Advanced Fuel Cycle Cost Basis Report: Module D1-3

Uranium-Based Ceramic Particle Fuel Fabrication

Nuclear Technology Research and Development

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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004		Version of AFC-CBR in which this module first appeared: 2004 as Module D1-3
	2021	All	Latest version of module in which new technical data was used to establish unit cost ranges: 2021
			New technical/cost data which have recently become available and may 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 United States is working on MHR development. They may have done some of their own economic analyses; however, these are likely to be proprietary information. Two U.S. corporations, CENTRUS Corporation (Oak Ridge, TN) and Global Nuclear Fuels (Wilmington, NC), are now partnering with X-Energy on TRISO fuel development in both the United States and Japan (CENTRUS 2017; WNN 2019b; WNN 2020b). - BWX Technologies (or BWXT) of Lynchburg, VA is planning a small production line for TRISO fuel for modular and microreactors intended for defense, aerospace, and special industrial applications. Any cost information is likely to be proprietary (WNN 2019a; WNN 2020a; WNN 2020c; WNN 2020e). - Ultra Safe Nuclear Corp plans to use TRISO-coated particles for its fully ceramic encapsulated fuel. This fuel type has possible application as an accident tolerant fuel for water reactors. Their development center will be located in Salt Lake City, UT (Patel 2021). Again any cost information is likely to be proprietary. - HOLOS-GEN has prepared a TRISO-based fuel cartridge design for a portable microreactor for use by the military in remote locations. - FCRD-SA&I staff will continue to monitor the trade press for TRISO developments which might provide insights on fuel fabrication economics.

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ACKNOWLEDGEMENT

This latest version of the *Module D1-3: Uranium-Based Ceramic Particle Fuel Fabrication* is the cumulative effort of many authors who have contributed to the *Advanced Fuel Cycle Cost Basis Report*. It is not possible to identify and acknowledge all those contributions to the *Advanced Fuel Cycle Cost Basis Report* and this module. All the authors, including the four primary authors, 15 contributing authors, the 12 contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to developing and writing this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

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

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CONTENTS

FIGURES

TABLES

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ACRONYMS

AFC-CBR	Advanced Fuel Cycle Cost Basis Report
AFCI	Advanced Fuel Cycle Initiative
AGR	Advanced Gas-Cooled Reactors (UK)
ATF	accident tolerant fuel
BISO	Bistructural Isotropic
BWXT	BWX Technologies
CBR	Cost Basis Report
CDB	Cost Data Base
DOE-NE	Department of Energy-Nuclear Energy
D-T	deuterium-tritium
EEDB	energy economic data base
FCF	Fuel Cycle Facility
FCM	fully ceramic microencapsulated fuel
FCRD	Fuel Cycle Research and Development (program of DOE-NE)
FHR	fluoride-salt high-temperature reactor
FSR	fluoride salt reactor
FOAK	first-of-a-kind
G4-ECONS	Generation IV- EXCEL Calculation of Nuclear Systems
GA	General Atomics Corp
GNF	Global Nuclear Fuels
HALEU	high-assay, low-enriched uranium
HALEUOX	high-assay, low-enriched uranium dioxide
HALEUF6	high-assay, low-enriched uranium hexafluoride
HM	heavy metal
HOLOS-GEN	HOLOS Generators Company
HS&E	Health, Safety, and Environmental
HTGR	high-temperature gas-cooled reactor
HTR	high-temperature reactor
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
Kg	kilograms
KP	Kairos Power
LCC	life cycle cost

LCOE	levelized cost of electricity
LEU	low-enriched uranium
LUEC	levelized unit electricity cost
LEUF6	low-enriched uranium hexafluoride
LEUO2	low-enriched uranium dioxide (a.k.a., LEUOX)
LUEC	levelized unit electricity cost
LWR	light-water reactor
MEU	medium-enriched uranium
MHTGR	modular high-temperature gas-cooled reactor
MIT	Massachusetts Institute of Technology
MMR	micro-modular reactor
MPBR	modular pebble bed reactor
MOX	mixed oxide
MPC&A	materials protection, control and accountability
MTHM	metric tons of heavy metal
MW(th)	megawatts thermal
N/A	not applicable or not available
NEA	Nuclear Energy Agency (part of OECD)
NECSA	Nuclear Energy Corporation of South Africa
NEI	Nuclear Energy Institute (USA)
NASAP	Nonproliferation Alternative Systems Assessment Program
NGNP	Next Generation Nuclear Plant
NOAK	Nth-of-a-kind
NPP	nuclear power plant
NPR	new production reactor
NRC	Nuclear Regulatory Commission (USA)
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
OSU	Ohio State University
PBMR	pebble-bed modular reactor
Pu	plutonium
PWR	pressurized-water reactors
QA	quality assurance
QC	quality control
PF	packing fraction

