Module D-PR Fuel Fabrication Preface to the D-Modules

Fuel Cycle Technology

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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
			Much of the material in this first document of the FY 2021 AFC-CBR Module D (Fuel Fabrication) Update appeared as *Preface to D-Modules* in Module D of the 2017 AFC-CBR (Dixon et al. 2017) public-release document. Also appearing in this 2021 document is some of the material from *Module Series D1: Fabrication of Contact-handled Fuels: Preface And Introduction* from the same 2017 public version (Dixon et al. 2017).
	2021	All	Recognizing the growing interest in HALEU (high-assay, low-enriched uranium) fuels and ATFs (accident-tolerant fuels) Changing the names of some D1 and D2 submodules to better recognize the nuclear material content of the fuels and the type of reactor system in which they might be utilized. Updating the current status of the remaining submodules D1-2 through D1-6, D1-8 through D1-9, and modules D2-1 through D2-2 for which 2021 updated reports have not yet been completed and issued. Modules D1-1 (*Uranium-based Pelletized Ceramic LWR Fuels*) and D1-7 (*Uranium-based Pelletized Ceramic PHWR Fuels*) are also both briefly discussed in part 1 (MODULE D-PR) of this three-module document, but in considerably more detail in parts 2 and 3 (full D1-1 and D1-7 submodules). These last two uranium-based water reactor fuel types, LWR (D1-1) and PHWR (D-7), were lumped together in this three-part document since their basic performance requirements and manufacturing processes are similar, and together they constitute over 95% of the nuclear fuel manufactured worldwide. Recognizing regulatory requirements for manufacturing facility robustness are driven by the nature and amounts of the nuclear material handled. In the United States, the Nuclear Regulatory Commission designates three classes of facilities as Categories I–III, with the lower numbered category facilities having more stringent security and safety requirements (and likely higher associated life cycle costs). Appendix B of this Module D-PR provides these definitions. Since issuance of the 2017 AFC-CBR (Dixon et al 2017), some very comprehensive, government-funded comparative fuel fabrication life cycle cost studies from the 1960s through the 1970s have been located. These reports are being used to better define the what-it-takes (WIT) unit cost ranges for many of the D-Modules. Those modules benefitting from these data are noted in this report. Most of the useful reports were from the Non-Proliferation Assessment Systems Analysis Program (NASAP) of the late 1970s. Escalation/inflation factors and new economic spreadsheet models have been used to convert the NASAP results to today's dollars.

			These reports also dealt with the costs of re-fabricating many fuel types after aqueous reprocessing of the initial fabricated fuel. More information on and referencing of the NASAP reports appears as Appendix A to this document. In the 2017 AFC-CBR (Dixon et al 2017) Module D1 Preface, a unit cost WIT summary table appeared for all the D-1 submodules. This table is not included here, since many of the D1-2 through D1-9 Modules are (1) still in preparation, (2) have not yet started revision, or (3) are slated for elimination or reassignment to another type of fuel. Future publicly released module updates will include for each module the new WIT unit cost data that have been developed by SA&I staff.

ACKNOWLEDGEMENT

This latest version of the *Module D-PR: Fuel Fabrication Preface to the D-Modules* is the cumulative effort of many authors who have contributed to the *Advanced Fuel Cycle Cost Basis Report*).All the authors, including the four primary authors, 15 contributing authors, 12 contributors acknowledged, and the many other unacknowledged contributors from the 2017 report, have contributed various amounts to developing and writing this module prior to this current revision. Unfortunately, there is no history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

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

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FIGURES

ACRONYMS

$/kgHM	dollars per kilogram of heavy metal
$/kgiHM	dollars per kilogram of initial heavy metal
AFC-CBR	Advanced Fuels Campaign-Cost Basis Report
ATF	accident-tolerant fuels
BWXT	BWX Technologies, Inc.
CANDU	Canadian deuterium-uranium
CH	contact handled
ERDA	Energy Research and Development Administration
GCR	gas-cooled reactors
HA	higher actinides
HALEU	high-assay, low-enriched uranium
HM	heavy metal
HTGR	high-temperature gas-cooled reactor
HTR	high-temperature reactor
IAEA	International Atomic Energy Agency
IFR	integral fast recycle
INL	Idaho National Laboratory
LEU	low-enriched uranium
LWR	light-water reactor
MOX	mixed-oxide
MTHM	metric tons of heavy metal
NASAP	Non-Proliferation Alternatives Systems Analysis Program
NATU	Natural uranium
NOAK	Nth-of-a-kind
USNRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PHWR	pressurized-heavy-water reactors
Pu	plutonium
PUREX	Plutonium-Uranium Extraction
PWR	pressurized-water reactors
R&D	research and development
RH	remote handling
SA&I	Systems Analysis and Integration

SFR	sodium-cooled fast reactor
SNF	spent nuclear fuel
Th	thorium
TRISO	tristructural-isotropic
U	uranium
UF6	uranium hexafluoride
UOX	uranium oxide
USAEC	U.S. Atomic Energy Commission
WIT	what-it-takes

MODULE D-PR
FUEL FABRICATION PREFACE TO THE D-MODULES

D-PR-1. INTRODUCTION

Generic Technical Factors Affecting Fuel Fabrication. Many in-reactor physical, chemical, metallurgical, mechanical, thermodynamic, and nucleonic factors influence the design and functionality of nuclear fuel. Detailed discussion of these technical factors is beyond the scope of this cost-oriented preface document; however, the following three references are suggested for a more comprehensive discussion of fuel design requirements for both commercial and special use (military and remote location) reactors: IAEA-TECDOC-1686 (IAEA 2012), the *World Nuclear Association* webpage "Nuclear Fuel and its Fabrication (WNA 2020a), and INL/EXT-20-54641 (Mariani 2020). To aid the reader's understanding of how design affects life cycle costs, a few technical factors are also briefly discussed in the sections below.

As there are many variations in reactor designs for a given type (e.g., pressurized-water reactors [PWRs]), there are even more variations in fuel design which is charged to this reactor type. For example, today's commercial light-water reactors (LWRs) operate on over 20 different fuel designs, but all contain the same basic ceramic chemical form, either UO2 (UOX) or mixed UO2/PuO2 (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 other major nuclear transmutation, such as higher-Z (atomic number) isotope production via neutron absorption, inside the reactor. For unirradiated fuel, this fuel meat is the initial heavy metal (or its ceramic chemical compounds) plus any totally blended alloying or heterogeneous matrix constituents. For irradiated fuels, 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 is generally not included in fuel cycle mass balance and economic calculations. The cost estimating figure-of-merit for front-end fuel fabrication and back-end fuel cycle steps such as spent fuel reprocessing or spent fuel storage is often expressed in dollars per kilogram of initial heavy metal ($/kgiHM). For a particular fuel type, the design variation is mainly in the fissile enrichment of the fuel meat, the geometric configuration of the fuel rods, and the nature of the zirconium metal or other alloy hardware which support them. (Some fuel types, such as a particle fuel like TRISO, might be encased in a refractory non-nuclear material such as graphite or silicon carbide). For an example of fuels in widespread use, each of the major LWR fuel types, vendors, such as GE-Hitachi, AREVA, Westinghouse, TVEL, etc., have their own proprietary fuel designs particular to the class (boiling-water reactor [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 government-owned industries or commercial fabrication vendors for their manufacture. Large scale means capable of servicing a fleet of advanced reactors. Cost information is based on the extrapolation of small scale or pilot plant construction and operations costs. These 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 the U.S. Nuclear Regulatory Commission [USNRC]) before large-scale irradiation can commence. It should be noted for all fuels, the fuel fabrication step is basically a value-added service step, in that the cost incurred is for transforming 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 finished, completely inspected fuel assemblies 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 the conversion

of pre-fabrication source material to the fuel-grade metal or ceramic compound in the fuel meat (e.g., low-enriched UF6 from an enricher [to fuel-grade UO2 powder for LWRs]). For LWR fuel, the mining, milling, U_3O_8 to UF6, and enrichment costs are not part of the fabrication cost and are covered in Modules A, B, and C. The cost of the PuO2 for MOX fuel is generally part of the overall reprocessing cost for the spent fuel from which the Pu is separated. The purchase of non-nuclear fuel assembly components, such as cladding material (e.g., zirconium) or matrix material (e.g., 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 (USD or $) per kilogram of heavy metal ($/kgHM, $/kgU, and $/kgTh), even though the actual fuel is in the form of an oxide, alloy, or other possible ceramic compounds. This convention is adopted because 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. For the what-it-takes (WIT) unit cost values reported in each module, the intent is to develop and provide the unit cost values for Nth-of-a-kind (NOAK) facilities capable of providing fuel to multiple reactors.

