4 MODULE INTERFACES

The feed MOX mixture fed to the vibrator/tube-filler must have a very well-defined particle size distribution (enabled by sieving) and particle shape characteristics (small shards or crystals). The powder characteristics of material coming from electrochemical reprocessing techniques are better suited for VIPAC; however, it is still quite possible to fix the morphology of aqueous precipitation-derived MOX powders.

VIPAC feasibility has been examined for LWR fuels including  $UO_2$ . A DOE-NERI report suggests that spheroidal powder could be vibropacked into annular cladding as one of several fuel options, which would allow higher power density and extended burnup with their beneficial economic consequences

(Kazimi 2002). The higher fabrication costs for annular fuel are predicted to be overcome by the lower mills/kWh fuel cycle cost component of the cost of electricity resulting from the use of less fuel. No detailed cases with cost numbers were presented in the report.

### **D1-5.5 SCALING CONSIDERATIONS**

No data were available. Any scaling would be similar to fast reactor pelletized fuel facilities.

### **D1-5.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES**

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

In 1998, Russian engineers prepared a cost estimate for converting and operating the BN-600 Fast Reactor to a partial MOX core of vibropacked fuel as part of the joint U.S./RF Plutonium Disposition Program (State of Scientific Center of Russian Federation–IPPE 1998). Their estimate concluded that a BN-600 VIPAC fuel assembly could be produced for less than \$100,000 per unit. Because each fuel assembly contains approximately 28.7 kg of heavy metal (MOX with >20% Pu O<sub>2</sub>), a unit cost of ~\$3,500/kgHM could be calculated for production from the pilot-plant sized facility that would need to be operated to supply these assemblies. Because this is a pilot scale facility number, it would be expected that a large fuel fabrication plant of this type could produce fuel at a lower cost. Converting the above Russian number to the U.S. wage rate and industrial conditions, however, would elevate the cost. Regulatory costs in the U.S. would also be higher.

An OECD report (NEA/OECD 2006) gives unit cost projections for advanced fast reactor fabrication and reprocessing steps in an integrated (one building) facility. For the fabrication step, which involved gelation<sup>e</sup> and vibrocompaction, the following unit costs are given:

Present (2001):     \$4,900/kgHM

Future:             \$1,600/kgHM

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

### **D1-5.7 DATA LIMITATIONS**

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

### **D1-5.8 COST SUMMARIES**

**2009 Cost Summary.** Module D1-5-1. The summary shows the reference cost basis (constant year \$U.S.), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references,

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e. Gelation rather than electrochemistry produces "rounder" particles which can be vibrationally compacted. Such a process is sometimes called "spheropak."

contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Table D1-5-1. WIT cost summary table.

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

**2012 AFC-CBD Update Cost Summary.** The nominal unit fabrication cost of \$3600/kgHM in the 2009 AFC-CBR was based on the assertion, largely derived from Russian sources, that the unit fabrication cost would be 10% lower than for pelletized contact-handled ceramic MOX FR fuel. If the same logic is applied the new value for VIPAC FR fuel fabrication will be a reduction of 10% from the new (Module D1-4) nominal ceramic MOX FR value of \$4500/kgHM. The resulting Module D1-5 value of \$4050/kgHM is rounded to \$4000/kgHM to indicate that the value is a rough approximation for a technology still under development. The same ~10% reduction is also applied to the low and high values.

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

Table D1-5.2. Year 2012\$ “What-it-takes” (WIT) Vibrocompacted fast reactor fuel fabrication unit.

Fuel Type	Low Value (2012 \$/kgHM)	Medium or Ref Value (2012 \$/kgHM)	High Value (2012 \$/kgHM)
(U, Pu) O <sub>2</sub> VIPAC Fuel	2300	4000	6300

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

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

Table D1-5-3. Year 2017\$ “What-it-takes” (WIT) Vibrocompacted fast reactor fuel fabrication unit.

Fuel Type	Low Value (2017 \$/kgHM)	Mode (2017 \$/kgHM)	Mean (2017 \$/kgHM)	High Value (2017 \$/kgHM)
(U, Pu) O <sub>2</sub> VIPAC Fuel	720	900	1020	1440

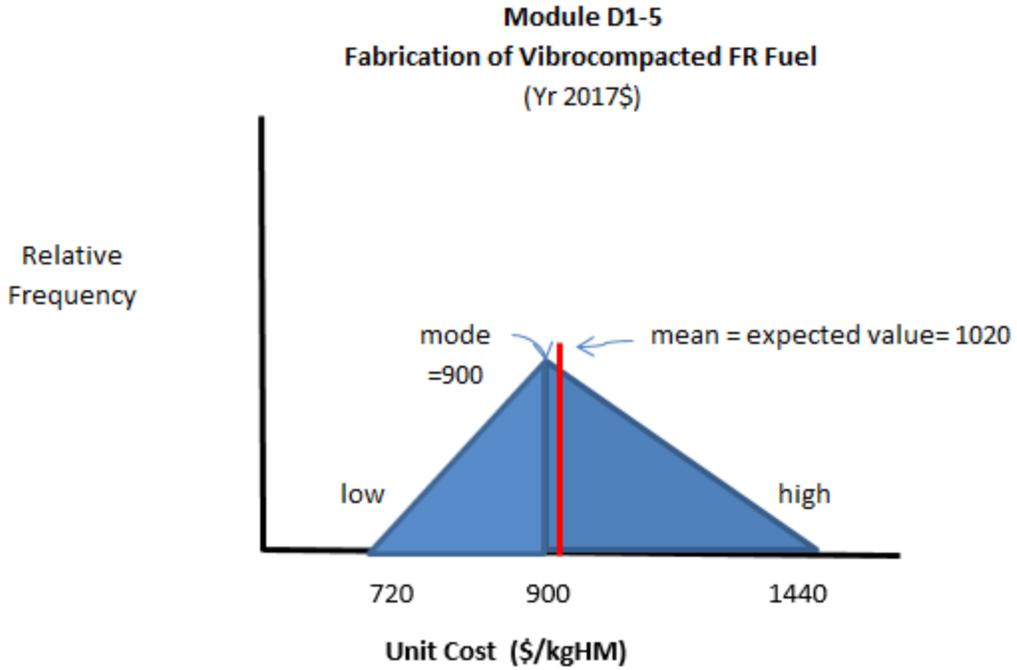


Figure D1-5-4 Probability Distribution for VIPAC MOX Unit Fuel Fabrication Cost

### D1-5.9 SENSITIVITY AND UNCERTAINTY ANALYSIS

None provided at this time.

**Module D1-6**

**Metallic or Alloyed Reactor Fuel**



## Module D1-6

### Metallic or Alloyed Reactor Fuel Fabrication

#### D1-6.MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** Not applicable since no cost are presented
- **Nature of this 2017 Module update from previous AFC-CBRs:** Module name change to reflect inclusion of possible LWR metal fuel
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:**
  - No cost information
  - Mention of possible Pu disposition application
  - Mention of Lightbridge Corporation development activity on metal alloy LWR fuels

#### D1-6.RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module D1-6. In this 2017 update the Module name has been changed from *Metallic or Alloyed Fast Reactor Fuel Fabrication* to just *Metallic or Alloyed Fuel Fabrication*. This reflects the fact that metal fuel is now being considered for LWRs in addition to fast reactors.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** Not applicable since no numerical “what-it-takes” unit cost estimates are currently readily available
- **New technical/cost data which has recently become available and will benefit next revision:**
  - Plutonium disposition reports prepared by DOE-NNSA and its contractors concerning alternatives to the SRS MOX plant and the irradiation of SRS MOX in LWRs
  - Papers and press releases from Lightbridge Corporation on metal alloy LWR fuel

### D1-6.1 BASIC INFORMATION

**2009 AFC-CBD Status.** Metallic reactor fuel, such as is produced by casting operations, is generally part of refabrication schemes associated with on fast reactor-site closed fuel cycles where the reprocessed and refabricated fuel must be handled in hot cells (remote-handling), with the higher actinides allowed to remain in the fuel for partial destruction in the next irradiation cycle. No cost information was found on metallic fuels not arising from a reprocessing plant or a transmutation/separation facility (all remote-handling); although that does not mean that such contact-handling schemes do not exist. [Some Pu-based metallic fuel for the now-closed Hanford FFTF (Fast Fuel Test Facility) was prepared via contact-handling without high concentrations of higher actinides (Np, Am, Cm).] Generally the higher actinide metals are alloyed with uranium and another heat-resistant metal such as zirconium. The INL MFC Integral Fast Reactor fuel cycle is one such cycle. The processes and costs associated with these remotely refabricated fuels are discussed in Module F2/D2. Unfortunately no data on separated reprocessing and refabrication costs were found. As noted above small amounts (a few hundred kilograms) of sodium-bonded metal fuel were fabricated for the now-deactivated FFTF reactor at Hanford (Westinghouse 2004). Government-owned plutonium was used for this fuel. No costs for its manufacture have been found by the author. **It should be noted that metal-fueled SFRs might have to be initially fueled with Pu arising from aqueous reprocessing of LWR fuel. This lower-activity material could be**

**contact-handled. Weapons-grade Pu destined for irradiation in a PRISM-type fast reactor could also be contact-handled.**

Metallic or alloyed fuels have been extensively used in (nonelectricity) production and research reactor applications where high temperature is not needed, but high fast or thermal neutron fluxes exist. Much of this fuel, which is mostly uranium alloyed or mixed with aluminum or molybdenum, or even silicides, is produced by pressing or extrusion type metallurgical operations. Because this fuel is usually 19% or greater in fissile content and is made in relatively small quantities, the unit costs for fabrication are usually high (i.e., a few thousand dollars to tens of 1,000s of \$ per kgHM). Dispersion type fuels, such as those proposed by the AFCI Fuels Working Group, for the Generation IV Gas-cooled Fast Reactors, are discussed in Section D1-9.

**2012 AFC-CBD Update Status.** No new technical or cost information was found on this fuel type. It should be noted that metal fuel has been advanced as the major fast reactor fuel type for integral type FR fuel cycles where the fissile materials recovered from electrochemically reprocessed FR metallic fuel are blended with make-up uranium and recast (refabricated) in the same remote-handling facility as the recycle steps. These remote handling steps are considered in the D2 Modules.

It should be noted that fresh U, Pu, Zr alloy pins have been prepared in contact-handling type facilities for irradiation in prototype fast reactors. Since these fuels did not contain fission products and higher actinides were minimal, they could be prepared in glovebox facilities. For this process one puts the constituents in a coated graphite crucible sets the crucible down in an induction coil, heats it up via AC power, moves coated quartz molds down into the melt, pressurizes the furnace, and produces up to hundreds of 18” metal fuel pins in a single run. All of this takes place in one machine, the casting furnace. After cool-down one removes the fuel pin assembly, breaks off the quartz, and crops the metal slugs to length. The slugs are inserted into cladding tubes pre-loaded with a bit of metallic “bond” sodium. The tubes are capped, sealed, welded, heated, and tapped in a vertical fashion to seat the slug at the bottom of the cladding and have the sodium flow upward around the slug. QA checks are then made. All these steps beyond the casting furnace can be done in a single “pin processor” machine.

Unit costs for large scale deployment of contact-handled FR U, Pu alloy fuel are likely to be lower than for U, Pu MOX due to comparative process simplicity. Unit costs for metal Pu alloy FR fuel are likely to be slightly below MEU pellet FR fuel for NOAK facilities. Since this type of fuel is unlikely to be produced on a large scale, no WIT values are presented.

Higher enrichment metallic uranium alloy FR fuel has also been prepared for experimental use. Such contact-handled fuels (U or (U, Pu)) might be used on a larger scale for start-up of fast reactor systems. No cost estimates were found for preparation of these fuel types. Based on technology complexity only, the cost of (U, Pu) alloy fuels prepared under glovebox conditions would probably be less than those for (U, Pu) MOX fast reactor fuels (Module D1-4). The complexity of non-process factors, however, such as safety, security, HVAC, etc., would push the ultimate unit (U, Pu) alloy unit cost closer to that of (U, Pu) MOX.

The MEU/HEU uranium unit fabrication cost for metal alloy fuel would also be on the same order as that for oxide FR uranium “start-up” fuel discussed in Module D1-4. Process complexity would be the major cost driver. It is known that MEU/HEU specialty and research reactor fuels incur fabrication costs in the several thousands of \$/kg of heavy metal. It should be noted that Russia has used contact-handled uranium alloy fuel in maritime reactors, and that Lightbridge Corporation in the U.S. is trying to stimulate interest in this U-fuel type in the West for water reactors.

2017 Update Status. Since 2012 NNSA has commissioned some reports (Lightbridge 2009, Lightbridge 2011, Malone, et al. 2012) looking at the costs of irradiating weapons-grade Pu in PRISM-type fast reactors. The Pu metal from weapons would be melted, blended, and cast into metal rods. Projected costs of building and operating such a facility at the Savannah River Site were examined and

could be included in future more-detailed module updates. There is also consideration of the use of metal alloy fuels in LWRs. Lightbridge Corporation (Lightbridge 2016) in the United States is developing this technology and has found a commercial reactor to irradiate some test assemblies. Future versions of this module should include analysis of information from Lightbridge.

## **D1-6.2 FUNCTIONAL AND OPERATIONAL DESCRIPTION**

See Modules D1-9, and F2/D2.

## **D1-6.3 PICTURES AND DIAGRAM**

See Modules D1-9 and F2/D2.

## **D1-6.4 MODULE INTERFACES**

See Modules D1-9 and F2/D2.

## **D1-6.5 SCALING CONSIDERATIONS**

No data available.

## **D1-6.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES**

See Modules D1-9 and F2/D2.

## **D1-6.7 DATA LIMITATIONS**

See Modules D1-9 and F2/D2.

## **D1-6.8 COST SUMMARIES**

See Modules D1-9 and F2/D2.

## **D1-6.9 SENSITIVITY AND UNCERTAINTY ANALYSES**

No data available.



## **Module D1-7**

### **CANDU Fuel**



# Module D1-7

## CANDU Fuel Fabrication

### D1-7.MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:** Reassessment in 2012 of fabrication costs based on increased cost of zirconium. Basically same rationale as for LWR fuels in Module D1-1

### D1-7.RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2004 as Module D1-7. In 2005 a special section on the DUPIC concept was added. The DUPIC discussion, based on information from a paper by Choi et al. (Choi 2001), has been moved to Module D2 as a special topic. The DUPIC process requires remote handling, thus, the discussion was moved to D2-2.1. In 2012 AFC-CBR Module unit costs of CANDU fuels fabricated from reprocessed uranium were added
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2012
- **New technical/cost data which has recently become available and will benefit next revision:**
  - CANDU fuels with thorium added to the uranium are being seriously considered.
  - CANDU fuels fabricated from Reprocessed U is being slated for use in Chinese PHWRs
  - Status of Canadian fuel fabrication facilities should be updated

### D1-7.1 BASIC INFORMATION

**2009 AFC-CBR Status.** Because the advanced CANDU ACR-700 heavy-water reactor design at one time started Nuclear Regulatory Commission (NRC) certification in the U.S. and is being offered for sale on the international market, it is useful to briefly consider the projected manufacturing cost for its fuel and that of its other CANDU cousins. CANDU fuel is fabricated in Canada by two firms: GEH Canada and as Zircatec Ltd (a division of Cameco). Present generation CANDU fuel is not made from enriched uranium, hence no UF<sub>6</sub>/enrichment steps are needed in the front-end fuel cycle. The “spec-powder” oxide feed required by the fabricator for pelletization can be prepared in a facility adjacent to the mill (natural UO<sub>2</sub> can be used for fuel in a water reactor with a heavy water moderator/coolant). The newer-type ACR-700 fuel, however, will be slightly enriched uranium at around 2% U-235. Its fuel assembly and the older CANDU NATUO<sub>2</sub> fuel assemblies, however, do not at all look like an LEU LWR fuel assembly. The fuel assemblies are much shorter but still use stacked UO<sub>2</sub> pellets.