RF	Russian Federation
SA&I	Systems Analysis and Integration (part of DOE-NE-FCRD)
SWU	separative work unit
TCR	Transformational Challenge Reactor
Th	thorium
TRISO	tristructural isotropic (particle fuel)
U	uranium
UC	University of California
UK	United Kingdom
UN	uranium nitride
UNH	uranyl nitrate hexahydrate
UOC	uranium oxycarbide
UOX	uranium dioxide (a.k.a., UO2)
USNC	Ultra Safe Nuclear Corporation
VIPAC	vibrationally compacted
WEC	Westinghouse Electric Company
WIT	what-it-takes
WNA	World Nuclear Association
Zr	zirconium

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MODULE D1-3 URANIUM-BASED CERAMIC PARTICLE FUEL FABRICATION

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

- **Constant U.S. Dollar (USD or $) Base Year for 2021 Update: Fiscal Year (FY) 2020.**
- **Nature of this 2021 Update from Previous Advanced Fuel Cycle Cost Basis Reports (AFC-CBRs):** Extensive new background information on TRISO-based fuel has been added since many advanced reactor concepts now are calling for its use. This includes some reactor types which are not gas-cooled; hence, the change in the title of this module. It is also recognized that any near-term applications of particle fuel for electricity or heat applications will be confined to uranium with U-235 content less than the upper value for HALEU (high-assay low-enriched uranium) (i.e., 19.75%). Previous D1-3 modules mainly discussed early high-temperature reactor (HTR) fuel having U-235 content in the highly enriched uranium (HEU) range, with some as high as 93.5% (weapons grade). Some new cost information has been found in the literature and consideration (2021 Module D1-6A) of HALEU metal fuel fabrication in Nuclear Regulatory Commission (NRC) Class II (10 to 19.75% U-235) versus Class III (<10% U-235) facilities. This module presents a what-it-takes (WIT) unit fabrication cost range which excludes HEU-tristructural isotropic (TRISO) (and the high NRC Class I facility costs required to produce it).
- **Estimating Methodology for the Latest (2017 AFC-CBR) Technical Update Which Escalated this 2021 Update:**
  - Literature survey and some unit cost calculations for known modular high-temperature gas-cooled reactor (MHTGR) or gas-cooled reactor (GCR) fuel projects.
  - Some limited use of 1978 Nonproliferation Alternative Systems Assessment Program (NASAP) high-temperature gas-cooled reactors (HTGR) data, which was mostly for coated particle TRISO HEU drivers and bistructural isotropic (BISO)-coated particle thorium oxide blanket fuel. The NASAP data was based on a bottom-up estimate for a large 520 MTU/yr coated particle fuel plant for a fleet of HTGRs.
  - Cost goals for current fuel fabricators developing TRISO.
  - Consideration of projected unit costs for HALEU metal fuels from the updated Module D1-6A.
  - Information from feasibility studies by HOLOS-GEN for a transportable microreactor using TRISO-based fuel.

It should be noted that this module is based on a coated particle fuel fabrication technology that has been demonstrated on a pilot plant scale supporting a single reactor in various countries but has not been automated or scaled up to the tens of MTU/yr production levels required for a fleet of reactors. Production levels to date have been at most several hundred kgU per year. In the United States, fuel qualification efforts are progressing such that discussion with the NRC are underway for the eventual licensing of a production facility (Williams 2019).

D1-3.1. BASIC INFORMATION

D1-3.1.1. Generic Information on Particle Fuel and Its Possible Use in Various Types of Reactor Fuel Assemblies

Since the last published AFC-CBR (Dixon et al. 2017) interest in particle fuel has expanded well-beyond the use of TRISO in HTGRs. For this reason, the title of this module was changed to *Uranium-based Ceramic Particle Fuel Fabrication*. We are limiting this module to uranium-based since this nuclear material is where the current interest lies, and this module also falls in the D1-X contact-handling limitation. Some TRISO and BISO particle fuel-using cycles require the use and recycling of thorium/U-233, for which the refabricated particle fuel would require remote handling. One such HTGR equilibrium fuel cycle is shown on page 148 of *Nuclear Chemical Engineering* (Benedict and Pigford 1981).