From the standpoint of cost, a major discriminator between fuel types is the nature of the fuel fabrication facility, in other words, 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 module, CH fuels will be treated in the D-1 submodules. The CH definition will include facilities, such as (Pu,U)O2 MOX plants, with glovebox operations. In these glovebox-containing facilities, the final sealed fuel rod handling and bundling operations allow hands-on direct CH. In general, fuels that are refabricated from aqueous reprocessing can be at least partially CH, since the high-decontamination factor aqueous process effectively reduces the amounts of carry over fission products and higher actinides (HA) to the nitrate or oxide forms to be refabricated. The D-2 module will include fuels that are RH in highly shielded hot cells. These fuels all refabricated from the products of a dry process such as pyroprocessing involving molten-salt electrochemistry or processes involving gas-solid phase chemical separations. Decontamination factors for these processes are lower, hence more fission products are carried over. For some fuel cycles, HA are purposely refabricated for destruction by fast neutron irradiation in an advanced reactor.

Generally, the fuels that can be CH 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 nuclear 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 CH category only if their purity level or radioisotope content excludes or minimizes those isotopes or elements (such as many fission products, HA, 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. (As noted above, aqueous processing allows high-decontamination factors for removal of some HA, such as neptunium, curium, and americium, fission products (FPs), and decay daughters [such as those associated with U-233 production].) For many proposed proliferation-resistant closed or partially closed fuel cycles, complete separation of fission products and HA is neither required nor desired. The intent is to avoid the separation of pure plutonium (or fissile U-233) and make the separated product for fuel refabrication difficult to divert or steal because of its high associated radiation fields. These refabricated fuel forms will require very robust canyon-type RH facilities which will likely have to be immediately adjacent to the reactors and integral to the reprocessing operations. It is important the reader understand that when products arising from reprocessing of spent fuel are to be fabricated into new fuel, one must know exactly

which other radionuclides (FP and HA) will be carried over with the main recovered driver fuel HM product. As these radionuclides increase in concentration, the fuel will transition from the CH regime to an at least partially RH regime. (This will be true for some of the D-1 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 fabrication equipment similar to that 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 CH. Targets containing significant amounts of HA such curium and higher Pu and Np isotopes for burning/destruction are likely to require RH. This means that for some reactor types using heterogeneous fuel concepts, both RH and CH fabrication facilities will be needed.

The fissile isotope concentrations and overall mass inventory can be a major fuel fabrication facility cost driver, since in most nations, security and physical protection regulations are based on the attractiveness level of the in-process nuclear material. The USNRC recognizes three Security and Safeguards Categories (I, II, and III) in their rulemaking for facility security and material accountability. A Category I or II facility will require a larger security force, a more robust building structure, and many more material accountability procedures than a Category III facility. One would therefore expect a Category I or II facility to have a higher cost per square foot than a Category III facility and to also incur significantly higher annual operations and overhead costs. Appendix B of this module presents the definitions of Categories I–III from the standpoint of in-facility fissile material mass.

Generic Business-related Factors. From a business/commercial perspective, fuel fabrication differs from other steps of the fuel cycle in that its services and products are less fungible. An LWR reactor owner, for example, can contract with multiple possible commercial material or service provider entities for ore, conversion, enrichment, and reprocessing since all of the products therefrom are chemical entities such as U_3O_8, natural UF6, enriched UF6, U-metal, or PuO2 & UO2 from recycling. The product of the fuel fabrication step, finished fuel assemblies, must be matched directly with the reactor core design which will accept them as fresh fuel loadings. Not all fuel fabricators have the machinery that can produce fuel for any reactor design, and until recently, many fuel vendors fabricated fuel assemblies for only for their own company's designs/models. (For example, the Westinghouse Fabrication Facility at Columbia, SC used to only produce LEU fuel for Westinghouse PWRs.) In addition to the chemical and physical form of the fuel meat feed, fuel fabricators must deal with metal hardware, such as tubing, spacers, grids, nozzles, etc., that comprise the balance of the fuel assembly. Other fuel types, such as particle fuel, may require special matrix materials such as graphite or silicon carbide. These items are reactor core design-specific and must be manufactured in-house or purchased from a metal fabricator or specialty powder provider. The supply chain for these critical, non-nuclear specialty materials is an important consideration for managing a fuel fabrication facility.

Nuclear utilities usually order entire initial cores or full reloads, for which the production must be campaigned to fit the fuel fabricator's order book and manufacturing capacity. For utilities, on-time completion of fuel fabrication orders is essential since delays can be very costly in terms of lost electricity revenues if core loading is delayed. The issue of LWR fuel fabrication supply redundancy and possible economic damages due to delays is discussed in a report by Pacific Northwest National Laboratory (Seward 2011).

As mentioned earlier, the merit-of-interest cost figure in the D-modules is the USD ($) per kilogram of heavy metal ($/kgHM) required for the fuel fabrication service. "Heavy metal" here includes the elemental nuclear materials in the fuel meat (e.g., uranium, thorium, plutonium, HA, and any residual fission products). Nuclear materials fabricated in CH facilities are likely to be used for once-through or single-pass LWR MOX fuel cycles or the production of start-up fissile drivers (HEUO2 , high-fissile content MOX, or Pu metal alloy) for a fleet of fast reactors. RH of separated products for refabrication will be required for the spent fuels arising from continuous recycle and re-fabrication of HA-bearing fuel types, especially those involving electrochemical (pyrochemical) recycle or multiple-pass recycle.

A comparatively high $/kgHM fuel fabrication cost for advanced fuel in comparison 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 of generation, however, is likely to be less than for lower-burnup fuels because of the possibility of higher fuel burnup, or MW(th)-days per kgHM, and lower annual fuel consumption in the reactor. Therefore, we have a situation with less fuel required per fuel reload at a higher fabrication cost per unit of fuel.

For water reactors (LWRs and PHWRs), fuel fabrication price rather than cost in $/kgHM is usually discussed. There are not presently enough fabrication players in the advanced, non-water reactor world to establish competitive markets, so it is assumed that unit price equals unit cost in a future balanced world market having successful NOAK fabrication facilities for Generation IV reactors. The unit cost is assumed to include some return to investors or an imputed discount rate for the purpose of providing a profit.

D-PR-2. CONTACT-HANDLED FUELS (D1 SUBMODULES)

D-PR-2.1. Submodule Naming, Status, and Description

Nearly all the world's fuel fabrication facilities operating today are CH facilities. CH 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 or will be described in the D-1 Modules to be published as part of the overall update, including this report. Typically, a CH 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.

In the 2017 *Advanced Fuels Campaign-Cost Basis Report* (AFC-CBR) (Dixon et al.), the D-1 Module for CH fuel types was divided into nine sub-modules, generally based on the fuel physical form and type of reactor to which it is charged. For this update, it was decided to keep the same submodule numbering system; however, some D-1 and D-2 submodules required renaming to better reflect how the fuel type might actually be utilized in future advanced reactor systems. It was also decided to eliminate one submodule, since its subject fuel type could be better covered in other existing submodules. The status and priority of each submodule within the proposed overall update is also indicated.

D-PR-2.2. Uranium-based Pelletized Ceramic LWR Fuel Fabrication (Formerly "Pelletized LWR Uranium Oxide (UOX) Fuel Fabrication")

Uranium-based pelletized ceramic LWR fuel fabrication, used in PWRs and LWRs and burning either virgin or reprocessed/re-enriched (REPU) low-enriched uranium, is a mature fuel fabrication technology presently providing fuel to the majority of the world's nuclear powerplants. For the first time, Module D1-1 discusses accident tolerant fuels (ATFs) with specialized cladding or pellet matrix modifications to reduce the possibility of rapid fuel failure and melting under accident conditions. Some of these ATFs utilize ceramic materials other than UO2 such as uranium nitride or uranium silicide, thus the need to modify the name of this module. The possible use of high-assay, low-enriched (HALEU) fuels with U-235 assay > 5% is also discussed for the first time. Use of this HALEU fuel would allow higher burnups and lower fuel consumption. This new D-1 Module also benefits from an older NASAP study (Judkins and Olsen 1978) for which a non-proprietary plant design and bottom-up life cycle cost estimate for a PWR-UOX facility was presented. This newly discovered vintage information is now presented in detail and the economics updated to today's regulatory and economic environment. Appendix A to this report discusses the late 1970s NASAP effort and how the data was used for this study. This update is a high-priority module and is part of this first AFC-CBR fuel fabrication volume.