**2012 AFC-CBD Status.** As for LWR fuel (Module D1-1) a mature industry exists for production of CANDU reactor fuel from virgin natural uranium. The fabrication process, fuel description, and other technical information are described in the 2009 AFC-CBR. GE-Hitachi Canada Ltd continues to produce up to 1800 MTUO<sub>2</sub>/yr of natural uranium CANDU fuel. Two facilities in Ontario are used: the Toronto facility for UO<sub>2</sub> pellet production and the Peterborough facility for fuel bundle production. The relicensing of these facilities to produce SEU (slightly-enriched 1 to 2.5% U-235) fuel for advanced CANDU reactor designs is under consideration by Canadian nuclear safety authorities.

A recent development regarding CANDU fuel use is that China is considering large scale use of reprocessed uranium from LWR spent fuel reprocessing as a NATU-substitute fuel for their fleet of

CANDU reactors (Ellis 2007, Chen 2011). This reprocessing-derived material has U-235 enrichments in the 0.6 to 1.0% range (typically blended to ~0.9% U-235) suitable for substitution for natural U or SEU. The reprocessed U could come from Russian, European, or Japanese sources of stored reprocessed U. Ultimately China will also have their own LWR spent fuel reprocessing industry which can provide this feed material. If the U.S. were to ultimately reprocess LWR SNF, CANDUs could provide an excellent use for the large amounts of resultant reprocessed uranium.

The use of (U, Th) O<sub>2</sub> pellets is also being considered in CANDU-type fuel. Thorium-based fuels are discussed in Module D1-8.

## D1-7.2 FUNCTIONAL AND OPERATIONAL DESCRIPTION

**Basic Plant Configuration.** A CANDU fuel bundle (assembly) still uses pelletized ceramic UO<sub>2</sub> fuel; so, most of the pellet and rod loading manufacturing process steps are the same as for LWR fuel. Because the fuel bundle is an order of magnitude shorter and lighter than LWR fuel, the steps at the end of the manufacturing process are somewhat simpler. However, one should note that the quality control costs are higher per kilogram of heavy metal because each closure weld applies to much less heavy metal than for LWR fuel. Batch size control and criticality concerns are minimal to nonexistent in CANDU fuel fabrication plants as compared to LEU PWR and BWR fuel fabrication plants.

CANDU reactors can also be operated on plutonium-bearing MOX fuel. Atomic Energy of Canada Limited has irradiated some weapons-derived MOX fuel in their experimental heavy-water reactor at Chalk River, Ontario. This PARALLEX MOX project with Russia and the U.S. was part of the joint U.S./Russian Federation Plutonium Disposition Program. A plant that would produce production quantities of CANDU MOX fuel would be nearly identical to fuel fabrication plants producing PWR or BWR MOX fuel, except that the resulting final fuel assembly form would be much smaller and would appear the same as UO<sub>2</sub> CANDU fuel.

## D1-7.3 PICTURES AND DIAGRAMS

Figure D1-7-1 shows the ACR-700 assembly, which resides in the reactor horizontally rather than vertically. Each of the parallel tubes is filled with ceramic oxide pellets. The assemblies are fed continuously to the pressure-tube type reactor while it is running rather than in reload batches during shutdowns (per the LWR). Figure D1-7-2 from ACR data submitted to the USNRC (AECL 2005) shows this operation.



Figure D1-7-1. The ACR-700 CANDU fuel assembly (AECL, 2005).

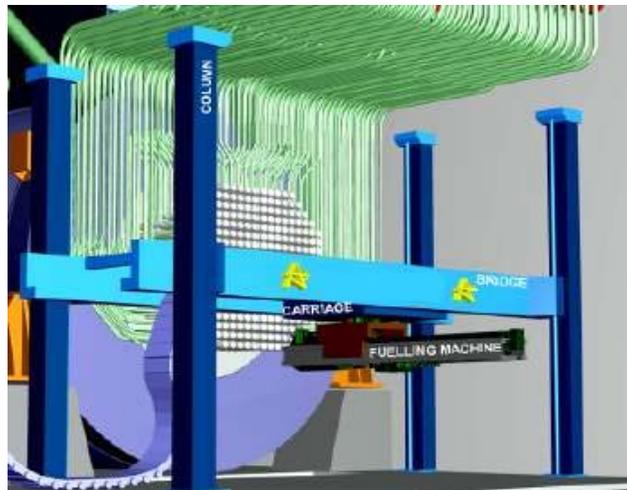


Figure D1-7-2. Horizontal on-line refueling for the ACR-700 CANDU reactor (AECL, 2005).

## D1-7.4 MODULE INTERFACES

**Front end Interfaces.** A CANDU fuel fabrication plant preparing slightly enriched  $\text{UO}_2$  ACR-700 fuel will require enriched  $\text{UF}_6$  conversion ( $\text{UF}_6$  to  $\text{UO}_2$ ) before the pellet preparation steps. For present generation CANDU reactor fuel, which is natural uranium (NATU), reactor grade sinterable  $\text{UO}_2$  powder can be prepared as a final milling step rather than as a front-end step in the fuel fabrication plant.  $\text{NATUO}_2$  CANDU fuel bundles are shipped in conventional cartons to the reactor sites. Criticality safety is not a concern. The ACR-700  $\text{EUO}_2$  fuel may require a certified shipping package as does LWR fuel in the U.S.

**Back-end Interfaces.** CANDU reactors have larger cores than LWRs for the same power capacity. Volume-wise, there will be more spent fuel that needs to be stored and ultimately disposed by geologic repository emplacement. Reprocessing requirements would be similar to those for  $\text{UO}_2$  LWR fuels.

## D1-7.5 SCALING CONSIDERATIONS

The same observations on fabrication plant scaling apply for this type fuel as for LWR fuel (Subsection D1-1).

## D1-7.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES

**2009 AFC-CBD Data.** Assuming that the manufacturing/fabrication process for this slightly enriched uranium fuel assembly is the same as for past CANDU NATU assemblies, the unit cost should be similar. If the 1991 NATU value from the NEA/OECD fuel cycle study (OECD NEA 2006) is escalated to 2009 constant dollars, a fabrication cost of \$~105/kgU results. To this should be added a conversion cost for slightly enriched  $\text{EUF}_6$  to ceramic-grade  $\text{UO}_2$  powder, a step that is not needed for natural uranium CANDU fuels. The author of this report assumes that \$30/kgU cost would be appropriate, for a total cost of \$135/kgU. This is smaller than for LWR fuel; however, the CANDU fuel assembly/bundle is simpler by design.

Fabrication costs for CANDU MOX fuels would be expected to be in the lower end of the ranges for LWR MOX fuel as presented in Section D1-3.

**2012 AFC-CBD Update Data.** Like LWR fuel fabricators, the Canadian CANDU fuel fabricator does not publish information regarding costs of fuel production or publish prices received for finished fuel bundles. Because of similarities in production methodology, Canadian vis-à-vis U.S. regulation, quality assurance requirements, and fuel cladding materials (zirconium and zirconium alloys), however, the same factors affecting LWR fuel fabrication from 2009 to 2012 will also affect CANDU fuel. In

Module D1-1 the nominal fuel fabrication unit cost was increased by 40% to account for these factors. If the same 1.4 factor is applied to the 2009 AFC-CBD CANDU fuel unit cost value of 135 \$/kgU, a nominal value of 189 \$/kgU results.

One can also use the “complexity factor” (subject fuel unit cost divided by PWR fuel unit cost) from (Olsen et al. 1979), a 1979 ORNL report comparing several large-plant fuel fabrication technologies on a “level-playing field” basis. If the factor of 0.59 (for pressurized heavy-water reactor NATU fuel) is applied, a unit cost of \$207/kgU results when applied to the \$350 \$/kgU nominal values from the first line of the D1 option in summary Table S-1, or from Table D1-2 in submodule D1-1.

If reprocessed U (RU) from LWRs is used in CANDUs, the CANDU fuel fabricator will face the same ES&H issues arising from U-232, U-236, and fission product impurities that would affect an LWR fuel fabricator. The additional costs would result in a unit cost “penalty” for RU use. (EPRI 2010) has an analysis which utilizes a 30% increase from the unit cost of fabricating CANDU fuel arising from virgin NATU. Even with this fuel fabrication cost increase, the overall cost of the front end of an open CANDU fuel cycle using LWR-RU is lower than for a cycle using virgin NATU. The savings are due to not having to purchase and process new uranium ore (U3O8).

### D1-7.7 DATA LIMITATIONS

The reliability of the cost data is good, since CANDU fuel production is a fully commercialized operation.

### D1-7.8 COST SUMMARIES

**2009 AFC-CBD Summaries.** The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table D1-7-1. The summary shows the reference cost basis (constant year \$US), the reference basis cost contingency (if known), the cost analyst’s judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Table D1-7-1. Cost summary table for CANDU ACR-700 fuel (2009 AFC-CBD).

What-It-Takes (WIT) Table (2009\$)			
Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
Unit cost=\$135/kgU	\$115/kgHM	\$155/kgHM	\$135/kgHM
No fab plant capital cost data available.	None identified	Use of enrichments over 1% U-235	Use reference value

**2012 AFC-CBD Update Summaries.** The following “what-it-takes” values and a corresponding probability distribution shape are recommended for use in future fuel cycle studies:

Table D1-7.2. “What-it-takes” (WIT) CANDU fuel unit fabrication costs (2012 AFC-CBD Update).

Fuel Type	Low Value (2012 \$/kgHM)	Nominal Value (2012 \$/kgHM)	High Value (2012 \$/kgHM)
Pelletized Natural UO <sub>2</sub> Ceramic CANDU fuel	115	200	300
Pelletized UO <sub>2</sub> Ceramic CANDU fuel (RU from LWR spent fuel reprocessing or SEU)’	150	260	390

For uncertainty analyses triangular distributions should be used with the values in the table rows above. The unit fabrication cost values for NATU-derived CANDU fuel in the Table above were calculated by using similar multipliers (2012 AFC-CBR to 2009 AFC-CBR) to those used for LWR “virgin-U” derived fuel. As explained above, this is because of similarities in the LWR and CANDU fuel production, institutional, and regulatory environments. A sustained increase in the price of zirconium is factored into the assumptions. The nominal value of \$200/kgU is a rounded average of the \$189 and \$207 values derived in the section above.

For the new category of RU-derived CANDU fuel a 30% penalty is added to all 3 cases (low, nominal, and high) per the hypothetical case in (Del Cul et al. 2009). The same 30% factor is suggested for CANDU fuel made from slightly-enriched uranium (SEU). This accounts for the more stringent safety and security environment associated with enriched uranium use. Table D1-7.2. “What-it-takes” (WIT) CANDU fuel unit fabrication costs (2102 AFC-CBD Update).

Table D1-7-3 shows the 2012 Update values escalated to Year 2017\$ using an escalation factor of 1.09. No new CANDU cost information was gathered in the 2012 to 2017 time frame.

Table D1-7-3 “What-it-takes” (WIT) CANDU fuel unit fabrication costs (escalated to 2017\$)

Fuel Type	Low Value (2017 \$/kgHM)	Mode Value (2017 \$/kgHM)	Mean Value (2017 \$/kgHM)	High Value (2017 \$/kgHM)
Pelletized Natural UO <sub>2</sub> Ceramic CANDU fuel	125	218	224	327
Pelletized UO <sub>2</sub> Ceramic CANDU fuel (RU from LWR spent fuel reprocessing or SEU) <sup>1</sup>	164	284	291	425

The triangular distributions based on the costs in the latter WIT Table are shown in Figure D1-7-3. The distributions are not heavily skewed since there is considerable industrial cost experience with CANDU fuel.

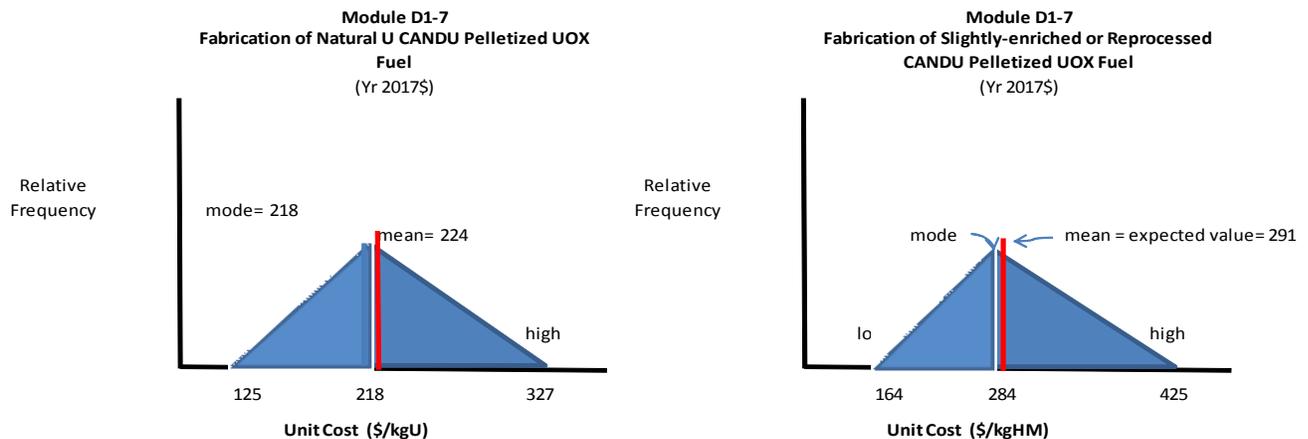


Figure D1-7-3. CANDU fuel estimated cost frequency distributions.

## D1-7.9 SENSITIVITY AND UNCERTAINTY ANALYSIS

No data were found or generated.



**Module D1-8**  
**Thorium-based Fuels**



# Module D1-8

## Thorium-based Fuel Fabrication

### D1-8.MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant \$ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:** Literature review and analysis of data in 2012 resulted in revised unit costs. Fuels considered were:
  - Enriched U (~19.95% U-235) oxide and fertile Th oxide MOX fuel pelletized fuel burnable in LWRs
  - All ThO<sub>2</sub> blanket pellets
  - All (U, Th)O<sub>2</sub> fertile “blanket” pelletized fuel burnable in LWRs designed on “seed/blanket concept”
  - (Pu, U, Zr) extrudable metal alloy rod usable as a driver along with ThO<sub>2</sub> blankets in seed blanket concept. (Proposed as Pu disposition technique for weapons-grade Pu capable of contact handling before reactor insertion.)
  - Liquid fuels such as those proposed for thorium-based MSR fuel cycles are **not** considered. Costs for these are considered in the Salt-cooled reactor modules

### D1-8.RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2005 as Module D1-8. In 2012 fertile ThO<sub>2</sub> pellet blanket fuel was added to this module.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2012
- **New technical/cost data which has recently become available and will benefit next revision:**
  - Ceramic fertile thorium particles have been used in MHRs. Some cost information might be available.
  - Lightbridge Corporation continues to investigate seed-blanket concepts for LWRs. Some of these involve thorium.