Most particle fuel consists of tiny ceramic kernels of a uranium compound surrounded by coatings designed to prevent the escape of fission products from the kernel, thereby acting as a first line-of-defense in case of a loss-of-coolant event. The coating process has been under development since the 1960s and the multicoating product has been dubbed TRISO. These TRISO particle are then imbedded a non-fissile matrix material to form a fuel form of some geometry such as a sphere (a.k.a., pebble). circular cylinder (prismatic), or rectangular solid. Figure D1-3.1 shows the generic process for fabricating a particle fuel product, which may be as complex as multiple identical geometric fuel forms as described above pressed in a large block of heat conducting material (such as machined graphite or silicon carbide) or as simple as a molded sphere or pebble with thousands of TRISO microspheres dispersed within.

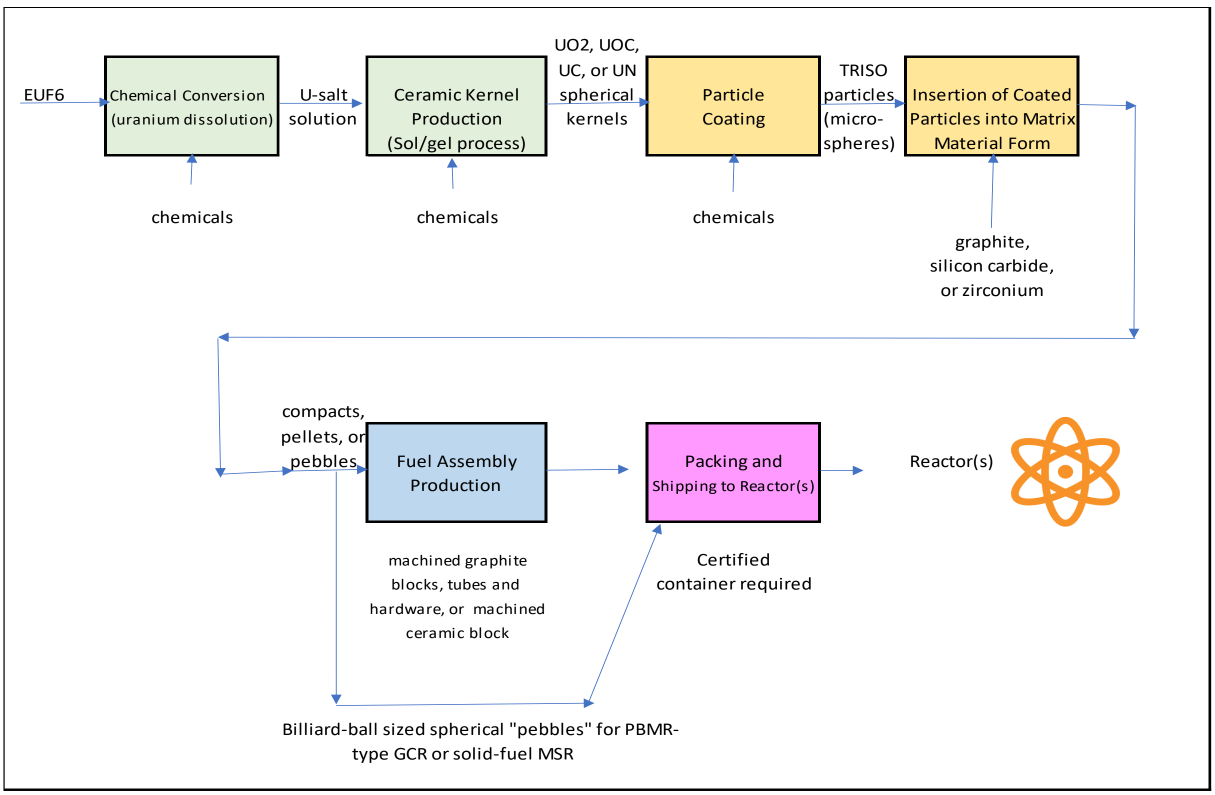


Figure D1-3.1. Generic process steps for particle fuel fabrication (not specific to a particular reactor technology).