D-PR-2.3. Pelletized LWR Mixed-oxide (U,Pu MOX) Fuel Fabrication

Pelletized LWR mixed-oxide (U,Pu MOX) fuel fabrication, a substitute for some or all low-enriched UOX assemblies in LWRs and PWRs, mostly in Europe and Japan, is a mature fuel fabrication technology for separated Pu as oxide arising from aqueous reprocessing of spent UOX or spent MOX fuel. This module now benefits from bottom-up cost data provided in the late 1970s NASAP studies in which the ORNL authors modified a UOX PWR facility design to produce U-Pu MOX fuel. This necessitated the addition of gloveboxes, more robust ventilation systems, and security upgrades from a Category III nuclear facility to a Category I facility. The resulting new life cycle cost estimate and its update to today's economic conditions will be presented in a separate second 2021 D1-2 Module Update. Data for the re-fabrication of aqueously reprocessed MOX spent fuel have also been added to this module.

D-PR-2.4. Uranium-based Particle Fuel Fabrication (Formerly "High-temperature Reactor Particle Fuel Fabrication")

Uranium-based particle fuel fabrication can be used in graphite-moderated, gas-cooled reactors (GCRs) or in solid-fueled, molten-salt cooled, graphite moderated reactors (MSCRs) or in a dispersed form in ATF pellet fuels for LWRs. The technology utilizing TRISO (tristructural-isotropic) particles

imbedded in graphite spheres (pebbles) or cylindrical compacts for GCRs has been tested at prototype or first-of-a-kind (FOAK) scale in several nations for over 50 years. As of 2017, the fabrication technology is just beginning to reach the maturity required for large-scale, semi-automated plants. This has occurred first in China; however, two U.S. fuel manufacturers, BWXT in Lynchburg, VA and Global Nuclear Fuels in Wilmington, NC, are both starting up production lines which might produce hundreds of kgU per year of TRISO. Most current R&D on TRISO fuels is with uranium; however, the TRISO concept can be utilized for plutonium or thorium. Because of significant interest in this fuel for microreactors and small modular GCR and MSCRs, the priority for updating and publishing this Module D1-3 will be increased. It can also benefit from the late 1970s NASAP studies, which considered several variants of TRISO-type fuels for proliferation-resistant, thorium-based fuel cycles. The updated D1-3 has yet to be developed, and it will be a separate follow-on document to this report.

D-PR-2.5. U and U,Pu-based Ceramic Pelletized Fast Reactor Fuel Fabrication

U and U,Pu-based ceramic pelletized fast reactor fuel fabrication are similar to D1-1 and D1-2 in concept but require pellet-diameters and rod cladding materials compatible with the liquid sodium coolant for fast reactors. Pilot plants or small fabrication facilities have been built in several nations to provide this fuel for prototype fast reactors. Fuel meat can be ceramic (U,Pu), HALEU, or HEU, all as oxides, carbides, or nitrides. Maturity is such that the fabrication process could be readily adapted to large scale production. Because of process similarities, this module will be published along with *Module D1-5: Vibrocompacted Fast Reactor Fuels*. Mixed oxide fast reactor fuels such as (U,Pu)O2 were also part of the NASAP study. The updated life cycle cost data therefrom is incorporated in this module which will be in a follow-on document to this document.

D-PR-2.6. Ceramic Vibrocompacted Fast Reactor Fuel

Ceramic vibrocompacted fast reactor fuel is similar to D1-4 except that ceramic 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. Because of process similarities, this module will be published along with *Module D1-4: Ceramic Pelletized Sodium-Cooled Fast Reactor (SFR) Fuel Fabrication.*

D-PR-2.7. U and U,Pu-based Metallic or Alloyed Reactor Fuel Fabrication

Metal fuel has heat transfer and higher burnup advantages in sodium-cooled fast reactors. It has been tested in experimental fast reactors (EBR-II and FFTF) in the United States. For CH, the fissile materials therein, HALEU, HEU, or U,Pu must be clean and free of fission products or HA capable of producing high-radiation fields. Alloying metals such as zirconium or molybdenum are also required for better fuel performance. The alloying/casting process required has been extensively tested on a pilot scale. This cleaner 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 R2/D2. In Russia, such U-alloy metal fuel is used for marine reactors. In the United States, Lightbridge Corporation is conducting some private sector R&D for LWR fuels utilizing metal fuel. This type of fuel may have superior heat transfer characteristics. Metal fuels such as U,Pu alloys were also part of the NASAP study. The updated life cycle cost data therefrom is incorporated in a Module D-6 Update which will be in a follow-on document to this volume. Module D1-6 will be divided unto Module D1-6A for uranium-only fuel and Module D1-6B for U,Pu alloyed fuels.

D-PR-2.8. Uranium-based Pelletized Pressurized Heavy Water Reactor Fuel Fabrication (Formerly "Pelletized CANDU Reactor fuel fabrication")

Uranium-based pelletized PHWR fuel fabrication is similar to D1-1 except that natural assay or slightly enriched UO2 is used, and the fuel assemblies are short and loaded into the CANDU reactors horizontally for on-line refueling. This is a mature fuel fabrication technology employing large-scale facilities in Canada and India and smaller facilities in other nations with PHWRs. This fuel manufacturing technology was also studied as part of the NASAP effort; however, the 1978 NASAP analysis has recently been validated and updated by the SA&I team for today's regulatory and economic conditions. These results are incorporated in the WIT data appearing in the 2021 Module D1-7 Update that is part of this report. Fuel issues associated with the Generation IV version of the PHWR, the Canadian Supercritical Water Reactor (SCWR) design, are also briefly discussed.

D-PR-2.9. Thorium-based Fuel Fabrication

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 UO2 and ThO2 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). Thorium has also been suggested by Lightbridge Corporation for use in LWRs employing a driver metal seed/ceramic blanket concept. This module is a lower priority for updating since there is less ongoing R&D and commercial vendor interest in this area.

D-PR-2.10. Advanced Fuels

Much of the recent R&D work on advanced fuels is for the transmutation fuel types which would contain HA and even small amount of fission products from reprocessing. These fuels would require RH, hence should be covered in Module R2/D2. 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 (ATFs). Such concepts include special fuel road coatings, alternative claddings, such as silicon carbide, and the use of coated particles, such as TRISO imbedded in a clad matrix material. These fuels could likely be handled in contact-type facilities. Discussion of these ATFs has now been moved to Module D1-1 and D1-3. Since these ATF options now have or will be moved to other modules, this update's Module D1-9 may be eliminated. In the future, it might be advisable to add a new Module D1-9 dealing with liquid fuels, such as nuclear materials dissolved in molten salts required for liquid-fueled MSR designs. Many different salt types have been proposed.

D-PR-2.11.1. Inclusion of Blanket and Target Material Fabrication

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 UF6 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. Such cores or reloads, however, include some rods or assemblies that may not include fissile driver materials. This fabrication fuel cycle category should also apply to manufactured blanket or target materials that are irradiated in a reactor along with the driver fuel (i.e., a heterogeneous core reactor system). Unit costs for these materials are also calculated.

D-PR-2.11.2. Generic Technical Issues for the D-1 Modules

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 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 high-Z elements, such as plutonium and other HA, present a significant radiotoxicity hazard. As noted below, the radioactivity nature of the elements within the fuel will determine whether fuel is CH and will be covered in this D1 series of modules or is RH and will be covered in the F2/D2 modules. The nature of the fuel-handling environment has a very large effect on fuel fabrication 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. The USNRC has recognized this by defining category levels for nuclear facility security (see Appendix B). 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 for overall fuel cycle evaluation, since avoided costs for other fuel cycle steps such as ore procurement and enrichment 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.
3. Fabricated fuel assemblies take many different physical forms. Every September, *Nuclear Engineering International* (2012) publishes diagrams and design data for fuel assemblies required by most of the world's commercial reactors (i.e., PWRs, Voda-Vodyanoi Energetichesky Reaktors [VVERs; Russian PWRs], BWRs, and PHWRs).
4. 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 specifications for enriched uranium oxide [EUO2] and 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 post-irradiation examination (PIE) of test fuel ampoules and lead test assemblies.
5. 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.