### D1-8.1 BASIC INFORMATION

**2009 AFC-CBD Status.** For sustainability (U-conservation) and nonproliferation reasons the use of thorium/U-233 LWR fuels has recently received considerable attention (Kazimi 2003; Greneche 2006; Reuters 2007; Lifton 2007; Filippov 2007; India’s Atomic Energy Agency 2006, Norway Thorium Report Committee 2008) and some DOE research and development funding (as part of NERI, and the Russian plutonium disposition programs). A U.S. company, Thorium Power (now part of Novastar/Lightbridge), is working on one such concept, called the Radkowsky Thorium-Plutonium Incinerator (RTPI) with the Kurchatov Institute in Moscow, Russia. The intent is to develop a two-part hybrid [ceramic (U, Th) O<sub>2</sub> blanket, metal Pu-Zr alloy seed driver] LWR fuel assembly that could deeply burn enriched uranium or plutonium without producing additional higher actinides (Washington Post 2009). The use of a plutonium driver is not necessary if the mission is to only produce electricity and not to disposition plutonium. Pelletized UO<sub>2</sub>/ThO<sub>2</sub> MOX fuel can be used in lieu of low-enriched UO<sub>2</sub>. The UO<sub>2</sub> mixed with the ThO<sub>2</sub> must be at a U-235 content (19.95% U-235 to still qualify as LEU) considerably above that of typical

LWR LEU fuel (2 to 5% U-235). The U-233 that is formed or “bred” by neutron irradiation of thorium helps to sustain the life of the nuclear fuel such that residence times of as long as 9 years are deemed possible (if cladding can be developed with such a long life). Such long residence times mean higher fuel burnup or utilization and less consumption of nuclear fuel. Thus there is the potential for a reduction in the fuel cycle component of the busbar levelized cost of electricity from a reactor. Most thorium-related fuel development work to date in the U.S. has been on LWR and gas-cooled reactor fuels. This section will deal mainly with possible LWR applications, mainly U.S. and Russian PWRs (VVERs).

World thorium resources are estimated to be three times those of uranium, and several nations, such as Brazil, Australia, Norway, and India, and even the U.S. have significant indigenous thorium sources. India has the largest thorium program, and is actually including its future use in its energy planning activities. China is also showing increasing interest in thorium cycles (Platts 2009). In the U.S., Thorium Power is the major advocate for this fuel cycle; they base their arguments mainly on the fact that the major waste products have shorter decay times and that fewer long-term heat-producing radioisotopes are generated (Washington Post 2009)

**2012 AFC-CBD Update Status.** In the last five years there has been increased interest in the use of thorium fuel cycles, especially by those in academia, non-governmental organizations, and outside the U.S. nuclear industry. The purported Th resource availability, non-proliferation and waste production/management benefits of thorium-based fuel cycles are the subject of dozens of recent reports and papers too numerous to list here. Very little information in the area of economics, for the fuel cycle, the required new reactors, or existing reactor modifications, has been presented.

As a target of past extensive research and development thorium and its fuel cycles are nothing new. Very extensive programs were conducted by USAEC and its contractors in the 1950s through the 1970s. Some early LWRs, such as Shippingport, actually operated with thorium in their cores. ORNL and General Atomics produced many reports on molten salt reactor fuel cycles and HTGR fuel cycles, respectively. Many of these are now available in electronic form. Research and development on thorium-based fuels for several reactor types was well documented, and some “level-playing field” type life cycle cost estimates were prepared for fabrication of several thorium fuel types. The estimates combined the attributes of both “bottom-up” and parametric “top-down” cost estimates for both capital and operations costs. For purposes of comparison, the costs of uranium-only and plutonium-based fuels were included. One such ORNL study from 1978 (Olsen et al. 1979) is cited below.

The 2009 AFC-CBR contained somewhat detailed and much more recent cost information on a Russian “seed-blanket” concept (Radkowsky concept) which could use either enriched uranium or plutonium fuel in a metal alloy driver fuel and (U, Th) O<sub>2</sub> pellets in the surrounding rod/bundle structure typical of PWRs. No new cost information has become available on this “Radkowsky” seed-blanket concept since the 2009 AFC-CBR document.

It was decided that this section could best benefit from a new look at the old (1960-1970s vintage) cost estimates. These are basically for ceramic type fuels which could be either (U, Th) O<sub>2</sub> pellets for LWRs or TRISO type (U, Th) O<sub>2</sub> or (U, Th) CO particles imbedded in graphite for HTRs. These will be the subject of the next section of this module.

The liquid-fueled molten-salt reactor (MSR) concept has also enjoyed considerable recent interest (Pickard 2002). Since it does not require a fuel fabrication facility and the fuel cycle is integral to the reactor, its fuel cycle economics are not covered here, but, rather in the R7-module. In an MSR breeding cycle thorium salts are the main fertile make-up feedstock and are converted to fissile U-233 salts.

## **D1-8.2 FUNCTIONAL AND OPERATIONAL DESCRIPTION**

For a reactor using only UO<sub>2</sub>-ThO<sub>2</sub> (U-Th MOX) pellets, the fuel fabrication facility would be very similar to a low-enriched UO<sub>2</sub> facility such as that at West Columbia, South Carolina (BNFL/Westinghouse). Figure D1-8-1 shows the major process steps. The major differences would be at

the front end of the plant, where a  $\text{UO}_2/\text{ThO}_2$  blending step would be needed. Prior to this, some purification/conversion of the original thorium feed form, such as a nitrate  $[\text{Th}(\text{NO}_3)_4]$ , would be required. The uranium conversion step ( $\text{UF}_6$  to  $\text{UO}_2$ ) would have a major difference from that in an LEU plant, however. The higher U-235 enrichment (19.95% U-235) would require special criticality control and smaller batch sizes prior to blending with  $\text{ThO}_2$ . Pellets of this type have been successfully produced on a small scale and irradiated in commercial reactors.

For a reactor using the RTPI concept, such as for plutonium disposition, essentially two fuel plants are needed. The plant described in the paragraph above would provide the “blanket” fuel in which a high conversion of Th-232 to U-233 would take place, and the fission of bred U-233 would augment the fission of U-235 from the uranium component. Within each fuel assembly there would also be a driver fuel that would consist of long, thin, trefoil rods of plutonium (or highly-enriched U) metal alloyed with zirconium. Most of the neutrons for fission would be produced in the driver. Figure D1-8-2 shows how each RTPI fuel assembly would have driver rods surrounded by rods containing blanket (U, Th) $\text{O}_2$  pellets. The Pu alloy driver fuel plant would require complex chemical and metallurgical operations that must be performed in a glovebox environment, such as exists for production of (U, Pu)  $\text{O}_2$  MOX fuel. None of the proposed operations, which include conversion, reduction, pressing, and extrusion of plutonium compounds or alloys, have been performed in a large-scale commercial facility. Figure D1-8-1 shows the steps required for the driver fuel production for a plant envisioned to support possible Russian VVER-PWR disposition of 38 MT of Russian Federation plutonium over ~16 years. Compared to a proposed similar weapons plutonium-disposition scheme using French MOX (U, Pu) technology (Module D1-2) in Russia, the RTPI scheme appears considerably more complex and is likely to also be much more expensive.

### **D1-8.3 PICTURES AND DIAGRAMS**

The top part of Figure D1-8-2 shows an RTPI mockup hexagonal fuel assembly for a Russian VVER-1000 PWR. The two-part assembly (blanket and driver separable) has the metal-alloy, twisted, trefoil drivers in the middle surrounded by tubes of blanket pelletized ceramic fuel. A cross section of a driver rod is shown bottom left. A cross section of an annular blanket pellet is shown bottom right.

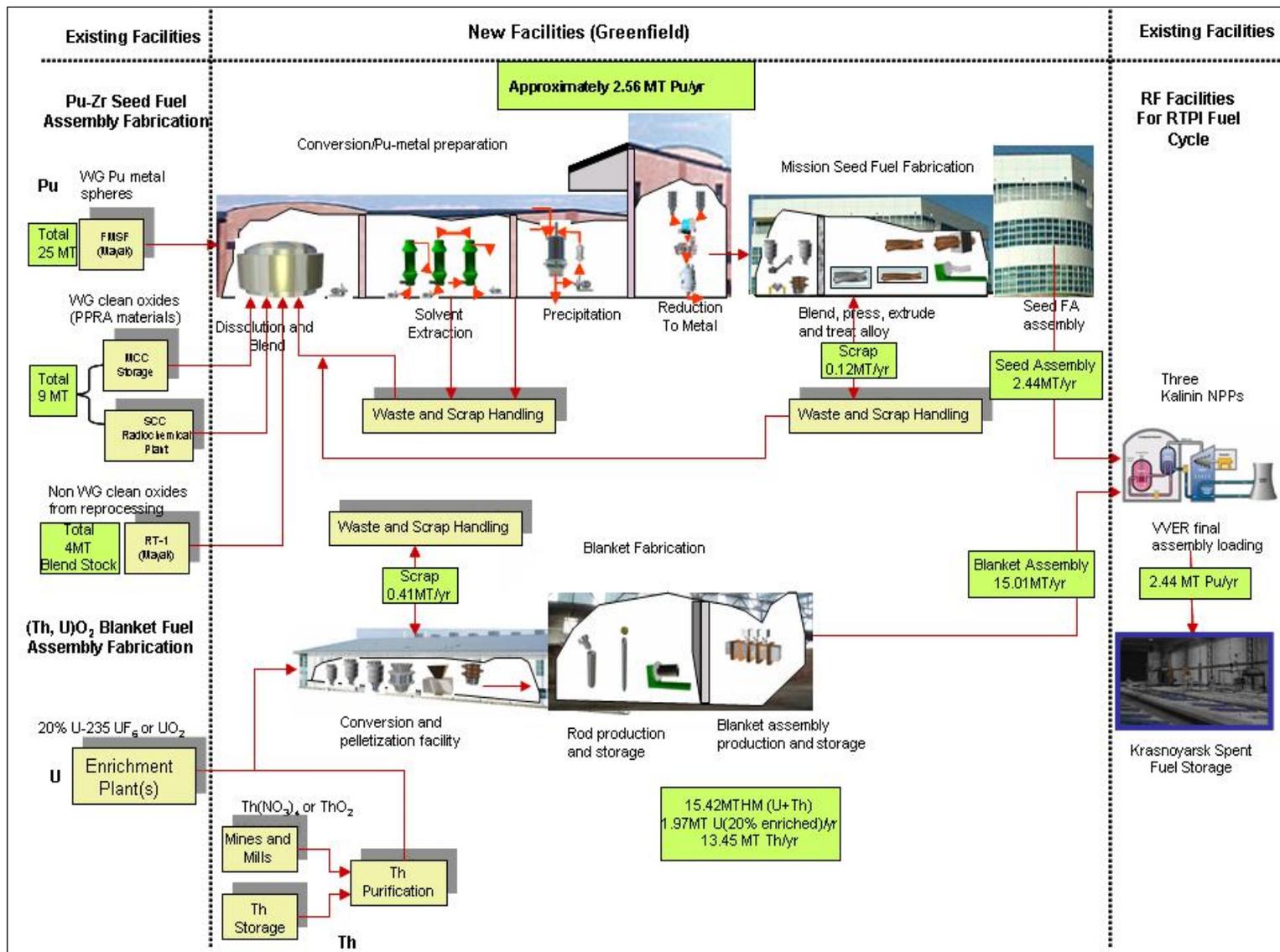


Figure D1-8-1. Fuel fabrication facility process schematics for a thorium concept utilizing both a blanket (U, ThO<sub>2</sub>) pelletized fuel and a metallic Pu-Zr driver fuel (RTPI concept proposed for Russian Pu-disposition) (ORNL, 2005).

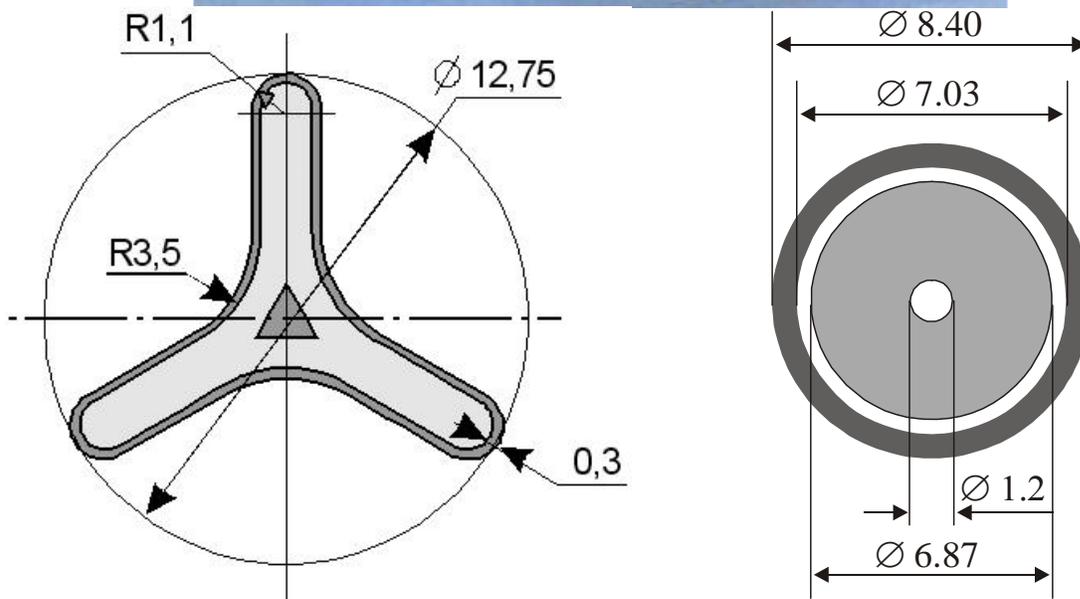


Figure D1-8-2. RTPI blanket/driver fuel envisioned for plutonium-disposition (dimensions are in millimeters) (ORNL, 2005).

## D1-8.4 MODULE INTERFACES

**Front-end interfaces.** Thorium is three times as abundant in the earth's crust as uranium (see Module A20); hence there is plenty of thorium ore available for use. Like uranium, the thorium ore must be mined and milled. The thorium compound produced at the mill, such as an oxide or a nitrate, must be chemically purified to produce a reactor-grade thoria powder. The accompanying uranium is likely to be received as enriched  $UO_2$  produced from a new enrichment facility or blended from weapons-highly enriched uranium stockpiles. For the RTPI plutonium-disposition concept, the plutonium is envisioned to come from nuclear weapons as impure metal or as impure  $PuO_2$  from other military facilities. This plutonium must be chemically purified before it is reduced to metal and alloyed with zirconium. Front-end process conversion steps involving aqueous chemistry are required. Over 10 years of fuel qualification would likely be required for the RTPI concept before it could be commercially implemented.

**Back-end interfaces.** These thorium fuel cycles are envisioned to achieve high burnups and be operated on a once-through basis. The spent fuel is likely to be more radiotoxic than normal low-enriched

UO<sub>2</sub> spent fuel. The driver and blanket spent fuel for the RTPI application will be separable. Casks for transportation and final geologic disposal would need to be developed.