The major fuel fabrication steps are as follows (note that various TRISO developers may have different proprietary sub-step process variants for each generic step):

- Conversion: Most likely HALEUF6 will be delivered to the fabrication facility and will need to be dissolved into the aqueous feed form needed by the sol-gel process used to produce uniform microspheres.
- Ceramic Microsphere Production: Uniform semi-liquid gel particle are produced in an immiscible fluid column or tube where surface tension spheroidizes them prior to washing, followed by drying and calcination/sintering step which converts them into high-density, ceramic kernels.
- Particle Coating: Fluidized beds are used to apply the TRISO coatings. More process details will be provided in a section below.
- Insertion of Coated Particles into a Mechanically Stable Matrix Capable of Transferring Heat to Coolant: For high-temperature reactors such as GCRs or FHRs a refractory non-nuclear material such as graphite or silicon carbide is used. For GCRs this form is likely a billiard-ball-sized pebble or circular cylindrical compact. For FHRs this form might be pebbles or planks which can be suspended in the molten salt. For advanced light-water reactor (LWR) and FR fuels silicon carbide or zirconium metal respectively might be used to form a microencapsulation medium for a pressed ceramic fuel or dispersion fuel pellet.
- Fuel Assembly Production: For GCRs or FHRs the cylindrical compacts or planks might be imbedded in a larger machined or 3D printed graphite or silicon carbide fuel assembly structure' For pebble bed GCRs or FHRs the billiard-ball-sized pebbles are the fuel assemblies and contact the coolant directly. These moveable pebbles can be continuously charged to and discharged from the reactor.
- Packaging and transportation: The fuel assemblies must be packaged in a secure and criticality-safe package for transport to the reactor.

Several reactor concepts in addition to the traditional HTGR-GCR are being considered for use of particle fuel. The following slide (Figure D1-3.2) from a U.S. DOE presentation (Feltus 2019) shows many such concepts and their developers (note: earlier U.S. DOE TRISO development efforts were called AGR for advanced gas-cooled reactor).

Beyond the AGR TRISO Program

GEN IV International Forum

Can TRISO fuel be used in other reactor designs?

- Molten Salt-cooled (e.g., FLiBe, FLiNaK,) reactor concepts use graphite matrix TRISO fuel directly, e.g. Kairos Power based on University of California – Berkeley pebble bed design
- Fast Gas Reactors, using SiC or other non-graphitic matrix compacts
  - French helium fast gas design ZrO_2 coating
  - UC fuel kernels in metallic cladding
  - GA's EM^2 alternate design
- Encapsulated fuel for LWR Accident Tolerant Fuel
  - TRISO in SiC matrix with SiC tubes or Zircalloy cladding (ORNL)
- Fast sodium/metal cooled reactors
  - Dispersion fuels, TRISO-like fuel in metallic matrix, metallic clad
  - TRISO in SiC Mixed Oxide fuel pellets (FFTF or MOX cores)
- Extreme high temperature reactors using refractory metals, UC or UN fuels
  - Space reactors, or niobium (Nb), tantalum (Ta), molybdenum (Mo), rhenium (Re), vanadium (V) and tungsten (W) alloys.