D-PR-2.11.3. Summary of D-1 Module Assumptions

The following assumptions are made for the cost analysis for all the submodules in Module D1:

1. WIT unit fabrication cost values and probability distributions will be presented for each fuel variant within each D1 submodule. For some submodules both first-pass fabricated fuel and refabricated fuel for a second irradiation pass are considered.
2. Again, for this Module D1, all fuel types are assumed to be CH. This means that the radioactivity level of the fresh, unirradiated driver fuel, refabricated fuel, or blanket/target fuel is low enough that the rods and bundled fuel assemblies can be safely handled outside of hot cells. (Gloveboxes with robust shielding 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 dry non-aqueous recycling (reprocessing) process and are not easily decontaminated to the extent that they can be CH.
3. Transportation costs from a centralized fuel fabricator to the reactor fleet are included as part of the fabrication cost. For fuels that can be CH, these costs are generally quite small compared to the manufacturing costs. Costs of transportation cask purchase or rental should be included. For dry-reprocessed fuels (Module F2/D2), the fuel never leaves the reactor site since it is reprocessed in a facility connected to the reactor cooling pool.
4. For enriched uranium fuels, the feed material to the fabrication plant is assumed to be either virgin (never irradiated) or aqueously reprocessed and reconverted UF6 from enrichment plants or HEU-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. For the NATU required for PHWRs, no fluorine-related steps are required, since there is no enrichment step requiring UF6. For MOX fuels (both LWR and foreign reactor), the feed material is assumed to be clean PuO2 or (Pu, Np)O2 powder from an aqueous reprocessing plant or a facility capable of preparing clean PuO2 from weapons program feedstocks. Virgin uranium or thorium fuel materials are those ore-derived feeds 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 depending on the type of fuel considered. The production of LWR and PHWR 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. The intent of the AFC-CBR is to project unit fabrication costs for fuels fabricated in FOAK facilities servicing a fleet of reactors.

D-PR-3. REMOTE-HANDLED FUELS (D2 SUBMODULES)

Generic Technical and Economic Issues Associated with Remote Fuel Fabrication and Refabrication. Module D2 has evolved into *Module F2/D2: Dry Reprocessing Processes with Integrated Fuel Refabrication* because of the integral nature of reprocessing and refabrication for RH technology. The F2 and D2 modules are now combined, and most fuel fabrication issues are handled in the F-Modules. The inseparability of refabrication and reprocessing for dry processes is true especially for presentation of life cycle costing.

In the 2017 AFC-CBR (Dixon et al. 2017), the dry non-aqueous metal-based refabrication process considered was the electrochemical/pyrochemical process for SFR metal alloy U,Pu,Zr fuel. In the integral fast recycle (IFR) version of this technology, metal fuel refabrication by a blend/cast technology is part of the overall process. It is deployed at the reactor site in a highly shielded remote canyon-type building immediately adjacent to the SFRs, so the spent fuel can be moved from the reactor island area in shielded tunnels, obviating the need to treat, package, and transport fast reactor SNF to a centralized reprocessing facility. The WIT unit cost information in the 2017 AFC-CBR was based on data from 1990s vintage ANL and General Electric reports listed in the 2017 AFC-CBR Module F references. It was

impossible to distinguish the separations part of the IFR process from the refabrication part for purposes of determining a unit cost for SFR metal refabrication alone. It should be noted that the separated and carefully re-blended metallic actinide material to be refabricated would contain (1) higher trace fission product content compared to aqueous-derived material and (2) significant amounts of HA, both of which would necessitate totally remote fuel handling in a canyon-like environment. The inclusion of HA in the material to be refabricated is intentional, since an important mission for the SFRs is to operate as actinide burners, thereby reducing the amount of long-lived separated transuranics normally bound for a repository. The heat load and emplacement volume of the geologic repository is also reduced if most transuranic radionuclides are burned rather than treated, packaged, and emplaced.

These refabricated fuels are likely to contain significant amounts of HA, such as americium and curium, and may also include some unseparated fission products such as elements from the lanthanide series. These Module F2/D2 fuels are likely to be metal alloy fuels such as those envisioned for the General Electric/Materials and Fuels Complex Integrated Fuel Recycle fuel cycle. Fuel target materials, such as HA oxides, arising from an advanced aqueous reprocessing process, such as UREX 1-a, where HA and small amounts of lanthanides are not disposed (i.e., transmutation fuels) also would require remote refabrication.

The updated 2021 F2/D2 Module will also discuss dry integrated processes such as gas-phase solid reaction schemes such as DUPIC and fluoride volatility. The new 2021 Module Update will be a follow-on report to the set of Fuel Fabrication D Module Updates now in preparation.

D-PR-4. REFERENCES

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NOTE: *NASAP Reports are discussed and referenced in Appendix D-PR.A below.*

Appendix D-PR.A

NASAP-informed Methodology for Derivation of 2017-2021 Reference Fabrication, Re-fabrication, and Reprocessing Unit Cost Information

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APPENDIX D-PR.A
NASAP-informed Methodology for Derivation of 2017-2021 Reference Fabrication, Re-fabrication, and Reprocessing Unit Cost Information

D-PR.A-1. RATIONALE FOR USE OF 40 PLUS-YEAR OLD COST ESTIMATES ON NUCLEAR FUELS

For the various fuel types considered in the D-submodules, it is desired the unit cost information ($/kgHM) provided for multiple fuel types be comparable. By comparable, it is not meant that the unit costs be numerically close to each other, but rather that the numbers are derived on a consistent methodology and are calculated where possible for fuel fabrication plants of similar mission scope. This attribute allows realistic comparison of unit costs based on fuel fabrication technology differences rather than financial or project execution differences. Scope in this case means plants of similar average production capacity, deployment status (commercial, stand-alone NOAK western facilities), and assumed plant operating life (50 years). The overall scope of the life cycle costs required to calculate the unit cost for all fuel types should include front-end capital costs (design, construction, licensing, and start-up), all recurring costs (O&M labor, materials, and utilities), major equipment replacement costs, and D&D (decontamination and decommissioning) costs for the facility at end-of-life.

First, recent information on nuclear fuel pricing (or cost estimating) is very difficult to find due to the proprietary nature of the highly commercialized fuel fabrication industry. In addition, it should be noted that fuels contracts are also often rolled into reactor vendor contracts with a utility (e.g., the first few reloads are included in the initial reactor build contract), or fuel can be rolled into a large service and maintenance contract. Second, most fuel types beyond MAGNOX and AGR in the UK and LWR and PHWR fuel worldwide have not enjoyed high volume production and the economies of scale which should accrue to it. For example, only enough fast reactor and HTR fuel has been produced to operate single prototype reactors and not a whole fleet of similar power plants.

Fortunately, there has been a previous effort to estimate the unit costs associated with large scale NOAK commercial fuel fabrication facilities. In the years of 1976–1978, the U.S. plans for closed or partially closed nuclear fuel cycles were reversed by presidential decree due to concerns about the possible separation of fissile materials for non-peaceful use in nuclear weapons. Non-proliferation aspects of nuclear fuel cycles became an overriding concern, and two programs were initiated to examine many aspects of possible nuclear fuel cycles including technical feasibility, availability of source materials, ease of proliferation, and economics. The domestic U.S. evaluation was called the NASAP (Non-Proliferation Alternatives Systems Analysis Program), and the IAEA-sponsored international evaluation was called INFCE (International Fuel Cycle Evaluation). For the domestic effort, USAEC/ERDA national laboratories and nuclear materials production facilities were engaged to evaluate the major steps of the nuclear fuel cycle including uranium enrichment, fuel fabrication, and spent fuel reprocessing. The intent was to define and evaluate proliferation-resistant fuel cycles for not just LWRs, but also the SFRs (such as the proposed Clinch River Breeder Reactor) and for large HTGRs which were under development at the time. The Metals and Ceramics Division of Oak Ridge National Laboratory (ORNL) was assigned the task of evaluating reprocessing and fuel fabrication processes for LWR, PHWR (CANDU), FBR (SFR), and HTGR-based fuel cycles involving multiple source materials (uranium, plutonium, and thorium) and fuel types (ceramic, metal-alloy, and coated-particles [i.e., TRISO] imbedded in graphite.) Determination of the projected levelized unit production cost from hypothetical plants was a major part of the ORNL work scope. A single group of ORNL engineers and cost estimators was engaged to assess the unit cost for all fuel types under a uniform and consistent set of economics guidelines for parameters such as plant

life, interest rates, worker salaries, etc. A consistent methodology for calculation of the 20-year levelized unit cost of fabrication ($/kgHM) was also adopted.