Thorium-based spent fuels present special problems if they are reprocessed for recovery of U-233 and minimization of wastes. Along with U-233, small amounts of the isotope U-232 are produced. This relatively short-lived uranium radioisotope has decay daughters, such as thallium-208, which produce very potent gamma radiation. If the U-233 fuel refabrication operations are not performed quickly after reprocessing (which strips out the U-232 daughters but not the U-232 itself), U-232 daughters will build back up and present a significant radiological hazard in the fuel fabrication facility. The required shielding and handling procedures, perhaps even totally remote fabrication, will very significantly increase the unit cost of U-233 fuel refabrication. Thorium compounds are also harder to dissolve in aqueous processes, which also complicates reprocessing.

### **D1-8.5 SCALING CONSIDERATIONS**

No documented data were available. For (U,Th)O<sub>2</sub> blanket ceramic pellet fuel the plant scaling laws would be similar to those for LWR UO<sub>2</sub>. The Pu-Zr driver fuel would probably scale similarly to metal fast reactor fuel facilities.

### **D1-8.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES**

The Kurchatov Institute and Thorium Power Corporation have produced analyses claiming that their thorium fuel cycles are at least 20% cheaper than the conventional UO<sub>2</sub> fuel cycle on a mills/kWh basis (fuel component of the cost of electricity). The favorable economics are based on the high burnup and long residence time of the fuel assembly, with U-233 being continually produced and burned. Residence times up to 9 years are projected. Unfortunately, a fuel rod cladding that lasts this long has not been developed. If it were, it would benefit not only (U,Th)O<sub>2</sub> fuel but also any UO<sub>2</sub> fuel, thus the cost advantage over UO<sub>2</sub> may be illusory. As far as unit production (fabrication only) costs for (U,Th)O<sub>2</sub>, a detailed analysis by Lahoda (2004) indicates that they would be no more than 50% greater than those for low-enriched UO<sub>2</sub> LWR fuel (Section D1). Such fuel could be produced in a low-enriched UO<sub>2</sub> fuel line with some heating, ventilating, and air-conditioning (HVAC) and front-end modifications. A license amendment and significant building and procedure modifications would be needed to handle the 19.95% U-235 UO<sub>2</sub> component. Because of higher U-235 content, the total front-end fuel cycle cost (ores, conversion, enrichment, and fabrication) of the (U,Th)O<sub>2</sub> assembly, which is 13% uranium and 87% thorium, would be at least 60% higher than for low-enriched UO<sub>2</sub> fuel (\$784/kgHM versus \$476/kgHM). Lower Russian unit costs for these front-end fuel cycle steps are assumed (Cowell et al. ORNL 2005). The SWU component alone for 19.95% U-235 is \$5,000 to \$6,000/kgU or kgHM in the west.

The unit fabrication costs for the twisted, trefoil Pu-Zr alloy driver (Cowell et al. ORNL 2005) fuel are projected by Oak Ridge National Laboratory to be much higher than those projected by Kurchatov Institute. In terms of unit cost per unit of metal (plutonium + zirconium for fuel which is 15% plutonium) a value of \$27,000/kg metal was calculated by Oak Ridge National Laboratory. This is several times higher than unit costs for either fast reactor (U, PuO<sub>2</sub>) MOX or cast (U, Pu,Zr) metallic fuel. The high cost is based on the Oak Ridge National Laboratory analysis of the various chemical and metallurgical operations involved in extruded trefoil rod production under glovebox conditions. These high plutonium-handling costs are validated by U.S. cost experience with plutonium and its compounds and alloys in its weapons complex.

### **D1-8.7 DATA LIMITATIONS**

**Technical Readiness Status:** Planning for bench scale development is under way in Russia. A pilot plant for RTPI fuel would be at least 5 years away, and a large scale fabrication plant at least 12 years distant. If only (U,Th)O<sub>2</sub> or (Pu,Th)O<sub>2</sub> pellet fuel were to be used, these deployment times would be

considerably shorter. India, in fact, has shown interest in using such fuel because of the large amount of indigenous thorium and has performed some successful irradiation experiments.

A report by the Thorium Report Committee (Norway Thorium Report Committee 2008) discusses the problem of lack of economic data on thorium fuel cycles. It suggests that just the R&D required for such cycles will cost over \$1 billion. The report compares its level of development to that of Accelerator Driven Systems (ADS) for nuclear power.

## D1-8.8 COST SUMMARIES

**2009 AFC-CBD Cost Summary.** The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table D1-8-1. The summary shows the reference cost basis (constant year \$US), the reference basis cost contingency (if known), the cost analyst’s judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Table D1-8-1. Cost summary table for LWR thorium-based RTPI fuel now under development in Russia.

What-It-Takes (WIT) Table (2007 constant \$)			
Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
(U,Th)O <sub>2</sub> pellet fuel	\$800/kgHM in Russia  (HM is U+Th). Includes SWU component in uranium cost.  Longer fuel life than for LEUO <sub>2</sub>	\$3,000/kgHM  Higher fuel production costs due to need for 19.95% EU and HVAC modifications	\$1,600/kgHM in West (U component includes SWU cost)  [HM is U,Th]
Pu-Zr metal fuel for RTPI Pu-disposition application [in tandem with (U,Th)O <sub>2</sub> blanket]	High annual consumption of surplus Pu in LWR	Having both metal seed and oxide blankets makes very complicated and expensive fuel. Very long, expensive fuel qual program needed.	\$27,000/kg metal (U.S. or Russia)

If ThO<sub>2</sub> only pellets and rods were to be produced in the U.S. for “blankets” in LWRs, the fabrication-only cost would be on the order of \$400/kgHM or Th. However, reprocessing the blanket pellets to obtain fissile U-233 and its refabrication into U-233/U-238 LEU fuel assemblies would incur very significant costs and is not being seriously considered in the U.S.

2012 AFC-CBD Update Cost Data. This section presents cost data obtained from 2009 to 2012. Many old ORNL reports were found to have useful data, such as in Table D1-8-2 below.

Table D1-8.2. 1978\$ projected costs for various thorium-containing fuels (Olsen et al. 1979).

Table 11. Estimated Fabrication Cost Comparison<sup>a</sup> Summary

Reactor Type	Fuel Material	Relative Cost Factors				Estimated Costs, (\$/kg) <sup>b</sup>
		Capital	Hardware	Operating	Total	
<b>Part A</b>						
LWR (PWR)	( <sup>235</sup> U,U)O <sub>2</sub>	0.33	0.38	0.29	1.00	150 <sup>c</sup>
	(Pu,U)O <sub>2</sub>	1.49	0.38	1.45	3.32	500
	( <sup>235</sup> U,Th)O <sub>2</sub>	0.41	0.42	0.44	1.27	190
	( <sup>233</sup> U,Th)O <sub>2</sub>	2.18	0.42	1.60	4.19	630
	(Pu,Th)O <sub>2</sub>	1.49	0.38	1.53	3.40	510
CANDU	Normal UO <sub>2</sub>	0.33	0.09	0.11	0.53	80
	(Pu,U)O <sub>2</sub>	1.49	0.09	0.50	2.08	310
	( <sup>233</sup> U,Th)O <sub>2</sub>	1.98	0.12	0.55	2.65	400
	(Pu,Th)O <sub>2</sub>	1.49	0.09	0.55	2.13	320
LMFBR	(Pu,U)O <sub>2</sub>	3.19	0.58	2.10	5.87	880
	(Pu,U)C	2.68	0.37	1.66	4.72	710
	<sup>233</sup> U,Th	2.73	0.35	1.61	4.69	700
GFBR	(Pu,U)O <sub>2</sub>	3.19	0.90	2.29	6.38	960
	( <sup>233</sup> U,Th)O <sub>2</sub>	5.01	0.99	2.64	8.64	1300
	(Pu,Th)O <sub>2</sub>	3.64	0.90	2.40	6.94	1040
<b>Part B</b>						
HTGR	<sup>235</sup> UO <sub>2</sub> -ThO <sub>2</sub>	0.26	0.42	0.32	1.00	400 <sup>d</sup>
	<sup>233</sup> UCO-ThO <sub>2</sub>	1.23	0.42	0.96	2.61	1030
	<sup>235</sup> UO <sub>2</sub> -UO <sub>2</sub>	0.23	0.35	0.32	0.90	360
	PuO <sub>2</sub> -ThO <sub>2</sub>	1.23	0.42	0.96	2.61	1030

<sup>a</sup>All cost comparisons are relative to the given base case factors.

<sup>b</sup>1977 dollars assumed for total kilograms of heavy metal product with a plant output of 2 t/d and operating 260 d/year (520 t/year).

<sup>c</sup>Base case for metal clad fuel rods based on FABCOST 9 estimates [Source: A. L. Lotts, T. N. Washburn, and F. J. Homan, *FABCOST 9, A Computer Code for Estimating Fabrication Costs for Rod-Bundle Fuel Elements*, ORNL-4287 (August 1968).] escalated to 1977 with additions for current scrap and waste treatment requirements.

<sup>d</sup>Base case for all HTGR (Prismatic Fuel Element) cases based on data from personal communication, A. L. Lotts, Oak Ridge National Laboratory, April 11, 1975.

Two old ORNL reports (Olsen et al. 1979) and (Sease 1966) from the “heyday” of the USAEC thorium utilization program provide the best detailed information on the projected costs of adding thorium to more conventional uranium fuels. Table D1-8.1 above from (Olsen et al. 1979) breaks down projected unit costs for several Th-containing fuel types. These comparative estimates and projected unit costs are useful because they were prepared by the same people within a common organization, which provides a level playing field for evaluation. They also can be compared to conventional LWR UOX fuel for which we have real cost/price information. Figure D1-8.1 below reprinted from the earlier (Sease 1966) is also useful since it attempts show how the mode of production (glovebox, full remote, et al.) affects the unit cost. In essence what we have are “complexity factors which might be applied to updated 2012\$ unit costs

for conventional fuels. For relatively simple Th-containing fuels, such as (U, Th)O<sub>2</sub> pellets, these “complexity factor” ratios are probably quite useful and applicable.

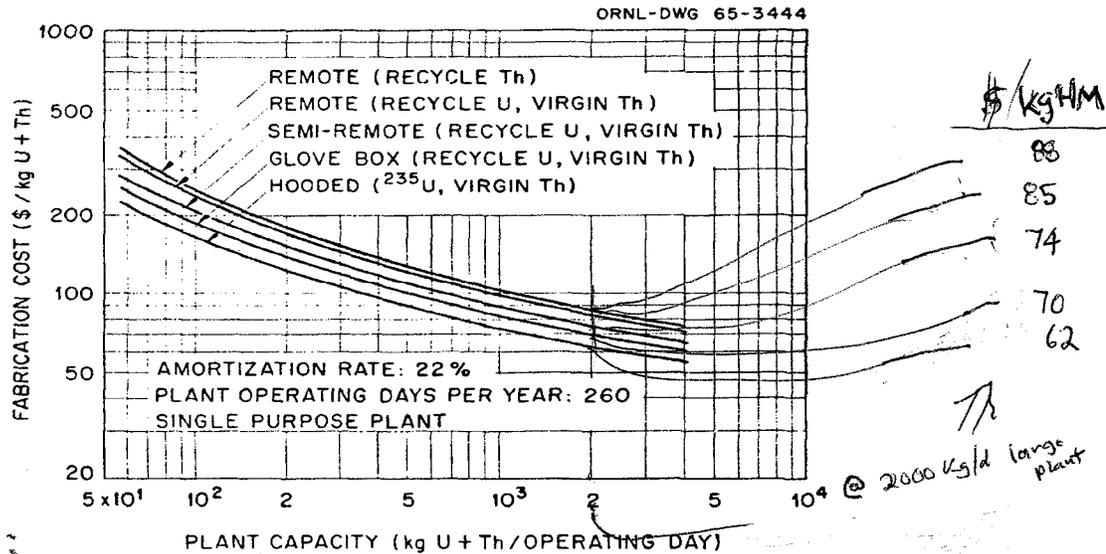


Figure D1-8.2. How mode of fabrication affects projected unit costs of thorium-containing fuels in 1965 dollars (Sease 1966).

For more complex fuels requiring remote handling the author of this section questions the validity of applying simple complexity ratios and the subsequent application of historical escalation. Regulatory, security, Q/A, and institutional factors have greatly increased the cost of both glovebox and remote handling nuclear facilities vis-à-vis contact handling ones. The ratio of the “remote” facility unit costs to the “hooded” (contact handled) unit costs in the above figure are too small (1.5 or less) to be realistic for a high-capacity fabrication plant.

Contact-handled (U,Th)O<sub>2</sub> pelletized fuel using unirradiated U and Th source materials can be used in LWRs, and if the spent fuel is reprocessed, fissile U-233 can be recovered for LWR use, much as Pu is recovered for eventual use in LWR MOX fuel. (It should be noted that thorium-containing fuels are more difficult to reprocess because of the lower solubility of ThO<sub>2</sub> and the higher radiation hazard associated with U-232 daughters which also accompany U-233 production. This is discussed in Module F1. Any U-233 arising from LWR burning and reprocessing of (U,Th)O<sub>2</sub> fuel would have to be refabricated in a remote-handling fabrication facility.) The enrichment of the uranium burned along with the thorium must be considerably higher (> 15% U-235) than the 3 to 5% U-235 for conventional UO<sub>2</sub> fuel. This is a result of the high neutron absorption by fertile thorium and the need to keep the core critical. The higher (U,Th)O<sub>2</sub> pellet fuel unit fabrication cost is a result of the higher criticality safety and security requirements for handling MEU and the additional HVAC requirements to keep thorium decay daughters (radon and its daughters) at acceptable levels. (Olsen et al. 1979). indicates a “complexity factor” of 1.26 for (U,Th)O<sub>2</sub> fabrication versus UO<sub>2</sub> fabrication.

As noted above, UO<sub>2</sub> fabricated with significant amounts of U-233 present in the fuel would present very high fabrication costs and if data were available would be covered in Module D2 for remotely-fabricated fuels. The U-235 + U-233 content of such fuel would have to be at least 2 to 3% for LWR fuel containing only uranium.

Pellets of ThO<sub>2</sub> only could also be fabricated using contact handling and might be used as blanket or target material for U-233 production in breeding fuel cycle. Because of greater HVAC requirements for Th handling, the unit cost for this operation would be somewhat above that for NATUO<sub>2</sub> or DUO<sub>2</sub> LWR

blanket fuel. The following table shows projected unit costs in 2012\$ for various Th-related fuels calculated by complexity factors applied to the unit costs for uranium-only fuels.

Table D1-8.2. Thorium-based fuel unit fabrication costs calculated per references (contact-handled fuels only).

Study or Ref/Year	Low Value (\$/kgHM)	Reference Value \$/kgHM	High Value (\$/kgHM)
DEC 2009 AFC-CBR  (U,Th)O <sub>2</sub> pellets for Radkowsky seed/blanket scheme (blanket)	N/A	50% higher than PWR UO <sub>2</sub> per Lahoda ref in 2009 report: 1.5 x 250 = 375	N/A
Pu,U,Zr metallic alloy driver fuel for Radkowsky scheme (mostly glovebox-handled Pu (This Pu-related cost is included since the HEU or Pu metal alloy driver is an integral part of the Radkowsky concept for LWRs.))	N/A	27,000 (from study by ORNL for NNSA a part of PU-disposition program)	N/A
Pelletized (U,Th)O <sub>2</sub> for LWRs. (U > 15% U-235)  [Complexity factor from (Olsen et al. 1979)]	N/A	Complexity Factor of 1.26 applied to 2012 AFC-CBR 350\$/kgU unit cost for LWR UO <sub>2</sub> 440	N/A
Pelletized pure ThO <sub>2</sub> for LWR blankets  [Complexity factor from (Olsen et al. 1979)]	N/A	Complexity Factor of 1.26 applied to U-blanket unit cost (450 \$/kgU) in 2012 AFC-CBR Module D1-4  570	N/A
Pelletized (U, Th)O <sub>2</sub> for LWRs [IAEA 2005]	N/A	300	N/A

Some adjustment of these values for the What-it-takes Table D1-8-3 are needed. The more recent report by Ed Lahoda (Lahoda 2004) cited in the 2009 AFC-CBR suggests that fabrication of (U, Th) O<sub>2</sub> fuel will cost 50% more than for UO<sub>2</sub>. This 1.5 factor is greater than the 1.26 complexity factor suggested in the 1979 reference and probably better reflects regulatory and ES&H realities. The high, low, and nominal values in the table below use the 1.5 factor applied to the corresponding values in the “WIT” table for LWR UO<sub>2</sub> fuel in Module D1-1.