33

Beyond the AGRTRISO Program

Reactor Design Concepts and Advanced Fuel Designs Using TRISO Fuel

GEN IV International Forum

Company or Research Group	TRISO Fuel Form, Reactor Type, Design Concept	Deployment (target date)
Near-term Fuel and Reactor Concepts		
X-Energy	TRISO pebble bed HTGR **Xe-100 Reactor, TRISO-X fabrication facility** (Current funding: ART-15, 2 Industry FOAs, ORNL CRADA at $11.5M); Collaboration with Global Nuclear Fuel for DOD Micro-reactor and NASA nuclear thermal propulsion for space exploration. Collaboration with Centrus for X-energy TRISO fabrication facility	2024-2030
NGNP Alliance/**AREVA**	TRISO compacts, prismatic TRISO fueled HTGR **SC-HTGR** (steam cycle)	2027-2030
NC-II **AREVA** (Poland)	TRISO compacts, prismatic HTGR **SC-HTGR** (steam cycle) for Europe, Poland	2027-2030
Dept. of Defense	TRISO fueled mobile micro-reactors for strategic combat locations. Possible designs: HALOS, GA-vSMR, BWXT Nuclear, etc.	2025 demo 2028 FOAK
BWXT	TRISO fuel fabrication for DOD microreactors, Potential DOD microreactor	2022 (DOD)
Kairos Power	TRISO pebble bed, fluoride salt (Li_2BeF_4) cooled FHR, 3 cm dia. Pebbles, **Mark 1 Pebble-Bed FHR** (DOE Funding: 2 Industry FOAs announced)	2030 Demo, 2035 FOAK
Urenco, Amec Foster-Wheeler	TRISO compacts, prismatic HTGR, UCO or Th/U/O TRISO kernels for **U-Battery** 10 MW and 20 MW. Canadian review underway	2025 Demo 2030 FOAK
StarCore Power (USA)	TRISO in graphite matrix pebbles, helium-cooled HTGR, 20 or 80 MW, **STARCORE 20, STARCORE 80,** StarCore Nuclear (Canada) Canadian review underway.	2025-2030
General Atomics	UC bare kernels in SiC tubes. May use TRISO-like coating(s) as an optional design for fast-gas reactor **Energy Multiplier Module (EM^2)**	2030-2035
ORNL Accident Tolerant Fuel	FCM TRISO particles in SiC matrix pellets inside Zr, SiC or Stainless Steel cladding, as future LWR **ATF replacement** fuel	2030-2035
Longer-term Fuel and Reactor Concepts		
NASA	TRISO fueled compact reactor for future long-range missions for Mars for Space Nuclear Thermal Propulsion (UC or UN)	
MIT (Forsberg)	TRISO compacts, prismatic HTGR Fluoride salt (Li_2BeF_4) cooled FHR	
UltraSafe Nuclear	Various TRISO fuel forms: FCM TRISO in SiC matrix pellets in SiC tubes to replace LWR fuel pins, CANDU bundle rods, TRISO with refractory coatings for Space Applications, Canadian review underway.	

Abbreviations:
FCM Fully Ceramic Micro-Encapsulated
CANDU Canadian Deuterium U reactor
HTGR High Temperature Gas Reactor
LWR Light Water Reactor

34

Figure D1-3.2. Reactor concepts and developers with interest in TRISO-coated particle fuel (Feltus 2019).

Note that some special high-temperature microreactor applications might require the kernel to utilize ceramic uranium compounds uranium nitride (UN) or uranium carbide to attain an in-core fissile atom density to maintain reactivity with a high neutron-leakage system. Other concepts which might use TRISO include U-Battery (UK and Canada), Framatome (France), and Westinghouse Government Services (eVinci reactor in USA), The upper portion of Figure D1-3.3 shows below some of the geometric fuel forms possible for HTR concepts such as the fluoride-salt high-temperature reactor (FHR) and HTR. The bottom portion of the figure shows the coatings applied to the TRISO kernel in successive layers to provide fission product containment.