A starting point for the analysis was a bottom-up cost estimate for a 520 MTHM/yr UO2 (UOX) pelletized ceramic PWR fuel plant. This reference-plant design was much like the one for the at-the-time recently completed Westinghouse PWR fuel fabrication facility in Columbia, SC (Rosser 2012). (This reference UOX plant is discussed in detail in the Module D1-1 Update which is part of this overall document.) For other fuel types, including the more advanced PWR-MOX and FBR fuels, the evaluation team developed a methodology to convert the reference UOX plant to a subject plant capable of manufacturing fuel at a similar production rate under what might be vastly different fuel element geometry, plant safety, criticality, plant security, and radionuclide containment conditions. FORTRAN computer codes such as FABCOST (Lotts, Washburn, and Homan 1968) were developed to automate this conversion process. Unfortunately the computer codes and detailed documentation (notebooks) of the developed reference plant to subject plant conversion procedures no longer exist in ORNL's archives; however, the general procedures and assumptions used in the study are well-documented in five 1977–1980 ORNL technical memorandums (ORNL-TM reports [Carter and Rainey 1980; Kasten, Homan, and Allen 1977; Judkins and Olsen 1979a; Olsen 1979; Judkins and Olsen 1979b; Olsen et al. 1979]). (Section 3 of this appendix contains a short description of the information in each of these ORNL reports.) Close examination of these documents, many of which have common authors, indicates an excellent attention to detail and consistent methodology such that the unit costs results for different fuel types can be compared, and any $/kgHM differences are the result of real process technology and fuel design differences. For this reason, SA&I analysts chose to validate the ORNL unit cost data by means of new EXCEL spreadsheet analysis and then convert the life cycle cost data to today's constant dollar costing basis and under today's economic conditions. Possible plant design changes based on new regulations promulgated since 1978 were also considered. Historical data on cost escalation experience by nuclear projects from the 1970s to the present was also considered in the analyses. Such nuclear cost-escalation factors capture some of the cost effects of such mandatory regulation. The paragraphs below describe the scope and methodology of the NASAP study in detail.

D-PR.A-2. SUMMARY OF FABRICATION AND REFABRICATION COST ESTIMATES FROM NASAP

The ORNL/NASAP method used to estimate fuel fabrication and refabrication life cycle and unit costs for LWR, CANDU, HTGR, and FBR fuel cycle systems was similar to the method described in Appendix H of ORNL/TM-5565 and ORNL/TM-6648 (Carter and Rainey 1980; Kasten, Homan, and Allen 1977). Fuel fabrication flowsheets were developed for each type of reactor fuel, and the complexity and specialized equipment requirements compared. Since no commercial scale facility existed in 1977 for remote fuel fabrication, and the proprietary cost data for fresh PWR hands-on fuel fabrication were not generally available, a previous (1966) ORNL bottom-up estimate (Lotts and Washburn 1968) for LWR fuel fabrication was updated and used as a comparison baseline. A summary of the 1977 NASAP fuel fabrication study's results for multiple fuel types is contained in Figure D-PR.1, which is Table I.1 of ORNL/TM-5565 (Kasten, Homan, and Allen 1977) for plants with 2 MTHM/day production capacity. With downtime factored in, the adjusted production rates for these fabrication plants vary from 480 to 520 MTHM/yr depending on radiation protection complexity. Scaling factors can be used to estimate unit fabrication costs for plants smaller or larger than the 2 MTHM/day baseline.

Figure D-PR.1 provides a summary table from first NASAP fuel fabrication cost study (Kasten, Homan, and Allen 1977).

Table I.1. Estimated Fabrication Cost Comparison[a]

Reactor Type	Fuel Material	Relative Cost Factors				Estimated Costs ($/kg)[b]
		Capital	Hardware	Operating	Total	
PART A						
LWR (PWR)	$(^{235}U\text{-}U)O_2$	0.33	0.38	0.29	1.00	150[c]
	$(Pu\text{-}U)O_2$	1.49	0.38	1.45	3.32	500
	$(^{235}U\text{-}Th)O_2$	0.50	0.42	0.44	1.36	200
	$(^{233}U\text{-}Th)O_2$	1.98	0.38	1.45	3.81	570
	$(Pu\text{-}Th)O_2$	1.49	0.38	1.53	3.40	510
CANDU	Normal UO_2	0.33	0.09	0.11	0.53	80
	$(Pu\text{-}U)O_2$	1.49	0.09	0.50	2.08	310
	$(^{233}U\text{-}Th)O_2$	1.98	0.09	0.50	2.57	390
	$(Pu\text{-}Th)O_2$	1.49	0.09	0.53	2.11	320
FBR (L.M.)	$(Pu\text{-}U)O_2$	3.19	0.58	2.10	5.87	880
	(Pu-U)C	2.68	0.37	1.66	4.71	710
	$^{233}U\text{-}Th$	2.73	0.35	1.60	4.68	700
FBR (Gas)	$(Pu\text{-}U)O_2$	3.19	0.90	2.29	6.38	960
	$(^{233}U\text{-}Th)O_2$	4.55	0.90	2.40	7.85	1,180
	$(Pu\text{-}Th)O_2$	3.64	0.90	2.40	6.94	1,040
PART B						
HTGR	$^{235}UO_2\text{-}ThO_2$	0.26	0.42	0.32	1.00	400[d]
	$^{233}UCO\text{-}ThO_2$	1.21	0.42	0.95	2.58	1,030
	$^{235}UO_2\text{-}UO_2$	0.26	0.32	0.32	0.90	360
	$PuO_2\text{-}ThO_2$	1.21	0.42	0.94	2.57	1,030

[a] All cost comparisons are relative to the given base case factors.

[b] 1977 dollars assumed for total kilograms of heavy metal product with a plant output of 2 metric tonnes per day and 260 full operating days per year (520 MT/year).

[c] Base case for metal clad fuel rods based on FABCOST 9 estimates (A. L. Lotts et al., A/CONF, 49/P/062, 1972) escalated to 1977 with additions for current scrap and waste treatment requirements.

[d] Base case for all HTGR (Prismatic Fuel Element) cases based on data in "Summary Program Plan, Alternate Program for HTGR Fuel Recycle," April 11, 1975, Draft.

Figure D-PR.A.1 Fuels and processes considered during the NASAP studies of the late 1970s.

Fuel Fabrication Preface to FY 2021 Updates to the D-Modules

Cylindrical, metal clad fuels (Part A of Figure D-PR.A.1) and prismatic coated-particle TRISO-type fuels imbedded in graphite (Part B of Figure D-PR.A.1) were considered. Also considered in the NASAP study were the fuel reprocessing flowsheets (all aqueous PUREX-based) required to separate out the useful fissile/fertile products and the process flowsheets to refabricate them (with relatively low concentrations of carried over fission products and HA) for one or more additional irradiation cycles. The three actinide elements considered were uranium (both U233 and U-235 for fissile and U-238 for fertile), thorium (Th-232 for fertile), and plutonium (Pu-239 and Pu-241 for fissile), with little or no attention given to the inclusion of HA, such as neptunium, americium, and curium. Various combinations of these main actinide elements (U,Th,Pu) in both homogeneous and heterogeneous (driver/blanket) fuel cycles were considered, along with their chemical forms of oxides, carbides, and metals. Figure D-PR.A.1 extracted from ORNL/TM-5565 (Kasten, Homan, and Allen 1977) shows the various fuel types along with the reactor types which would utilize them. Detailed fuel descriptions (structure, mass, dimensions, cladding, etc.) and possible reprocessing/fabrication/refabrication process flowsheets were provided for each fuel type in the 1979 NASAP report ORNL/TM-5961 (Olsen 1979).