Table D1-8.3. What-It-Takes (WIT) table for LWR thorium-based fuels (2012\$).

Fuel	Low Value (\$/kgHM)	Reference Value \$/kgHM or \$/kgU	High Value (\$/kgHM)
DEC 2012 AFC-CBR  Pu,U,Zr metallic alloy driver fuel for Radkowsky Pu-disposition scheme (mostly glovebox-handled Pu)	N/A	27,000	N/A
Pelletized (U,Th)O <sub>2</sub> for LWRs. (U > 15% U-235)  (Complexity factor from Lahoda)  U-enrichment cost not included!	300	Complexity Factor of 1.5 applied to 2012 AFC-CBR 350\$/kgU unit cost for LWR UO <sub>2</sub>  525	750
Pelletized pure ThO <sub>2</sub> for LWR blankets  (Complexity factor from Olsen 1979)	250	Same as for FR natural or DUO2 blankets 450	630

Table D1-8-4 escalates the Table D1-8-3 data to 2017 dollars using an escalation factor of 1.09. No new thorium fuel cost data was gathered in the 2012 to 2015 periods.

Table D1-8.4. What-It-Takes (WIT) table for LWR thorium-based fuels – escalated to 2017\$.

Fuel	Low Value (\$/kgHM)	Reference Value (\$/kgHM)	Mean Value (\$/kgHM)	High Value (\$/kgHM)
DEC 2012 AFC-CBR  Pu, U, Zr metallic alloy driver fuel for Radkowsky Pu-disposition scheme (mostly glovebox-handled Pu)	N/A	29,400		N/A
Pelletized (U, Th)O <sub>2</sub> for LWRs. (U > 15% U-235)  (Complexity factor from Lahoda)  U-enrichment cost not included!	327	Complexity Factor of 1.5 applied to 2012 AFC-CBR 350\$/kgU unit cost for LWR UO <sub>2</sub>  573	573	818
Pelletized pure ThO <sub>2</sub> for LWR blankets	273	Same as for FR natural or DUO <sub>2</sub> blankets  490	483	687

For uncertainty analyses triangular distributions should be used with the second and third entries in this table. Figure D1-8-3 shows the unit cost probability distributions for two thorium fuel types.

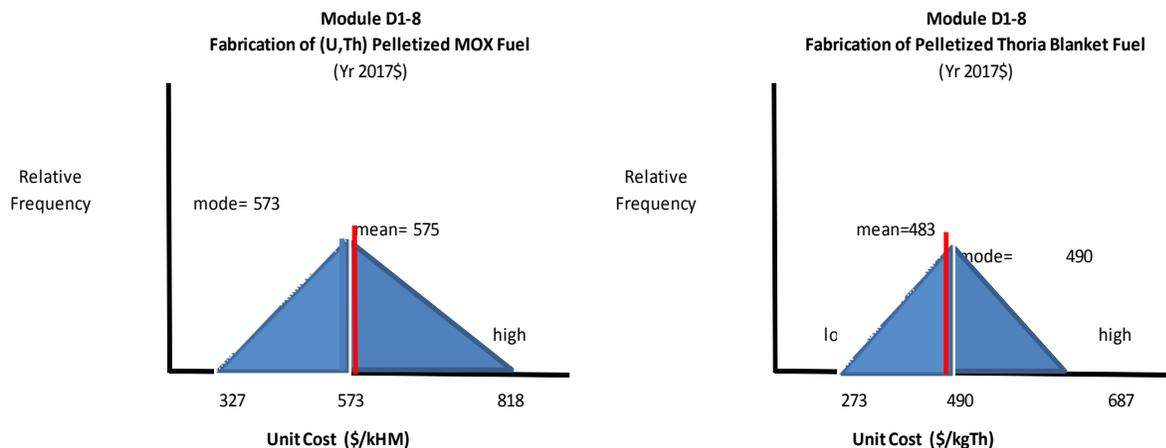


Figure D1-8-3 Uncertainty Distributions for Thoria Fuel Types.

A complexity factor applied to FR blankets (as in Table D1-8.4) probably overstates the cost, since UO<sub>2</sub> FR blankets would already be more expensive on a unit cost basis than LWR UO<sub>2</sub> blankets because of smaller pin size and FR fuel bundle complexity. (Note: Some natural UO<sub>2</sub> pellets are often used at the ends of LWR fuel rods for reactivity control.) The author assumes that pure thorium oxide blanket fuel for LWRs is equivalent in complexity to pure uranium oxide blanket fuel for fast reactors. For this reason the assigned unit costs are the same as for fast reactor UO<sub>2</sub> blankets in Module D1-4.

The same type of comparison logic could be applied to TRISO type HTR fuels containing thorium. This might represent a future modification of Module D1-3.

## D1-8.9 SENSITIVITY AND UNCERTAINTY ANALYSES

None provided at this time.

## **D1-8.10 OTHER THORIUM UTILIZATION NOTES**

Thorium can also be used as a fertile material in fuel cycles other than those in water reactors. It has actually been used in TRISO-type fuels for gas-cooled reactors in both the U.S. (Fort St. Vrain) and Germany (THTR). The durability and long life of TRISO fuels makes the thorium to U-233 conversion feature beneficial for high fissile burnup. The additional economic impact of using thorium dioxide in addition to 8 to 20% U-235 UO<sub>2</sub> in TRISO fuel production is relatively low. HTGR applications are also discussed in the IAEA's 2005 report (IAEA 2005). Thorium oxide blankets on fast reactors (such as liquid metal fast breeder reactors) are also of interest, and fast reactors in India may in fact use plutonium driver fuel and some ThO<sub>2</sub> blankets. Thorium could also be burned in liquid molten salt-based reactor systems with online reprocessing. This concept was the basis of the Molten Salt Reactor Experiment (MSRE) at Oak Ridge in the 1960s–1970s. The fuel cycle can also be operated in a breeder or actinide burner mode (Pickard and Forsberg 2002).

## **Module D1-9**

### **Inert Matrix and Other Advanced Fuels**



## Module D1-9

### Inert Matrix and Other Advanced Fuel/Target Fabrication

Since no unit costs have been presented in this module, there is no Section D1-9.MD or D1-9.RH dealing with Costing Methodology and Cost History

#### D1-9.1 BASIC INFORMATION

**Background and 2009 AFC-CBD Status.** Inert Matrix Fuels (IMFs) are those in which there are no or minimal fertile radioisotopes, such as U-238 or Th-232, that are transmuted to higher actinides. The advantages of such fuel are as follows:

- The generation of long-lived higher actinides which contribute to repository heat-loading is minimized.
- High fissile destruction fractions are attainable because no new fissile material is generated from fertile constituents. This can be an advantage for some open cycle concepts (INL 2010).
- Because the initial fissile fraction or percentage of the overall fuel mass must be high, the reactor volume and fuel mass per kilowatt thermal can be reduced. This is advantageous for small modular reactor and space reactor concepts. The associated high neutron fluxes can also effectively burn out any actinides introduced in the core, such as in fast reactor burner concepts.

The inert (diluent) materials in such fuels may be oxides of metals with low neutron absorption cross sections or metallic alloying constituents such as zirconium. Some suggested (Tulenko 2009) inerting materials are silicon carbide and magnesium oxide-pyrochlore ceramic-ceramic (cercers). Other rare earth ceramic oxides are also under investigation as IMF diluents.

Advanced Fuels are those special fuel types envisioned for some of the Generation IV Reactor Systems concepts such as the Gas-cooled Fast Reactor (GFR) and not included in Modules D1-1 through D1-8. Dispersion fuel, where ceramic fuel particles are dispersed in a metal or ceramic matrix, is one such example of an advanced fuel. An example would be TRISO particles dispersed in zirconium.

It is too early to know definitively whether these two types of fuel would be fabricated in contact-handling (D1) or remote handling (D2) facilities. If significant higher actinides are to be included in a homogeneous IMF, the latter facility will be required. The reactor concepts and fuel cycle are still being defined as part of the Generation IV Program. Fuels of these two types have been produced as “specialty fuels” for use in research reactors or other special reactor applications. The manufacturing of these fuels is a batch operation with considerable human contact handling. Some such fuels have been used in (nonelectricity) production and research applications where high temperature is not needed, but high fast or thermal neutron fluxes exist. Much of this “specialty-type” fuel is produced by pressing or extrusion type metallurgical operations. Because this fuel is usually 19% or greater in fissile content and is made in relatively small quantities, the unit costs for fabrication are usually high (i.e., a several thousand to tens of 1,000s of dollars per kgHM). Some types of research reactor fuel cost over \$19,000/kgHM.

**2012 AFC-CBD Update Status.** Since the 2009 AFC-CBR no new data on the economics of these advanced fuel or target types have been located. (Note that “targets” and “driver fuels” will probably need to be separated from a cost standpoint as well as a physical standpoint for any further economic analyses, since their production requirements are likely to be vastly different depending on fuel/driver isotopics and impurity considerations. This observation is especially true for transmutation systems.)

Calculation of unit costs for some of these fuel types will need to be developed by using parameterization applied to fuel types for which costs are known. Among the “parameters” are radiation environment and building requirements, thermal conditions, number and complexity of manufacturing steps, cost of cladding materials and other non-nuclear materials, quality assurance requirements, and extent to which processes can be automated.

Most of these driver fuel/target types rightly belong in the D2 set of modules, since remote handling is likely to be necessary.

Among the possible future fuels which might be considered here (Section D1 “contact-handled” fuels) are the suggested post-Fukushima accident-resistant LWR fuels (Enhanced Accident Tolerant Fuels) that involve cladding materials other than zirconium or materials with higher melting points (NERAC 2011). The DOE Fuels R&D Program is considering some of these concepts; however, no cost estimates for large scale production of these fuels have been developed.

## **D1-9.2 FUNCTIONAL AND OPERATIONAL DESCRIPTION**

No data were available on processes for the large scale production of such fuels. As Generation IV research and development continues, such manufacturing processes will be further defined.

## **D1-9.3 PICTURES AND DIAGRAMS**

Figure D1-9-1 shows two types of IMF fuel pellets produced by a fuels research and development program (LANL 2002).

The two IMF pellets (solid solution and macro-dispersed) are shown at the beginning of life before irradiation in the frame of the OTTO project. The pellet on the left is a representative pellet made of  $\text{Er}_x\text{Y}_y\text{Pu}_z\text{Zr}_{1-x-y-z}\text{O}_{2-(x+y)/2}$  material. The pellet on the right is a composite material pellet. Visible microspheres made of  $\text{Er}_x\text{Y}_y\text{Pu}_z\text{Zr}_{1-x-y-z}\text{O}_{2-(x+y)/2}$  are partially popping out of the pellet’s white surface, which is made of  $\text{MgAl}_2\text{O}_4$  spinel.

Figure D1-9-2 shows the types of dispersion fuel being considered by the Generation IV Gas-cooled Fast Reactor Program.

## **D1-9.4 MODULE INTERFACES**

There is not yet enough fuel cycle definition to describe these interfaces.

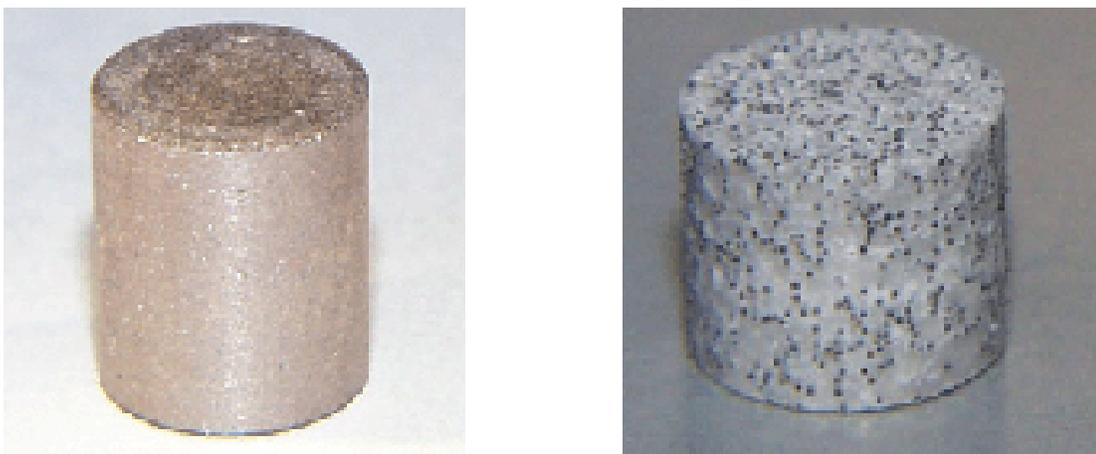


Figure D1-9-1. Solid solution and macro-dispersed inert matrix fuel pellets.

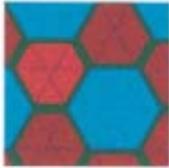
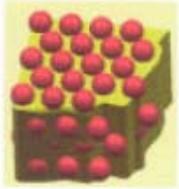
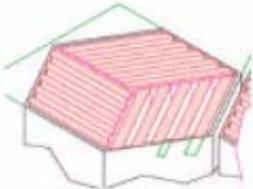
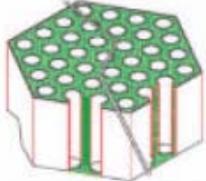
	Fuel	Fuel element	Sub-assembly
1- DISPERSION FUEL	Cylindrical or Hexagonal sticks 	Coated compact 	Pseudo-hexagonal sub-assembly with compact stack 
	Spheres / particles 	Coated plates 	Sub-assembly with plates  Prismatic block type with coated channels 

Figure D1-9-2. Dispersion fuel concepts.

## D1-9.5 SCALING CONSIDERATIONS

No data available.

## D1-9.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES

No cost data on these fuel types were found. For contact-handled IMF or Advanced Fuel, the cost data in Sections D1-3 (Gas-cooled Reactors) and Section D1-6 (Metallic and Alloyed Fuels) might provide some idea of unit costs for production quantities. For remote-handled IMF or Advanced Fuels, the comments in Section F2/D2 should apply.

## D1-9.7 DATA LIMITATIONS

There is not enough cost data available to define cost limitations

## D1-9.8 COST SUMMARIES

For these fuels a considerable fraction of the fuel mass (not including clad or assembly hardware) will not be a diluent heavy metal (HM) such as uranium. The figure of merit used should be \$/kg base fuel metal. Because of the high fissile content of such fuels, the cost is expected to range from several thousand to tens of thousands \$/kg, depending on quantities produced and the manufacturing environment. As is the case with other fuel types, the unit fabrication cost of IMF could easily rise exponentially with the amount of higher actinide (Pu, Am, Np, and Cm) present. A “step” in this cost function is likely where the high actinide content forces the transition from contact-handling to remote-handling.