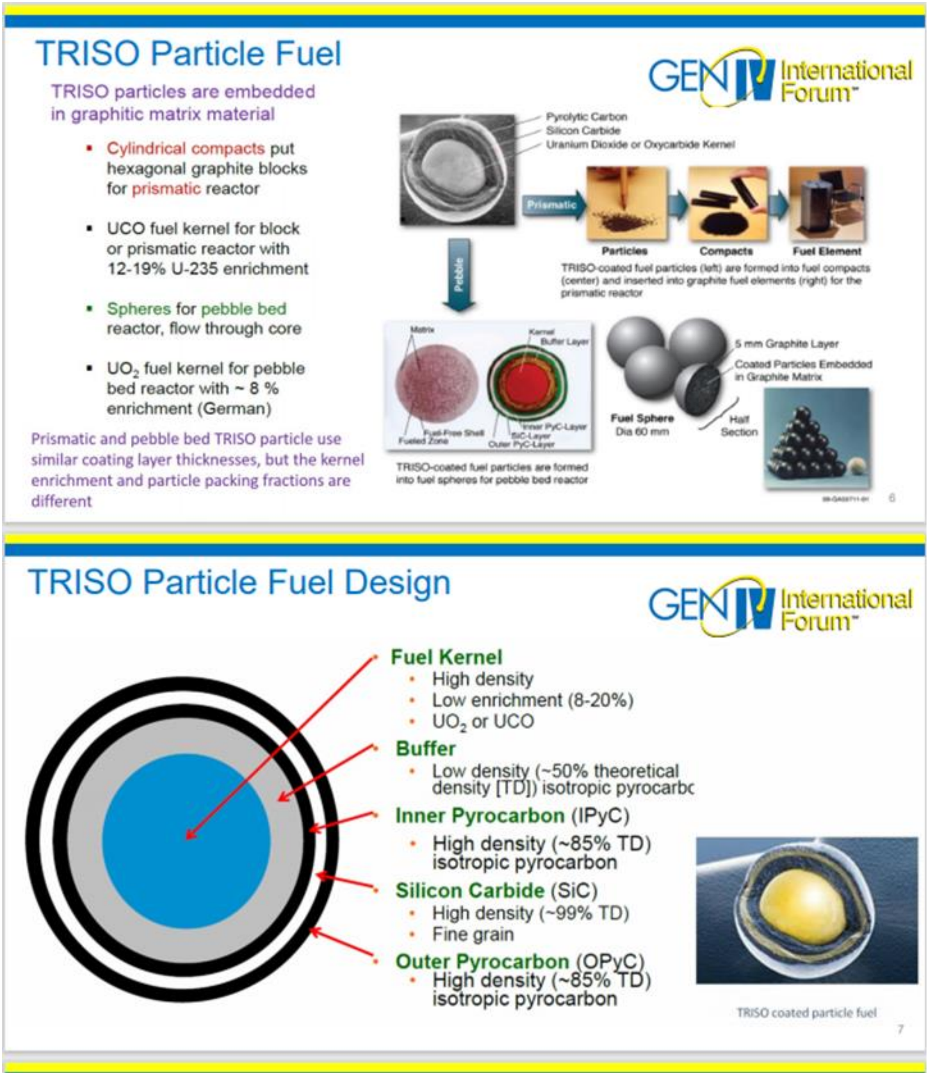


Figure D1-3.3. TRISO microsphere particle design and some fuel forms in which the particles can be incorporated (Feltus 2019).

Other reactor and fuel assembly configurations utilizing TRISO fuel are shown in the figures below. Figure D1-3.4 shows a fuel module for a proposed HOLOS-GEN portable microreactor and how it is constructed starting with TRISO enmeshed in a refractory matrix followed by insertion into multiple fuel bricks. Transportable microreactors of this type could realize widespread use in the military and in remote locations such as mines. This would create a significant market for TRISO microspheres in addition to normal stationary power reactor applications. Other companies working on microreactors are included on Figure D1-3.2. It should be noted that additive manufacturing (a.k.a., 3-D printing) is being investigated for use with complex fuel block shapes where TRISO is the imbedded fuel. Oak Ridge National Laboratory (ORNL) is investigating one such concept called the TCR or Transformational Challenge Reactor (Nelson 2019; Terrani 2020; Trammell 2019).

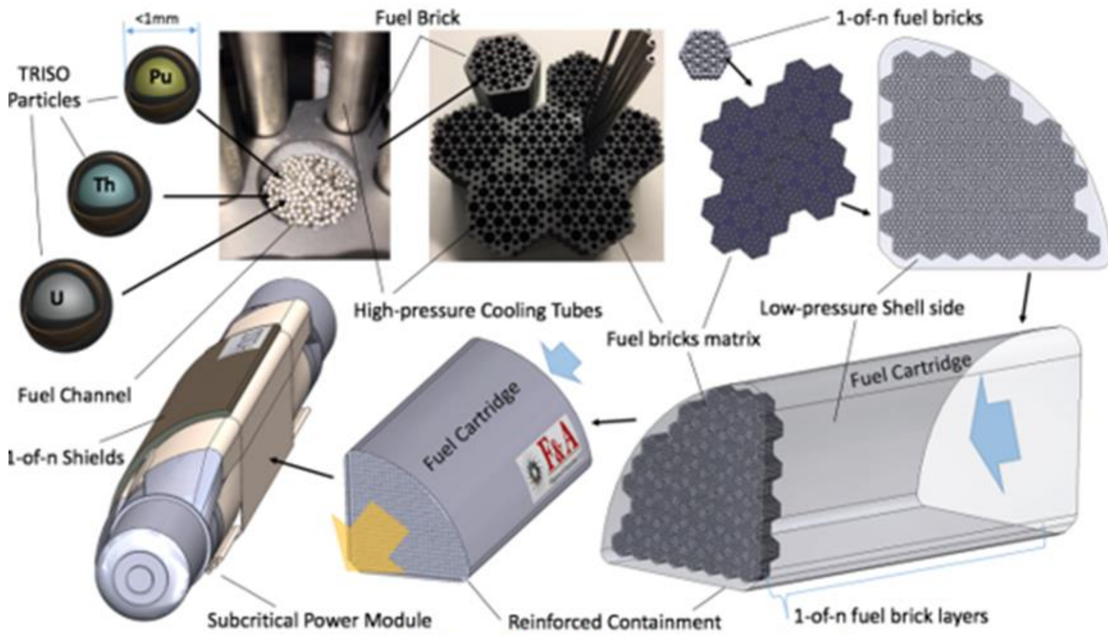


Figure D1-3.4. Fueling concept for HOLOS-GEN microreactor (Fillipone et al. 2018).