It should be noted that in the 1977–1979 timeframe, the projected and selected average discharge burnups for these fuels were much lower than current LWR experience and lower than today's (2021) projected fuel burnup assumptions for proposed advanced reactor systems such as SFRs and MHTRs. In the late 1970s, the production of HA during irradiation in generation I-III reactors, including higher isotopes of plutonium, was calculated to be much lower than anticipated for today's Generation IV fuel cycles of interest. Reprocessing facilities and refabrication facilities for today's fuel cycle concepts, which require accommodating higher burnups and greater handling of HA and Pu-240, might have to be more robust from a radiation shielding, criticality, and personnel protection standpoint; however, the basic chemical (front-end conversion and PUREX-type aqueous reprocessing) and metallurgical technology (fabrication techniques) associated with newer fuel designs is pretty much the same as that envisioned in 1978. The NASAP studies did not consider dry or electrochemical reprocessing or the integral type operations (ANL-INL-IFR) where fuel refabrication is handled as part of the same overall flowsheet as reprocessing. They also did not anticipate interest in refabricating fuels for actinide-burning fuel cycles in which the HA would be processed in the front end of the fuel cycle along with uranium and plutonium. The NASAP fuel fabrication analysts did, however, carefully factor transuranic containment and radiation shielding into their designs and costs on a consistent basis, with three categories designated: (1) all CH (abbreviated C in the NASAP reports), (2) remote handling with contact maintenance (RH-CM), and (3) RH with remote maintenance (RH-RM). In terms of necessary process containment equipment, these respectively include open human handling under hoods (UO2 and ThO2), glovebox operations ([U,Pu]O2 MOX) , and more heavily shielded glovebox and robotic hot cell operations (U-233-, Th-, and Pu-based fuels with higher Pu isotopes.) How these fuel handling categories were factored into the design and cost is described in the paragraphs below.

D-PR.A-3. COST ESTIMATION METHODOLOGY FOR NASAP FUEL FABRICATION ECONOMIC ANALYSES

The large variety of fuel materials and fuel element designs considered in the NASAP study, together with the limited task duration for NASAP precluded a formalized and detailed bottom-up estimation procedure for every fabrication plant design ,such as that done previously in the late 1960s (Lotts and Washburn 1968). One of the cases, however, from the 1966 studies formed the basis for the reference base case for metal clad cylindrical fuel rod types. This LWR (PWR all CH UOX fabrication) case from FABC0ST 9 (Lotts, Washburn, and Homan 1968) provided the appropriate distribution of cost elements under the major life cycle cost categories of capital, hardware, and operations. The costs in each category were escalated to 1977 USD in by the NASAP analysts from the 1966 FABCOST 9 data by assuming a 10% per year inflation rate, as was done in a previous study (Lotts and Washburn 1968) and adding both capital (50%) and operating (30%) increments to incorporate new (in late 1970s) features for current or proposed regulatory requirements for total liquid recycle, scrap reprocessing, and solid waste treatment. With this reference facility and bottom-up cost estimate as a basis, the fabrication process outline flowsheets given in Figures I.1 through I.4 of ORNL/TM-5565 Appendix I (Kasten, Homan, and Allen 1977) were used to make a relative design-factor-based estimate for incremental feature changes in each major life cycle category of cost for the new, non-PWR UOX subject fuel case of interest.

The hardware cost factors were based on available fuel element design data and evaluation of three design increments: cladding (with end caps), fuel rod internal component complexity, and assembly components complexity. All capital cost factors included design increments for buildings and equipment. A high level of mechanization was assumed for equipment, but the degree of automation varies as do the building costs in accordance with (1) the modes of plant operation from (a) all hands-on CH (b) moderate shielding and containment of some or all process steps, to (c) very significant shielding and containment of some or all fabrication process steps , and (2) the accountability and physical security/safeguards considerations depending on the subject fuel's fissile material in-facility inventory and its fissile enrichment. In 1978, the NRC had not yet defined Security and Safeguards levels Category I-III. Operating costs were derived from six weighted incremental processes covering cladding preparation, fuel preparation, rod loading, fuel element assembly, inspection, packaging, scrap recovery, and waste treatment. Although reference was made to some previous studies and cost estimations in developing the factors estimated for the various design/cost increments in each category, no attempt was made to normalize any non-LWR UOX case to such earlier studies—which were not available—for metal clad fuels. A new separate reference base case was derived for the unique configuration and fuel form (coated-particle fuel now designated TRISO) of the HTGR reactors using 1960s and early 1970s vintage HTGR fuel fabrication data. The resulting relative unit fabrication costs ($/kgHM) comparison is also presented in Figure D-PR.A.1, which is Table I.1 of ORNL/TM-5565 (Kasten, Homan, and Allen 1977). The absolute cost estimates are all given in 1977 USD and are all for a common production capacity plant of ~2 metric tons per day of heavy metal product with a capital fixed charge rate of 30% assumed, which was reasonable at that late 1970s era of high inflation. Within the accuracy of these estimates (~25% according to the NASAP authors), the cost scaling factors for plant capacity are probably equivalent to those presented in the Geneva 1972 paper of Lotts et al. (1972) from the FABC0ST 9 calculations; thus, a scaling factor can be derived from Figure D-PR.A.2 below, which is Table I.2 of ORNL/TM-5565 (Kasten, Homan, and Allen 1977). The cost estimates are based on a given fuel element design for each reactor type.

Table I.2. Fabrication Cost as a Function of Processing Rate

Rate (MT HM/day)	Cost Fraction
0.5	1.53
1.0	1.23
2.0	1.00
3.0	0.90
4.0	0.84
5.0	0.79
6.0	0.76
>7.0	0.73

Figure D-PR.A.2. Scaling Results for NASAP Fuel Fabrication (unit cost ratio versus production capacity) 2 MT/day is baseline for unit cost ratio of 1.0.

The base or reference case for cylindrical geometry metal-clad ceramic fuels in the NASAP work was the study of a PWR fuel plant reported in ORNL/TM-6501 (Judkins and Olsen 1979a). That report provided a somewhat detailed analysis of the facility, equipment, and operating requirements for the fabrication of ceramic pellet fuel for then current PWR designs. Capital and operating costs were estimated for a plant with a 2-MTHM/d production capacity. To relate other metal-clad fuels—including other PWR cases such as U,Pu MOX—to this base case, a direct comparison was made of fuel fabrication functions required for each fuel type. This was a systematic procedure in which the functional flowsheets for fabrication of the various fuels were compared with the reference PWR fuel fabrication flowsheet, and appropriate additions or deletions were made. The determination of requirements for each case is based on the fabrication of specific fuel assemblies previously described in the series of NASAP reports (Judkins and Olsen 1979a; Olsen et al. 1979; Olsen 1979; Judkins and Olsen 1979b). Floor space and equipment throughput requirements and manpower needs for the various process functions were assessed based on the designs of the fuel assemblies—number of fuel rods in each assembly, number of pellets in a fuel rod, rod lengths, etc.—and used in the following cost categories: (1) capital cost of facility, (2) capital cost of equipment, (3) annual material costs, and (4) annual operating costs. The procedure for relating estimates of any fuel type to the reference PWR-UOX case was similar for each capital-cost category. Figure D-PR.A.3 shows a schematic description of the transformation process from the reference PWR UOX facility to the subject fuel fabrication plant for a different fuel type.