## D1-9.9 RESULTS FROM SENSITIVITY AND UNCERTAINTY ANALYSES

No data available.

## MODULE D1 REFERENCES

References for all of the D1 Modules appear in this section. The sub-headings group them by the modules applicable to each fuel type addressed in the text. Note that some references are proprietary, copyrighted trade press newsletters, official government documents marked “official use only” or “applied technology,” or reports prepared by consulting firms with limitations on their release.

### PREFACE AND INTRODUCTION (MODULE SERIES D1)

Judkins, R. R. and A. R. Olsen, 1979, “Nuclear Fuel Fabrication and Refabrication Cost Estimation Methodology,” ORNL/TM-6640, Oak Ridge National Laboratory, November 1979.

Nuclear Engineering International, 2015, “Fuel Design Data,” September 2015.

Nuclear News 2017; *Accident-tolerant fuel: Enhancing safety*, September 2017; American Nuclear Society pg. 44

Olsen, A. R., R. R. Judkins, W.L. Carter, and J.G. Delene, 1979, “Fuel Cycle Cost Studies – Fabrication, Reprocessing, and Refabrication of LWR, SSCR, HWR, LMFBR, and HTGR Fuels,” ORNL/TM-6522, Oak Ridge National Laboratory, March 1979.

Williams, K.A.; *Top-down Life Cycle Costing for Nuclear Facilities*; Paper #9153; Global 2009 Fuel Cycle Conference; Sept 2009; Paris, France

### MODULE D1-1 LWR UO<sub>2</sub> FUEL

ABSCO Materials; Zirconium Industry Update: April 2012; Suffolk, UK;  
(<http://www.abscomaterials.com/pages/11046/zirconium-industry-update-2012>)

Bunn, M., et al., 2003, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Cambridge, Massachusetts, Project on Managing the Atom, Harvard University, DE,  
[http://belfercenter.ksg.harvard.edu/publication/2089/economics\\_of\\_reprocessing\\_vs\\_direct\\_disposal\\_of\\_spent\\_nuclear\\_fuel.html](http://belfercenter.ksg.harvard.edu/publication/2089/economics_of_reprocessing_vs_direct_disposal_of_spent_nuclear_fuel.html), Web page accessed August 25, 2009.

Bunn, M., et al., 2016, *The Cost of Reprocessing in China*, Cambridge, Massachusetts, Project on Managing the Atom, Harvard University, DE, January 2016.

Del Cul, G., Trowbridge, L., Renier, J., Ellis, R., Williams, K., Spencer, B., and Collins, E., “Analysis of the Reuse of Uranium Recovered from the Processing of Commercial LWR Spent Fuel,” ORNL/TM-2007/207, Oak Ridge National Laboratory, June 29, 2007.

Delene, J. G., J. Sheffield, K. A. Williams, et al., 2000, *An Assessment of the Economics of Future Electric Power Generation Options and the Implications for Fusion*, Rev. 1, ORNL/TM-1999/243/R1, January 2000.

Delene, J. G., K. A. Williams, B. H. Shapiro, 1988, *Nuclear Energy Cost Data Base: A Reference Data Base for Nuclear and Coal-fired Powerplant Power Generation Cost Analysis*, ORNL, DOE/NE-0095, September 1988.

De Roo, G. and Parsons, J. E., 2009, “Economics of the Fuel Cycle,” MIT Center for Energy and Environmental Policy Research, Viewgraph Presentation May 1, 2009.

Deutch, John et al., 2003, *The Future of Nuclear Power: An Interdisciplinary MIT Study*, Massachusetts Institute of Technology, 2003, Belfer Center for Science and International Affairs Science, Technology, and Public Policy Program, full text publication available at  
<http://web.mit.edu/nuclearpower/pdf/nuclearpower-summary.pdf>, Web page accessed August 25, 2009.

- Electric Power Research Institute (EPRI); *Parametric Study of Front-End Nuclear Fuel Cycle Costs Using Reprocessed Uranium*; EPRI Report No. 1020659; Jan 2010; (<http://brc.gov/sites/default/files/documents/1020659.pdf>)
- Energy Business Review, 2008, “Areva wins nuclear fuel supply contracts from U.S. utilities,” February 7, 2008, [http://www.energy-business-review.com/news/areva\\_wins\\_nuclear\\_fuel\\_supply\\_contracts\\_from\\_us\\_utilities](http://www.energy-business-review.com/news/areva_wins_nuclear_fuel_supply_contracts_from_us_utilities), Web page accessed August 25, 2009.
- Energy Resources International (ERI), 2006, Nuclear Fuel Supply and Price Report, cited in United States Department of Energy, “Proposed Long-Term Uranium Sales Strategy,” DOE Offices of Nuclear Energy, Environmental Management and Defense Nuclear Nonproliferation, August 4, 2006, <http://www.ne.doe.gov/pdFiles/proposedDoeLtUraniumSalesStrategyIndustryPresentationAug%204th2006.pdf>, Web page accessed May 15, 2007.
- Gingold, J. and L. Goldstein, 2002, “The Seven Percent Solution: A Contrarian View,” paper delivered at the NEI Fuel Cycle 2002 Conference, Chicago, Illinois, April 14–17, 2002.
- Gizitdinov, N., 2007, “Kazakhstan Aims to Be Biggest Nuclear-Fuel Producer (Update 1),” [www.bloomberg.com](http://www.bloomberg.com), July 11, 2007.
- Gregg, R. and A. Worrall, 2005, “Effect of Highly Enriched/Highly Burnt UO<sub>2</sub> Fuels on Fuel Cycle Costs, Radiotoxicity, and Nuclear Design Parameters,” Nuclear Technology (ANS), Vol. 151, August 2005.
- Gunnar, V. and S. Junkrans, 1998, “Perspectives on LWR Fuel Development,” The Uranium Institute Twenty Third International Symposium, 1998, [www.world-nuclear.org/sym/1998/vester.html](http://www.world-nuclear.org/sym/1998/vester.html), PDF, Web page accessed August 25, 2009.
- Hermes, W. H., et al., 2001a, *Thorium Nitrate Material Inventory Definition Report*, ORNL/TM-2000/163, June 2001, Official Use Only, p. E-14. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- Hermes, W. H., et al., 2001b, *Executive Summary Report for the Thorium Nitrate Stockpile Stewardship and Disposition Project*, ORNL/TM-2001/14, June 2001, Official Use Only, p. 9-9. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- IBR, 2006, *Direct Enrichment of Reprocessed Uranium at Siberian Chemical Combine*, International Business Relations Corporation (IBR), Moscow, 2006, Proprietary Report. (This document has a restricted distribution, may be proprietary, or both, and is not publicly releasable.)
- James J. and K. A. Williams, 1999, “Overview of Fuel Cycle for DOE Chicago Operations Office,” MOX Procurement Group, PowerPoint presentation by, ORNL, February 24, 1999. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- Kidd, Steve, 2005, “Fabrication: Is it different?,” Nuclear Engineering International (Web version), August 31, 2005, [www.neimagazine.com/story.asp?sc=2030109](http://www.neimagazine.com/story.asp?sc=2030109), Web page accessed August 25, 2009.
- Lahoda, E. J., 2004, “Costs for Manufacturing Thorium-Uranium Dioxide Fuels for Light Water Reactors,” *Nuclear Technology*, American Nuclear Society, Vol. 147, July 2004, pp 102–112.
- Massachusetts Institute of Technology (MIT); *The Future of the Nuclear Fuel Cycle* (full report); 2011; ([http://web.mit.edu/mitei/research/studies/documents/nuclear-fuel-cycle/The\\_Nuclear\\_Fuel\\_Cycle-all.pdf](http://web.mit.edu/mitei/research/studies/documents/nuclear-fuel-cycle/The_Nuclear_Fuel_Cycle-all.pdf))
- Michaels, G. E. and T. D. Welch, 1993, *Evaluation of Disposition Options for Reprocessed Uranium*, ORNL/TM-12326, February 1993.

- NAC Worldwide Consulting, 2004, "LWR Fabrication Plant Data," *Focus Journal of Nuclear Commerce*, Issue 68, Vol 2, 2004 (proprietary data). (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- Nuclear Engineering International 2011; "A changing market"; September 2011; Pages 38-42
- Nuclear Fuel Services, Inc., 2006, *NEI Recognizes BLEU Project with Top Industry Practices Award*, Nuclear Fuel Services, Inc. Press Release, Erwin, Tennessee, May 30, 2006.
- Nuclear Street, 2009, "Nuclear Fuel Services Inks Contract to Downblend Highly Enriched Uranium," July 2, 2009, [http://nuclearstreet.com/blogs/nuclear\\_power\\_news/archive/2009/07/02/nuclear-fuel-services-inks-contract-to-downblend-highly-enriched-uranium-424.aspx](http://nuclearstreet.com/blogs/nuclear_power_news/archive/2009/07/02/nuclear-fuel-services-inks-contract-to-downblend-highly-enriched-uranium-424.aspx), Web page accessed September 3, 2009.
- OECD NEA (1994) and IAEA (1994), *The Economics of the Nuclear Fuel Cycle*, 1994, <http://www.nea.fr/html/ndd/reports/efc/>, Web accessed August 25, 2009.
- OECD NEA, 2001, "Trends in the Nuclear Fuel Cycle: Economic, Environmental and Social Aspects", Paris, pp. 54, 127, 2001.
- OECD NEA, 2013, *The Economics of the Back End of the Nuclear Fuel Cycle*, 2013.
- Platts, 2006, *AREVA's Chemistry Business Unit Has Plans For a New Conversion Plant Dedicated to the Conversion of Reprocessed Uranium*, Platt's Nuclear News Flashes, June 13, 2006.
- Platts, 2007a, "U Market: ERI expects Drop in Price," Platt's Nuclear Fuel, page 20, July 2, 2007.
- Platts, 2007b, "New LWR fuel might double burnup, cut waste in half, Westinghouse says," Platt's Nuclear Fuel, June 4, 2007.
- Platts, 2007c, "TVEL lands first UK fuel contract," Platt's Nuclear Fuel, page 19, June 18, 2007.
- Platts, 2007d, "AREVA launches Comurhex II project, studies new REPU facility," Platt's Nuclear Fuel, pp. 1, 6, 7, and 8, June 4, 2007.
- Rothwell, G. and C. Braun, 2007, "Cost and Market Structures in International Nuclear Fuel Cycles," presentation at ANS Annual Meeting, June 25-28, 2007, Boston, Massachusetts.
- Rothwell, G. 2007, "The Cost Structure and Ownership Implications of the International Light Water Fuel Fabrication Industry," Stanford Institute for Economic Policy Research, June 2007.
- Rothwell, G. 2010, "International light water nuclear fuel fabrication supply: Are fabrication services assured?" *Energy Economics* Volume 32, Issue 3, May 2010, pgs 538-544
- Siebert, Hans-Uwe, 2006, "AREVA Secures Fuel Assembly Manufacturing of the Future," Conference paper from "Building the Nuclear Future: Challenges and Opportunities," 2006.
- Spencer, B. B., et al., 2005, *Spent Fuel Treatment Engineered Product Storage: Preferred Concepts for Uranium Disposition*, ORNL/TM-2005/20, July 2005, Applied Technology & Official Use Only. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- Tolley, G. S. and D. W. Jones, codirectors, 2004, *The Economic future of Nuclear Power: A Study Conducted at the University of Chicago*, August 2004, [http://www.osti.gov/bridge/product.biblio.jsp?osti\\_id=840374](http://www.osti.gov/bridge/product.biblio.jsp?osti_id=840374), Web page accessed August 25, 2009.
- Tousley, D., U.S. Highly Enriched Uranium (HEU) Disposition-Overview, Presentation to NEI Nuclear Fuel Supply Forum, January 26, 2005.

- USEC, 2007, “MIT Promises More Efficient Nuke Plants,” News item on Yahoo Finance Message Board for USEC Inc. (symbol USU), April 24, 2007.
- U.S. Geological Survey; Mineral Commodity Summaries, “Zirconium and Hafnium”; Jan 2012; pages 190-191; (<http://minerals.usgs.gov/minerals/pubs/mcs/2012/mcs2012.pdf>)
- UxC Consulting 2011, UxC Consulting, *Fabrication Market Outlook*: Table of Contents only; July 2011; Roswell, GA; (<http://www.uxc.com/products/FMO%202011-07%20TOC.pdf>)
- UxC Consulting; Nuclear Grade Zirconium Alloy Market Outlook (description of publication); 2011; ([www.uxc.com/products/rpt\\_zirc.aspx](http://www.uxc.com/products/rpt_zirc.aspx))
- Varley, G. and D. Collier, 1999, *Fuel Cycle Cost Data*, Atlanta: NAC Worldwide Consulting, October 1999. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- Varley, G., 2002, “Perspectives on Consolidation in the Nuclear Industry,” *Nuclear Energy*, Vol. 41, No 4, August 2002, pp. 259–264.
- World Information Service on Energy (WISE); Nuclear Fuel Cost Calculator: Default Cost Parameters; Nov 2009; Amsterdam, Netherlands; ([www.wise-uranium.org/nfcc.html](http://www.wise-uranium.org/nfcc.html)) [Note: WISE is an anti-nuclear NGO most active in Europe]
- World Nuclear News 2017, “Westinghouse launches its EnCore Fuel”, World Nuclear News website, June 15, 2017

## MODULE D1-2 LWR MOX FUEL

- Augusta Chronicle*; Senate follows House with more questions about construction of Savannah River Site’s MOX Plant; April 30, 2012 (<http://chronicle.augusta.com/latest-news/2012-04-30/senate-follows-house-more-mox-cost-questions>)
- Bunn, M., et al., 2003, op cit in Module D1-1 references.
- Delene, J. G., et al. 2000, op cit in Module D1-1 references.
- EPRI 2009, Electric Power Research Institute ; *Nuclear Fuel Cycle Cost Comparison Between Once-through and Plutonium Single-Recycling in Pressurized Water Reactors*; EPRI Doc # 1018575; Feb 2009 (<http://brc.gov/sites/default/files/documents/1018575.pdf>)
- Massachusetts Institute of Technology (MIT); The Future of the Nuclear Fuel Cycle (full report); 2011; ([http://web.mit.edu/mitei/research/studies/documents/nuclear-fuel-cycle/The\\_Nuclear\\_Fuel\\_Cycle-all.pdf](http://web.mit.edu/mitei/research/studies/documents/nuclear-fuel-cycle/The_Nuclear_Fuel_Cycle-all.pdf))
- MIT, 2003, “The Future of Nuclear Energy” (Appendix 5: Economics), 2005.
- MIT, 2009, Economics of the Fuel Cycle, DeRoo, G and Parsons, J., MIT Center for Energy and Environmental Policy Research, Viewgraph Presentation, May 1, 2009.
- National Academy of Sciences, 1995, *Management and Disposition of Plutonium: Reactor-related Options*, National Academy of Sciences, Washington, D.C., National Academy Press, 1995.
- Nature News and Comment; *Why has Britain done a U-turn on Plutonium?* ; December 5, 2011 ([www.nature.com/news/why-has-britain-done-a-u-turn-on-plutonium-1.9546](http://www.nature.com/news/why-has-britain-done-a-u-turn-on-plutonium-1.9546))
- NTI, 2007, “U.S. Energy Department to Move Forward on MOX,” NTI Global Security Newswire, Nuclear Threat Initiative, April 16, 2007, [www.nti.org](http://www.nti.org), Web page accessed September 3, 2009.
- Nuclear Energy Agency (NEA), 2001, *Trends in the Nuclear Fuel Cycle; Economic, Environmental, and Social Aspects*, Paris, 2001.