Figure D1-3.5 through Figure D1-3.7 deal with encapsulated fuel for use lower-temperature reactors (Terrani 2012) where traditional cylindrical pellets and cladding is used. The fission heat is transferred from the TRISO particles to the tubing wall by means of a ceramic or metallic matrix, depending on the reactor type. Both silicon carbide and zirconium metal are possible candidates. Figure D1-3.5 shows that such fully ceramic encapsulated fuel pellets proposed by Ultra Safe Nuclear Corporation (Patel 2021) appear very similar to conventional UOX pellets used for LWRs. The circular cross sections for two types of fully ceramic microencapsulated (FCM) pellets are compared to the circular cross section of a single typical UOX pellet in Figure D1-3.7.

Figure D1-3.6 shows the steps required to produce an FCM LWR fuel assembly from hundreds of thousands of TRISO microsphere particles (Ultra Safe Corporation).

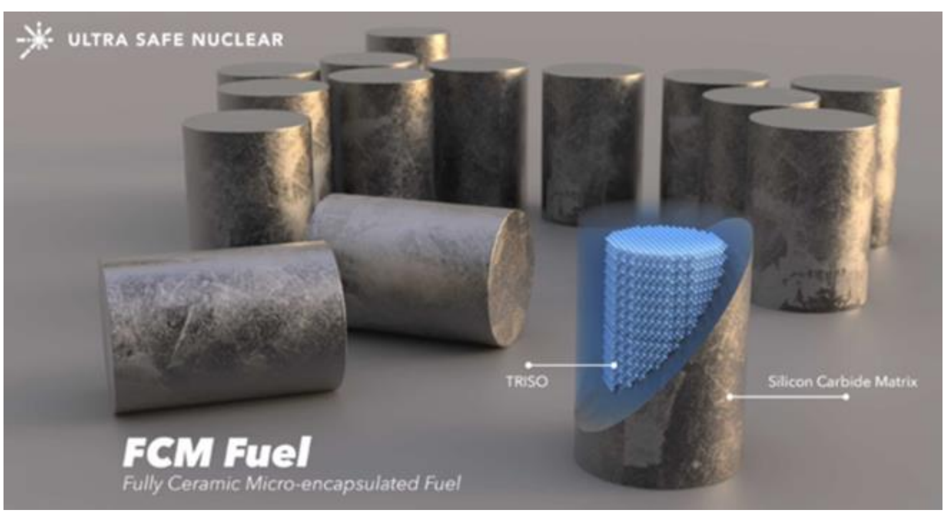


Figure D1-3.5. Photo of fully ceramic encapsulated fuel (FCM) pellets envisioned by Ultra Safe Nuclear Corporation (USNC) for use as an accident tolerant LWR fuel (Ultra Safe Nuclear Corporation).

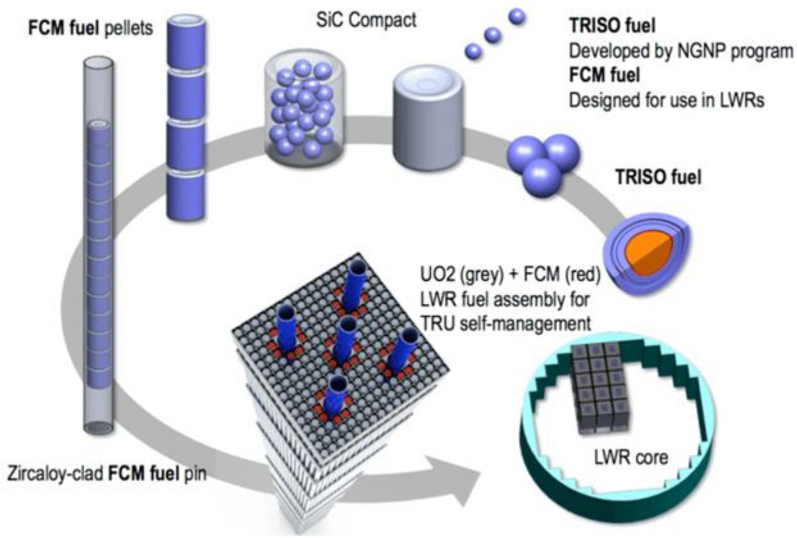


Figure D1-3.6. How TRISO particle fuel is incorporated into the FCM LWR fuel concept proposed by USNC.