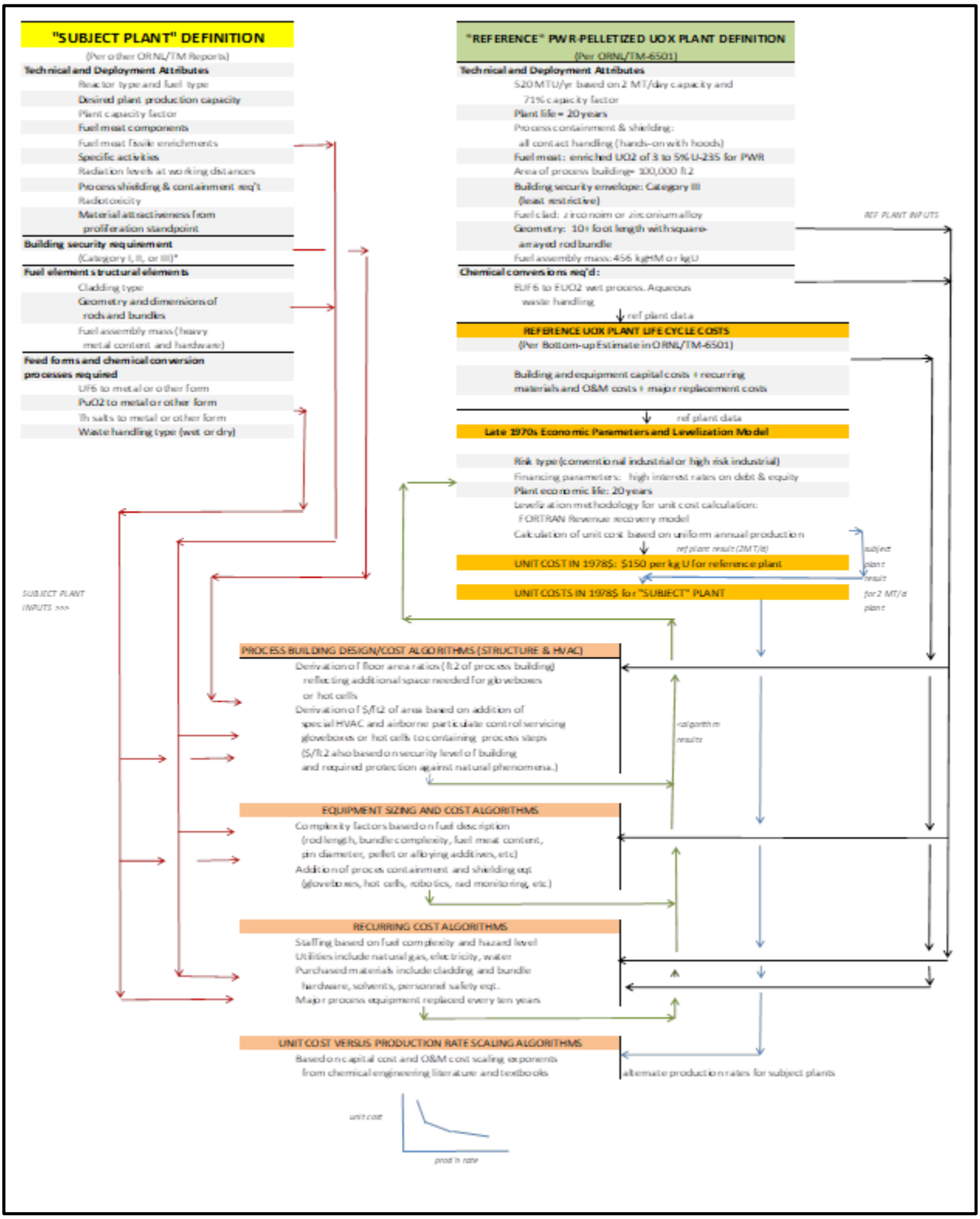

Figure D-PR.A.3. Transformation process from reference to subject plant.

In the 2021 AFC-CBR Module D1-1 Update, "Ceramic LWR Fuel Fabrication," section of this document, the methodology for converting the 1978 USD life cycle costs to 2017 USD costs will be discussed as well as the economic models used to generate levelized unit fabrication costs from the LCC data. The methodologies will be described in detail for the case of a 520 MTU/yr PWR UOX fuel fabrication facility. The issues of inflation, escalation greater than inflation, discount rates, and plant amortization are considered. The use of a well-vetted and documented economic model and EXCEL algorithms for reactor and fuel cycle facility levelized product cost calculation, G4-ECONS (EMWG 2007; Williams 2007), is also described therein. All subsequent fuel types (i.e., the remaining D1 Fabrication modules) use the same methodology for unit fabrication cost calculation.

D-PR.A-4. SUPPLEMENTAL INFORMATION ON NASAP STUDIES

This section provides a description of and bibliographic data on the seven studies from the 1970s on fuel fabrication and reprocessing from the ORNL studies used as the basis for cost revisions to Module D1 WIT data:

1. Oak Ridge National Laboratory and U.S. Atomic Energy Commission. 1971. "Reactor Fuel Cycle Costs for Nuclear Power Evaluation." WASH-1099, U.S. Government Printing Office. Available: https://books.google.com/books/about/Reactor_Fuel_Cycle_Costs_for_Nuclear_Pow.html?id=7l3RsNBQrPYC.

   - This report was commissioned by the USAEC to investigate the economics of fuel cycle which might be deployed over the next 50 years from 1971 onward. The LWR fuel cycle was still in its infancy, and projections were for thousands of nuclear powerplants in the United States by 2020.
   - Non-LWR reactor fuel cycles were analyzed against a base LWR fuel cycle for comparison.
   - Large reactor fleets were assumed; hence, supporting fuel cycle facilities were projected to be very large.
   - All fuel cycle facilities were considered NOAK for economic evaluation.
   - The report was prepared by ORNL with the help of the following organizations:
     - The Babcock and Wilcox Company
     - General Electric Company
     - Argonne National Laboratory
     - Pacific Northwest Laboratory
     - Westinghouse Electric Company
     - S.M. Stoller Associates
     - Idaho Nuclear Corporation
     - Nuclear Fuel Services, Inc.
     - E.I. duPont de Nemours & Company (Savannah River)
     - Allied General Nuclear Products, Inc (Barnwell owner).
   - The data and methodology developed for this report was extensively used when the issue of economics was revisited by NASAP from 1977–1980.
   - It is likely that many of the ORNL staff who prepared the NASAP reports (described below) also assisted in the preparation of this report. No author acknowledgements were found in this report.

- Eleven "WASH-series" USAEC technical reports for various reactor types and their fuel cycles were prepared prior to this report with the help of system proponents.
- Computer codes such as FABCOST were used for much of the analysis and are described in appendices to this report.
- This was a high-level report with a foreword written by Milton Shaw, director of the USAEC Division of Reactor Development and Technology.
- This report was not found in the ORNL or OSTI archives during earlier 2004–2019 searches. Google Books just recently digitized it and placed in their free library.

2. R.R. Judkins and A.R. Olsen. 1979. "Estimation of the Costs for Fabrication of Pressurized Water Reactor Fuel." ORNL/TM-6501, Oak Ridge National Laboratory. https://inis.iaea.org/collection/NCLCollectionStore/_Public/10/452/10452758.pdf.
   - Bottom-up estimate for a 520 MTHM/yr PWR UOX fuel fabrication facility only. This is the reference case for cylindrical fuels in the NASAP study.
   - Description of fuel assembly design and fabrication process flowsheet included.
   - Capital recovery life of plan is 20 years. Plant is assumed to be privately owned.
   - There is a level of detail at major process step level for direct capital and recurring O&M and material costs. Report includes detailed life cycle cost tables based on offline bottom-up estimating data and vendor quotes. These sheets, computer outputs, and quotes are not archived. Some predecessor data appears in the 1971 report WASH-1099 which is Item 1 above.
   - This was the reference plant for deriving costs of other fuel types using cylindrical, metal-clad fuel rods. Influence factors are used to calculate the cost effects of fuel design, process equipment design, and building design transitions are discussed in ORNL/TM-5961.
   - The 1978 ORNL authors calculated unit PWR price using a discounted cash flow business model for existing U.S. economic conditions and the corporate Federal tax and depreciation laws of the mid-1970s. Return to investors is included in the unit fabrication price.
   - For the current FCRD analysis, a levelized unit fabrication cost is calculated using a 50-year capital recovery and operating life. The plant is treated as if government-financed at a 3% real discount rate for interest during construction and capital recovery.
3. A.R. Olsen, R.R. Judkins, W.L. Carter, and J.G. Delene. 1979. "Fuel Cycle Cost Studies – Fabrication, Reprocessing, and Refabrication of LWR, SSCR, PHWR, LMFBR, and HTGR Fuels." ORNL/TM-6522, Oak Ridge National Laboratory. https://doi.org/10.2172/6420741.
   - This report includes unit costs for reprocessing of several fuel types in addition to fabrication and refabrication unit costs.
   - This 1979 document considers unit costs and their calculation for 20-year life plants under three financing scenarios: government, normal industrial project risk, and high-risk industrial. All discount rates used were much higher than today's interest rates.
   - Using information from this report, the SA&I spreadsheet can duplicate the ORNL authors' original unit cost results. The SA&I author used a generic non-business model with simpler G4-ECONS algorithms to calculate the unit fabrication costs under today's business conditions.
   - Unit cost versus facility production capacity information is provided.
   - Appendix A of ORNL/TM-6522 provides more detailed fuel design information such as fuel assembly heavy metal masses and sizes of typical reactor reloads.

4. A.R. Olsen. 1979. "Thorium Fuel Cycles-Fuel Fabrication Process and Cost Estimation." ORNL/TM-5961, Oak Ridge National Laboratory. https://doi.org/10.2172/5960321.