- OECD NEA, 1994, op cit in Module D1-1 references.
- ORNL, 1996, *FMDP Reactor Alternative Summary Report: Vol 1—Existing Reactor-related Alternative*, Oak Ridge National Laboratory, ORNL/TM-13275/VL, October 7, 1996.
- Platts, 2007e, “The UK’s Sellafield Mixed-oxide Plant, or SMP, Will Only Ever Achieve a third of Its Design Output of 120 MTHM/yr...,” Platt’s Nuclear News Flashes, March 3, 2007.
- Platts, 2007f, “Russia, U.S., Could Take Decisive Step in Plutonium Disposition Program,” Platt’s Nuclear Fuel, pp. 1 and 5, May 21, 2007.
- Red Impact, 2006, Final Report on the Economic, Environmental, and Societal Impact on Agreed Fuel Cycle Strategies, Red Impact: Impact of Partitioning, Transmutation, and Waste Disposal Technologies on the Final Nuclear waste Disposal, Deliverable D5.4, Nexia Solutions. (Not publically available)
- Stoll, W., 2002, *Lessons Learned at the Karlsruhe and Hanau Plants for Future MOX Technology Developments*, IIU, Inc., Germany (prepared for ORNL), IIU/MD-001, December 2002.
- Suzuki, Tatsujiro; Japan Atomic Energy Commission (JAEC); *Current and Future Prospects of Japan’s Nuclear Fuel Cycle Policies: Issues and Challenges*; presentation at Royal Society Proliferation Resistance Workshop; June 10-11, 2010 ([www.aec.go.jp/jicst/NC/about/kettei/100610.pdf](http://www.aec.go.jp/jicst/NC/about/kettei/100610.pdf))
- U.S. DOE 1997, “Record of Decision for the Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement”, January 14, 1997 (Federal Register, January 21, 1997)
- U.S. Department of State 2000, Plutonium Management and Disposition Agreement, signed September 1, 2000.
- Williams, K. A., 1999, *Life Cycle Costs for the Domestic Reactor-based Plutonium Disposition Option*, ORNL/TM-1999-257, Oak Ridge National Laboratory, October 1999.
- World Information Service on Energy (WISE); Nuclear Fuel Cost Calculator: Default Cost Parameters; Nov 2009; Amsterdam, Netherlands; ([www.wise-uranium.org/nfcc.html](http://www.wise-uranium.org/nfcc.html)) [Note: WISE is an anti-nuclear NGO most active in Europe]
- World Nuclear News; *Sellafield MOX plant to close*; August 3, 2011 ([www.world-nuclear-news.org/WR\\_Sellafield\\_MOX\\_plant\\_to\\_close\\_0308111.html](http://www.world-nuclear-news.org/WR_Sellafield_MOX_plant_to_close_0308111.html))

## **MODULE D1-3 HIGH TEMPERATURE REACTOR FUEL**

- Centrus 2017, “*X-energy and Centrus Energy to Develop Fuel for Advanced Nuclear Reactors*”, Press release, September 6, 2017.
- DOE, 1993, Gas-Cooled Reactor Associates and GA, *Modular High Temperature Gas-cooled Reactor Commercialization and Generation Cost Estimates*, DOE-HTGR-90365, November 1993. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- DOE/NP-24 and ORNL Cost Evaluation Technical Support Group, 1991, *New Production Reactors Program: Life Cycle Cost Report*, Rev 2, October 1991 unpublished.
- Forsberg, C. W. (ORNL), 2006, “Advanced High-Temperature Reactor Spent-fuel Characteristics and Repository Impacts,” Paper prepared for the 2006 International High-Level Waste Management Conference (ANS), Las Vegas, Nevada, April 30–May 4, 2006.
- Fuls, W. F. et al., 2004, “The Interim Fuel Storage Facility of the PBMR,” Paper from the 2<sup>nd</sup> International Topical Meeting on High Temperature Reactor Technology, Beijing, China, September 22–24, 2004.

- G4-ECONS, 2008, "G4-ECONS Software and Cost Estimating Guidelines for Economic Analysis of Generation IV Nuclear Energy Systems: Software Description and a PBMR Example Case," K. A. Williams, Oak Ridge National Laboratory, IAEA Technical Meeting on HTGR Economic Analysis, October 2, 2008, Washington DC.
- GA Technologies, 1994, *GT-MHR Plutonium Consumption Study: Phase 2 Final Report*, GA/DOE-051-94, GA Technologies Corporation, San Diego, California, 1994. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)
- GIF-004-00, 2002, Generation IV Roadmap, *R&D Scope Report for Gas-Cooled Reactor Systems*, December 2002.
- Goodin, D., et al., 2002, *Reducing the Costs of Targets for Inertial Fusion Energy*, GA-A23833, General Atomics Corp, April 2002.
- Holcomb, D.E.; Workshop Summary Report from First DOE-NE Fluoride Salt-Cooled High-Temperature Reactor Workshop; Sept 20-21, 2010; Oak Ridge National Laboratory; (page 5)  
[www.ornl.gov/fhr/documents/FHR\\_Workshop\\_Summary.pdf](http://www.ornl.gov/fhr/documents/FHR_Workshop_Summary.pdf)
- INL 2012, Technical Evaluation Study: Project No. 23843; Assessment of HTGR Capital and Operating Costs; Doc ID TEV-1196 Rev 1; Idaho National Laboratory; Jan 9, 2012  
([https://inlportal.inl.gov/assessment\\_of\\_high\\_temperature\\_gas-cool.](https://inlportal.inl.gov/assessment_of_high_temperature_gas-cool/))
- International Atomic Energy Agency (IAEA), 2001, *Current Status and Future Development of Modular High Temperature Gas-Cooled Reactor Technology*, IAEA-TECDOC-1198, February 2001,  
[http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/gcr\\_review\\_00.pdf](http://www.iaea.org/inisnkm/nkm/aws/htgr/fulltext/gcr_review_00.pdf), Web page accessed August 25, 2009.
- Miller, R.L.; Chapter 3 Economics and Costing (Fig 3.2-1); Web Report on ARIES Fusion Reactor:  
<http://aries.ucsd.edu/LIB/REPORT/STARLITE/FINAL/chap3.pdf>
- Nuclear Engineering International, 2005, "PBMR Awards Fuel Contract," *Nuclear Engineering International*, E-mail Report, (Nuclear Engineering International is a British Journal), May 13, 2005.
- Nuclear Fuel Industries 2012, Tokai Works Overview, [www.nfi.co.jp/e/company/tokai.html](http://www.nfi.co.jp/e/company/tokai.html)
- Olsen, A.R; Judkins, R.R; Carter, W.L.; Delene, J.G.; *Fuel Cycle Cost Studies – Fabrication, Reprocessing, and Refabrication of LWR, SSCR, HWR, LMFBR, and HTGR Fuels*; Oak Ridge National Laboratory; March 1979; ORNL/TM-6522;  
[www.ornl.gov/info/reports/1979/3445605115586.pdf](http://www.ornl.gov/info/reports/1979/3445605115586.pdf)
- Owen, Paul E., 1999, *Waste Characteristics of Spent Nuclear Fuel from a Pebble Bed Reactor*, MS Thesis in Nuclear Engineering, Massachusetts Institute of Technology, June 1999.
- Platts, 2005, "PBMR Ltd. Hires Unit of Germany's Thyssenkrupp for Fuel Plant Work," *Platt's Nuclear Fuel*, May 9, 2005.
- PJM Inc.; Letter to Cost Development Subcommittee; Escalation Indices; Web posting:  
<https://pjm.com/~media/committees-groups/subcommittees/cds/postings/201005>
- UC/OSU, 1998, "The Modular Pebble Bed Reactor Concept," a presentation of the 22.33/.033 Design Course for the University of Cincinnati/Ohio State University, September 29, 1998 (viewgraph presentation with 58 slides including an economic analysis).
- World Nuclear Organization; *China's Nuclear Fuel Cycle*; Updated April 2012; Website: [www.world-nuclear.org/info/inf63b\\_china\\_nuclearfuelcycle.html](http://www.world-nuclear.org/info/inf63b_china_nuclearfuelcycle.html)

## MODULE D1-4 CERAMIC PELLETIZED SODIUM-COOLED FAST REACTOR FUEL

- Bunn, M., et al., 2003, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Cambridge, Massachusetts, Project on Managing the Atom, Harvard University, DE, [http://belfercenter.ksg.harvard.edu/publication/2089/economics\\_of\\_reprocessing\\_vs\\_direct\\_disposal\\_of\\_spent\\_nuclear\\_fuel.html](http://belfercenter.ksg.harvard.edu/publication/2089/economics_of_reprocessing_vs_direct_disposal_of_spent_nuclear_fuel.html)
- CEA 1985, 17887555, *Fast Breeder Reactors*, (PDF)
- Delene 2000, *An Assessment of the Economics of Future Electric Power Generation Options and the Implications for Fusion, Revision 1*, ORNL/TM-1999-243/R1, September 1999
- EPRI 2010, Electric Power Research Institute (EPRI): Nuclear Fuel Cycle Cost Comparison Between Once-through and Plutonium Multi-Recycling in Fast Reactors; March 2010 (<http://brc.gov/sites/default/files/documents/1018575.pdf>)
- G4-EMWG, 2005, “Economic Data of the JNC Sodium Cooled Fast Reactor (JSFR) System Design,” *The 9th Meeting of the Generation IV Economic Model Working Group*, February 2005.
- G4-EMWG, 2006, “Sample Calculation of G4-ECONS Code on the JAEA JSFR System,” paper presented at the 14th Meeting of the Generation IV Economic Modeling Working Group, Tokyo, May 17–18, 2006.
- MIT, 2009, “Economics of the Fuel Cycle,” DeRoo, G and Parsons, J., MIT Center for Energy and Environmental Policy Research, Viewgraph Presentation, May 1, 2009.
- Nature News and Comment 2011, “Why has Britain done a U-turn on plutonium?” December 5, 2011
- Nuclear Energy Cost Database (NECDB) 1988, Delene et al., DOE/NE-0095, September 1988
- Nuclear Energy Agency (OECD/NEA), 2006, *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, OECD-Paris, 2006.
- OECD NEA, 1994, *Economics of the Nuclear Fuel Cycle*, 1994.
- Olsen 1979, op cit in Module D1-2 references. (ORNL/TM-6522)
- Red Impact, 2006, “Final Report on the Economic, Environmental, and Societal Impact on Agreed Fuel Cycle Strategies, Red Impact: Impact of Partitioning, Transmutation, and Waste Disposal Technologies on the Final Nuclear Waste Disposal,” Deliverable D5.4, Nexia Solutions, (Not publically available).
- SME Times (Tradeindia.com); Work on first fast-breeder fuel cycle facility next year; Sept 5, 2010; ([www.smetimes.in/smetimes/news/indian-economy-news/2010/Sep/06/work-on-first-fast-breeder-fuel-cycle-facility-next-year21072.html](http://www.smetimes.in/smetimes/news/indian-economy-news/2010/Sep/06/work-on-first-fast-breeder-fuel-cycle-facility-next-year21072.html))
- U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 2002, *A Technology Roadmap for Generation IV Nuclear Energy Systems*, GIF-002-00, December 2002.
- WNO 2012, World Nuclear Organization; Nuclear Power in Japan; Updated July 2012 ([www.world-nuclear.org/info/inf79.html](http://www.world-nuclear.org/info/inf79.html))

## MODULE D1-5 CERAMIC VIBROCOMPACTED FAST REACTOR FUEL

- JAEA, 2006, *Phase II Final Report of Feasibility Study on Commercialized Fast Reactor Cycle Systems—Executive Summary*, Japan Atomic Energy Agency, March 2006. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)

Kazimi, M., 2002, “High Performance Fuel Design for Next-Generation PWRs (Annular Fuel Project),” Massachusetts Institute of Technology, NERI Project 01-005, NERI Annual Report: 2002.

Mayorshin, A., V. Skiba, et al., 2000, “Practical Experience in Using MOX Fuel at Atomic Electric Power Station,” Scientific Research Institute of Atomic Reactors, Dimitrovgrad, Russia, *Proceedings of the 4th International Radioecological Conference “Utilization of Plutonium: Problems and Solutions,”* Krasnoyarsk, Russia, June 5–10, 2000.

OECD NEA, 2006, op cit in Module D1-4 references.

State Scientific Center of Russian Federation—IPPE, 1998, “Assessment of the Cost and Feasibility of Converting and Operating the BN-600 Hybrid Core Using Vibro-Technology Fuel for Plutonium Disposition,” State Scientific Center of Russian Federation—Institute of Physics and Power Engineering (IPPE), Obninsk, Russia, 1998.

Wade, D., 2005, “Generation IV Concept Summary: STAR-H2: The Secure Transportable Autonomous Reactor for Hydrogen (Electricity and Potable Water) Production,” NERI Project No 2000-0060, Argonne National Laboratory, <http://www.hydrogen.anl.gov/pdfs/STAR-H2summary.pdf>, Web page accessed December 20, 2005.

## **MODULE D1-6 METALLIC OR ALLOYED FAST REACTOR FUEL**

Lightbridge 2009, Lightbridge Fuel Technology, website: <https://ltbridge.com/fuel-technology/>

Lightbridge 2012, Malone, J. P., All-Metal fuel: Why, How, When?, Lightbridge Corp (formerly Thorium Power); presentation to World Nuclear Fuel Cycle 2011, Chicago, IL.

Lightbridge 2016, “Lightbridge says U.S. signs test assembly agreement”, Platts Nuclear News Flashes, November 9, 2016

Malone, J. et al., “Lightbridge Corporations, Advance metallic Fuel for Light Water Reactors”, Nuclear Technology, Vol. 180, December 2012, pp. 437-442

Westinghouse, 2004, “Westinghouse Nuclear Fuel Information Sheet,” [http://www.westinghousenuclear.com/Products\\_&\\_Services/docs/flysheets/NF-FE-0010.pdf](http://www.westinghousenuclear.com/Products_&_Services/docs/flysheets/NF-FE-0010.pdf), Web page accessed August 25, 2009.

## **MODULE D1-7 CANDU FUEL**

AECL, 2005, “Design data submissions to the U.S. NRC for certification of the ACR-700 Pressurized Heavy-Water Moderated Reactor, Atomic Energy Limited of Canada (AECL),” (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)

Chen, Mingjun; Demonstration and Implementation in China on use of Reprocessed Uranium in CANDU Reactor; 12<sup>th</sup> meeting of the Technical Working Group on Advanced Technologies for HWRs (TWG-HWR); July 26-28, 2011; IAEA HQ Vienna, Austria ([www.iaea.org/NuclearPower/Downloads/Technology/meetings/2011-Jul-26-28-TWG-LWR-HWR/Session-V/RU-reuse-in-China-CANDU-\(Chen-MJ\).pdf](http://www.iaea.org/NuclearPower/Downloads/Technology/meetings/2011-Jul-26-28-TWG-LWR-HWR/Session-V/RU-reuse-in-China-CANDU-(Chen-MJ).pdf))

Choi, H., W. Ko, and M. S. Yang, 2001, “Economic Analysis on Direct Use of Spent Pressurized Water Reactor Fuel in CANDU Reactors—1: DUPIC Fuel Fabrication Cost,” *Nuclear Technology (ANS)*, Vol. 134, May 2001.

Del Cul, G.D.; Trowbridge, L.D.; Renier, J.P.; Ellis, R.J.; Williams, K.A.; Spencer, B.B.; and Collins, E.D.; Analysis of the Reuse of Uranium Recovered from the Reprocessing of Commercial LWR Spent Fuel; ORNL/TM-2007/207; January 2009 ([info.ornl.gov/sites/publications/files/Pub14204.pdf](http://info.ornl.gov/sites/publications/files/Pub14204.pdf))

Ellis, R.J.; Prospects of Using Reprocessed Uranium in CANDU Reactors in the U.S. GNEP Program; Oak Ridge National Laboratory; Nov 2007; Summary prepared for ANS National Meeting ([www.ornl.gov/sci/scale/Idoc7152\\_ans\\_national\\_summary\\_nov2007\\_rje.pdf](http://www.ornl.gov/sci/scale/Idoc7152_ans_national_summary_nov2007_rje.pdf))

EPRI 2010, Electric Power Research Institute (EPRI): Nuclear Fuel Cycle Cost Comparison Between Once-through and Plutonium Multi-Recycling in Fast Reactors; March 2010 (<http://brc.gov/sites/default/files/documents/1018575.pdf>)

OECD NEA, 2006, op cit in Module D1-4 references.

Olsen, A.R; Judkins, R.R; Carter, W.L.; Delene, J.G.; *Fuel Cycle Cost Studies – Fabrication, Reprocessing, and Refabrication of LWR, SSCR, HWR, LMFBR, and HTGR Fuels*; Oak Ridge National Laboratory; March 1979; ORNL/TM-6522; [www.ornl.gov/info/reports/1979/3445605115586.pdf](http://www.ornl.gov/info/reports/1979/3445605115586.pdf)

## MODULE D1-8 THORIUM-BASED FUELS

Filippov, Y.A., 2007, “Plan for Plutonium-free Nuclear Electric Power Generation,” [www.proatom.ru](http://www.proatom.ru), Web page accessed June 13, 2007.

Greneche, Dominique, 2006, “The Thorium Cycle: an Assessment of its Potentialities with a Focus on Nonproliferation Aspects, AREVA Inc, presentation from ANS Winter Meeting, Albuquerque, New Mexico, Nov 14, 2006.

IAEA, 2005, Thorium Fuel Cycle—Potential Benefits and Challenges, IAEA-TECDOC-1450, May 2005, [http://www-pub.iaea.org/MTCD/publications/PDF/TE\\_1450\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/TE_1450_web.pdf) , Web page accessed August 25, 2009.

India’s Atomic Energy Agency, 2006, “Nuclear Power Programme – Stage 3 (Thorium Utilization),” Annual Report from India’s Atomic Energy Agency, 2006.

Kazimi, M.S., 2003, “Thorium Fuel for Nuclear Energy: An Unconventional Tactic Might One Day Ease Concerns That Spent Fuel Could be Used to Make a Bomb,” *American Scientist*, Vol. 91, No. 5, September–October 2003.

Lahoda 2004, op cit in Module D1-1 references.

Lifton, Jack, 2007, “Thorium: An Alternative to Uranium,” 2007 Update, [www.resourceinvestor.com](http://www.resourceinvestor.com), Web page accessed, February 22, 2007.

Norway Thorium Report Committee, “Thorium as an Energy Source – Opportunities for Norway,” January 2008.

Olsen, A.R; Judkins, R.R; Carter, W.L.; Delene, J.G.; *Fuel Cycle Cost Studies – Fabrication, Reprocessing, and Refabrication of LWR, SSCR, HWR, LMFBR, and HTGR Fuels*; Oak Ridge National Laboratory; March 1979; ORNL/TM-6522; [www.ornl.gov/info/reports/1979/3445605115586.pdf](http://www.ornl.gov/info/reports/1979/3445605115586.pdf)

ORNL 2005, Cowell, B., S. Fisher, K. A. Williams, et al., 2005, *Assessment of the Radkowsky Thorium-Plutonium Incinerator Concept for Plutonium Disposition*, ORNL/TM-2005/120, Oak Ridge National Laboratory, May 2005, Official Use Only. (This document has a restricted distribution, may be proprietary, or both; and is not publicly releasable.)

Pickard, P and Forsberg, C., “Molten Salt Reactors (MSRs),” Presentation for 2002 ANS Winter Meeting, Washington DC, November 18, 2002.

Platts Nuclear Fuel, “China Mulling Thorium Fuel Center for Baotou Site in Inner Mongolia, January 26, 2009.

Reuters, 2007, “Norwegian firm proposes thorium nuclear plant,” Reuters New Service, [www.reuters.com](http://www.reuters.com), Web page accessed March 30, 2007.

Sease, J.D.; Pratt, R.B.; and Lotts, A.L.; Remote Fabrication of Thorium Fuels; ORNL-TM-1501; April 1966 ([www.ornl.gov/info/reports/1966/3445605491143.pdf](http://www.ornl.gov/info/reports/1966/3445605491143.pdf))

Washington Post, 2009, “If Nuclear Power Has a More Promising Future...Seth Grae Wants to be the One Leading the Charge,” August 2, 2009.

## **MODULE D1-9 INERT MATRIX AND OTHER ADVANCED FUELS**

INL 2010, Economic Analysis: Deep Burn TRISO-actinide Fuel in SPC Inert Matrix in Zircaloy Clad for Deep Burn LWRs, unpublished paper, July 22, 2010, Idaho National Laboratory

LANL, 2002, “Status of research and development after the IMF8 Workshop,” <http://arq.lanl.gov/source/orgs/nmt/nmtdo/AQarchive/03springsummer/deguelder.html>, Web page accessed August 25, 2009.

NERAC 2011, Minutes of the Nuclear Energy Advisory Committee (NERAC) Meeting, December 13, 2011; ([www.ne.doe.gov/ncac/Meetings/Dec132011/Minutes%20final%20\\_121311\\_.pdf](http://www.ne.doe.gov/ncac/Meetings/Dec132011/Minutes%20final%20_121311_.pdf))

Tulenko, James, 2009, “Inert Matrix Fuel for Plutonium and Actinide Disposition,” Workshop viewgraph presentation, University of Texas, Austin, Texas, August 3, 2009.



**Module Series D2**

**Fabrication of Remote-handled Fuels**



# Module Series D2

## Fabrication of Remote-handled Fuels

### D2. PREFACE AND INTRODUCTION

Remote handled fuel fabrication technologies are generally those in which the new fuel charged to the reactor is composed in part of fissile products arising from the reprocessing of some type of nuclear fuel and containing radionuclides with high radiation fields. The term “re-fabrication” can be applied in many cases. The facilities required for remote handling consist of one or more hot cells which contain manipulators and/or robotics and shield the workers from intense gamma or spontaneous neutron radiation emanating from the fuel heavy metal being processed. The hot cell portion of such facilities generally costs in the range of \$10,000 to \$30,000 per square foot including process equipment. For the purpose of minimizing criticality, transportation, and security hazards, such operations and their economics can benefit being closely integrated with the reactor and the spent fuel reprocessing facility. The ANL/GE-Hitachi Integral Fast Reactor (PRISM/IFR) is one such concept.

This and other fuel cycle concepts are being considered for destruction of actinides and even long-lived fission products. Some of these concepts involve separate targets that include highly radioactive plutonium, neptunium, and curium radionuclides (or even fission products) that would have to be fabricated in a remote facility. (The driver fuel in this case might not require remote handling and could be fabricated elsewhere.) The following concepts are considered in this module:

- D2-1 Metallic Fast reactor refabricated fuel – This U, Pu, Zr alloy fuel is cast from fresh make-up uranium along with the higher actinides (mostly Pu) separated in an electrochemical (pyroprocessing) type integral reprocessing facility. Both reprocessing and refabrication are part of the same process line. This concept is amenable to fast reactor fuel cycles where the fast reactor fuel is continuously recycled and only fission products are separated and packaged for geologic disposal. This refabrication technology can also be used to in conjunction with an electrochemical reprocessing plant that recycles LWR spent fuel. This technology has been demonstrated on a pilot scale at Idaho National Laboratory. **Module D2-1 is combined with Module F2, since electrochemical reprocessing and metal fuel refabrication are part of an integrated recycle process, for which cost information is generally not separated.**
- D2-2 Other refabricated fuels –MOX fuels (or targets) and recycled TRISO fuels with higher actinides and/or U-233 would require remote fabrication. It is likely the refabrication process would take place in the same shielded reprocessing facility that handles the spent fuel. Recycle, including refabrication, of LWR MOX, FR MOX, and TRISO type fuels has not been demonstrated on even a pilot scale. No recent cost information is available on any of these processes. At present, module D2-2 contains a discussion of a concept that would utilize spent PWR fuel in CANDU reactors.



## **Module D2-1**

### **Metallic Fast Reactor Fuel Re-fabrication**

**(See Module F2)**



**Module D2-2**  
**Other Re-fabricated Fuels**



## D2-2.1 SPECIAL TOPIC: DUPIC: THE DIRECT USE OF SPENT PWR FUEL IN CANDU REACTORS

*Note: This material was formerly included in the section on fabrication of CANDU Fuel (Module D1-7. Because some fission products would remain in the refabricated DUPIC fuel, remote fabrication processes would be required. Hence, this material was moved to section D2.*

*No Sections D2-2.1.MD or D2-2.1.RH are included, since no costs are presented.*

After irradiation, PWR fuel still has a high enough fissile content that it could be further irradiated in CANDU reactors. The problem is that the fuel forms are different. South Korea has both PWRs and CANDUs and has been part of a cooperative program with the U.S. and Canada to see if irradiated PWR fuel could be declad, crushed, volatiles removed, reoxidized, and remade into CANDU pellets without separation of the nonvolatile transuranic or fission-product components. Doing so would solve the PWR spent fuel problem for Korea and allow use of a tandem PWR/CANDU fuel cycle. Figure D2-2-1 shows the benefits and challenges of this scheme as envisioned by the Korean Atomic Energy Research Institute (KAERI).

This type of fuel would have to be remotely handled all the way through its production process (see Figure D2-2-2) and through its insertion in the CANDU reactor. With continuous fuel loading machines, however, such shielded and automated loading may be feasible. Choi, et al. (Choi 2001) of KAERI have performed a conceptual design and cost study for a CANDU DUPIC fuel plant capable of manufacturing 400 MT/yr of fuel. For a 40-year plant and a 5% discount rate, the unit cost of CANDU DUPIC fuel production is calculated to be \$616/kgHM. Although much higher than for UO<sub>2</sub> CANDU fuel, this cost is counteracted by the much lower back-end fuel cycle costs for the PWRs. There are also greatly reduced uranium costs for the CANDU reactors.

Using relatively pure uranium oxide recovered from LWR reprocessing is also an option. Such REPU could have 0.7 to 1.2 % U-235 and could be obtained from future U.S. reprocessing operations. Use of this material would avoid expenditure for the purchase of new uranium ore. Basically the costs involved would be conversion of the reprocessing product (UNH or an oxide) into a sinterable UO<sub>2</sub> powder grade and fabrication into pellets and assemblies. Initial indications for high natural uranium prices (~\$100/lb U<sub>3</sub>O<sub>8</sub>) are that the upfront cost for the CANDU open cycle could be cut in half (Del Cul et al. 2009).

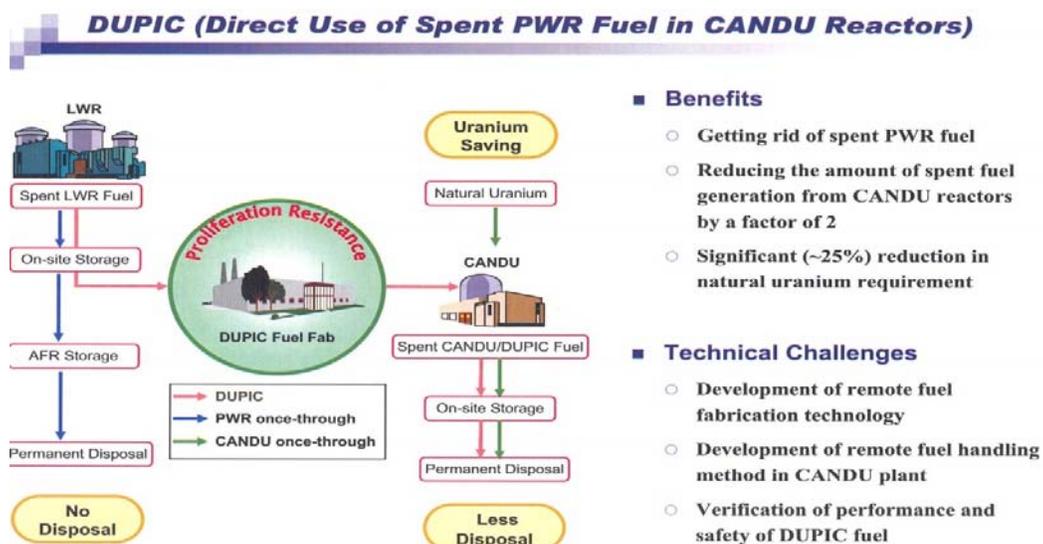


Figure D2-2-1. Benefits and challenges of turning PWR fuel into CANDU fuel (Yang et al., 2006).

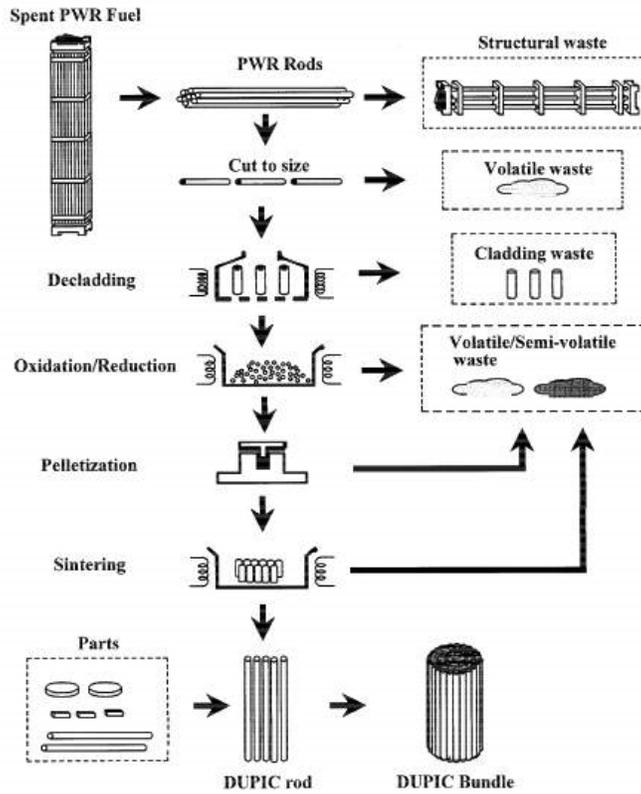


Figure D2-2-2. Process steps for DUPIC CANDU fuel fabrication (Choi, 2001).

## MODULE D2 REFERENCES

### MODULE SERIES D2-2.1

Choi 2001, op cit in Module D1-7 references.

Del Cul, et al. 2009, op cit in Module D1-7 references.

Yang, M.S., H. Choi, C. J. Jeong, K. C. Song, et al., 2006, “The Status and Prospect of DUPIC Fuel Technology,” *Nuclear Engineering and Technology* 38(4).