    - The abstract below prepared by the IAEA is an excellent summary of how the NASAP fuel fabrication and reprocessing study was conducted:

        > Early in 1976 a study was made to assess the relative economics and fuel utilization of thorium and uranium fuel cycles in various types of reactors. It was to be completed in approximately two months, so all component parts had to be developed in a short time with a high degree of dependence on existing information. One of the components required for the study was a consistent set of relatively accurate fuel fabrication costs for the various fuel-reactor combinations. A report documents the rationale used in generating these cost estimates and presents in some detail the basis and methodology employed. Since three type of thermal flux reactors (LWR, PHWR, and HTGR) and two types of fast flux reactors (liquid metal and gas-cooled) together with three fuel forms (oxides, carbides, and metal) were included in the study (with various combinations of the actinide metals U, Pu, and Th), it was necessary to define a methodology that would permit calculation of a rapid relative estimate for each case. Existing cost studies were chosen for a light-water reactor with low-enriched uranium fuel and for a high-temperature gas-cooled reactor with highly-enriched uranium and thorium fuel as the reference cases which could be compared with other reactor/fuel combinations (A.R. Olsen 1979).

    - Cost influence factors for transitioning from a reference LWR UOX design to other non-UOX and non-LWR fuel designs are discussed. This was done for fuels requiring both glovebox-handling (called CH) and for those requiring highly shielded (remote) operations and maintenance.

    - Table 7 of ORNL/TM-5961 summarizes the relative cost factors, and Table 11 therein presents a normalized fuel cost comparison for all fuel types.

    - Appendices A and B of ORNL/TM-5961 give detailed fuel design information and incremental cost factors for all designs.

5. R.R. Judkins and A.R. Olsen. 1979. "Nuclear Fuel Fabrication and Refabrication Cost Estimation Methodology." ORNL/TM-6640, Oak Ridge National Laboratory. https://doi.org/10.2172/5819027.

    - Fuel assembly design and fabrication process flowsheets are described for six different reactor fuel types.

    - For non-LWR UOX cylindrical metal-clad fuels, plant design and costs were prepared by revising and scaling the detailed PWR-UOX plant described in ORNL/TM-6501.

    - Many combinations of U, Pu, and Th were considered. Refabrication was considered by assuming remote in-process handling and equipment maintenance for the fuel fabrication facility.

    - For the SA&I effort PWR UO2 (aka UOX), PWR (U,Pu)O2 (also known as MOX), and metal U,Pu alloy are the cases which have merited further consideration by FCRD.

    - Table 8 of ORNL/TM-6640, giving required fab plant floor area increases above the reference PWR UOX plant and the additional $/ft^2 of floor area above UOX for all fuel types, presents this information for the major process and manufacturing steps. This was the starting point for the SA&I study.

    - Appendix A of ORNL/TM-6640 has the ORNL authors' summary level and annualized costs for the following cost categories: building capital, equipment capital (total for all process steps),

pre-operational costs, interest during construction, personnel costs, materials costs, utilities costs, replacement costs, and D&D costs. These data are presented for all fuel types.

- Simpler unit cost algorithms adopted by NASAP for non-UOX fuels are presented.
- Cost versus fabrication plant capacity scaling factors are presented.

6. W. L. Carter and R. H. Rainey. 1980. "Methodology for Estimating Reprocessing Costs for Nuclear Fuels." ORNL/TM-6648, Oak Ridge National Laboratory. https://inis.iaea.org/collection/NCLCollectionStore/_Public/11/540/11540580.pdf
   - This includes bottom-up capital cost for a Barnwell-type PUREX LWR SNF reprocessing plant (the "Reference Reprocessing Plant" for this ORNL report). This basic plant design is capable of reprocessing all the cylindrical fuels described in the NASAP reports above. The resulting fissile products are clean enough for refabrication by contact-handling in shielded gloveboxes.
   - The cost effects of new (middle 1970s) USNRC regulations on waste recovery and packaging are included.
   - Recurring annual costs were calculated by the ORNL NASAP authors, since the Barnwell Plant was never operated due to the 1976 reprocessing ban.
   - The reference PUREX plant flowsheet was modified somewhat by the ORNL NASAP authors to handle non-UOX SNF such as U,Pu MOX SNF and U,Pu SFR MOX SNF, and the life cycle costs associated with each recalculated.
   - The reference plant capacity was large at 1,500 MTHM/yr.
   - LWR UOX SNF was assumed irradiated to ~30,000 MW(th) days/MTHM.
   - Flow diagrams for LWR fuel cycles with denatured U,Th utilization are presented.
   - A simple cost versus production capacity scaling model is presented.
   - Three different financing options with different risk levels were considered.
   - The 1978 ORNL levelized unit cost calculation methodology is presented.
7. P. Kasten, F. Homan, A.L. Lotts, A.R. Olsen, E.J. Allen, J.D. Jenkins, J.E. Rushton, M.L. Tobias, D.E. Bartine, W.L. Carter, K.J. Notx, R.H. Rainey, and E.H. Gift. 1977. "Assessment of the thorium fuel cycle in power reactors." ORNL/TM-5565, Oak Ridge National Laboratory. https://doi.org/10.2172/7315559.
   - This study used life cycle cost data from the early 1970s such as Item 1 above (WASH-1099) of this list. A partial abstract is copied below:

     > A study was conducted at ORNL to evaluate the role of thorium fuel cycles in power reactors. Three thermal reactor systems were considered: LWRs, HTGRs, and PWHRs of the CANDU type; most of the effort was on these systems. A summary comparing uranium and thorium fuel cycles in fast breeder reactors (FBRs) was also compiled (Kasten et. al 1977).

   - This report was a longer transitional report between WASH-1099 and the later and shorter NASAP reports described above. There is considerable process data and methodology description therein which is repeated in some of the later NASAP reports. It should be noted that thorium fuel cycles were of interest due to perceived non-proliferation advantages and the fact thorium is approximately three time more abundant than uranium in the earth's crust. (Future nuclear source material resource availability was an issue at the time.)

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Appendix D-PR.B

Summary of USNRC Security and Safeguards Categories for Nuclear Facilities and Some U.S. Examples

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APPENDIX D-PR.B
SUMMARY OF USNRC SECURITY AND SAFEGUARDS CATEGORIES FOR NUCLEAR FACILITIES AND SOME U.S. EXAMPLES

In the United States, commercial fuel cycle facilities are licensed under 10 CFR 70 (Code of Federal Regulations) and reviewed by the USNRC as prescribed in the standard review plan (SRP), in NUREG-1520 Rev 1 (NRC 2010). USNRC-regulated fuel cycle facilities generally fall into three classes from the standpoint of security and safeguards, depending on the type of special nuclear material (SNM) handled:

1. Category I facilities handle “high strategic significance” SNM which would be separated plutonium, separated U-233, or HEU (i.e., EU with U-235 content 19.75% or higher). There are two privately owned government contractor fuel fabrication facilities in the United States which handle HEU for military applications such as naval propulsion fuel: NFS (a BWXT subsidiary) in Erwin, TN and BWXT Nuclear in Lynchburg, VA. The latter also receives HEU or down-blended HEU from NNSA’s Oak Ridge Y-12 Plant for fabrication into research reactor fuel. Government-contractor-manufactured HALEU fuel for small research reactors generally involves complex metal forming and subsequent machining operations. SFR metal HALEU fuel manufacture would involve a simpler casting process where no subsequent machining is required. Extruded HALEU fuel, such as proposed by Lightbridge Corporation for LWR seed-blanket concepts, would probably require some additional metal-forming and machining steps. NFS has also blended down legacy reprocessed HEU from shut down military production reactors at SRS to produce LWR UOX fuel for use in U.S. commercial reactors. MOX fabrication plants would be considered Category I facilities.
2. Category II facilities handle “moderate strategic significance” uranium in quantities of 10 kg or more falling in the assay range 10 to 19.75% U-235. A domestic facility fabricating HALEU fuel would fall under this designation. An enrichment facility producing HALEUF6 product would also be designated Category II. Any on-site facilities handling enrichment plant tails from this HALEUF6 plant (depleted UF6 of U-235 content < 0.7%) would be Category III facilities.
3. Category III facilities handle “low strategic significance” uranium in quantities of 10 kg or more of U-235 assay less than 10% U-235. Today's three existing U.S. UOX fabrication plants (GNF in Wilmington, NC, Westinghouse in Columbia, SC, and AREVA/Framatome in Richland, WA) fall in this category. If today's UOX fuel fabricators, who can process fuel from 0.71% U-235 (natural assay) up to 5% U-235 in their Category III facilities, want to produce material in the U-235 range 5 to 10% U-235, such as for higher burnup UOX fuel or some accident tolerant fuels, there would likely be some NRC relicensing required despite the fact that the facility would still be a Category III facility.

PART 2 (Full Module D1-1 Update) and PART 3 (Full Module D1-7 Update) are in preparation.