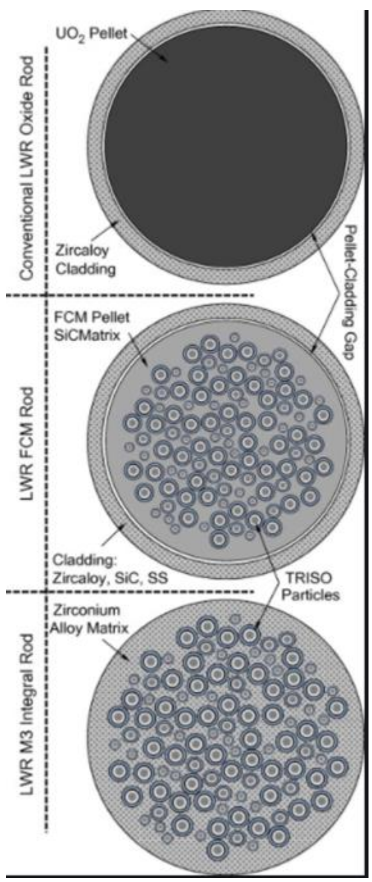


Figure D1-3.7. Comparison of FCM advanced fuel concepts with conventional UOX fuel (USNC).

The reader might note that little has been said about economics to this point. The reason that the multiple technical discussions are included above is to emphasize the fact that interest in microreactors, SMRs, and the TRISO-based fuel to feed them has grown markedly even since the last AFC-CBR published in 2017. A recent trade press article (Patel 2020) on the powermag.com website gives an excellent 6-page summary on recent TRISO development and some useful historical background on the TRISO technology which is now over 60 years old. All the recent interest in safer and more robust fuels indicates that a significant future market for TRISO in large quantities (tens to hundreds of MTU per year) might be evolving. It is likely that, like LWR fuel fabrication, there might be only two or three domestic providers of TRISO microspheres who would ship them to specialty fuel fabricators who manufacture the shapes, blocks, bricks, or tubular assemblies that are ultimately provided to various types of reactors. In essence the first three steps of Figure D1-2.1 would be a large-scale TRISO particle fabrication operation, and steps four through six would be reactor design-specific fabrication steps.

So far, all TRISO experience has been for HTGRs, so most cost information gleaned to date deals with that application. This background information and data from previous Module D1-3s in earlier AFC-CBRs is repeated below for the sake of completeness and to indicate how other fuel characteristics such as U-235 content and fabrication facility size are important cost drivers.

D1-3.1.2. Basic Information from 2009 AFC-CBD

In AFC-CBR's prior to this 2021 update the emphasis in this module was on graphite-imbedded HALEU or HEU-TRISO fuel intended for use in modular or monolithic HTGRs (e.g., HTRs or GCRs) cooled by high-pressure helium.

Fuel Form. The high temperatures envisioned for today's gas-cooled reactor 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 for FHRs), also affects the design of the fuel. The fuel form for GCRs is also intended to be the first line of defense-in-depth as far as safety is concerned, with the fuel form itself described as part of the overall containment philosophy. The volatile fission products are contained by the fuel coated-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 illustrated in Figure D1-3.8:

1. The prismatic concept in which a fuel assembly or block is in the shape of a hexagonal graphite cylinder with holes drilled for the 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 TRISO fuel particles dispersed within. This is the concept that has been developed over many years by General Atomics (GA) as the MHTGR and more recently the direct-cycle gas-turbine modular-helium reactor (GT-MHR). A *Scientific American* article by Harold Agnew (Agnew 1981) discussed these early monolithic HTGR reactor designs.
2. The other fuel assembly form is that of a billiard-ball-sized graphite sphere or pebble with the coated-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.)(Note added in 2021:China recently announced plans to deploy the PBMR concept and is preparing to fuel their first reactor module at Shidaowan (Nuclear Engrg Intl 2020). X-Energy in the United States is pursuing an 80 MW(th) smaller version of a PBMR called the XE-100.

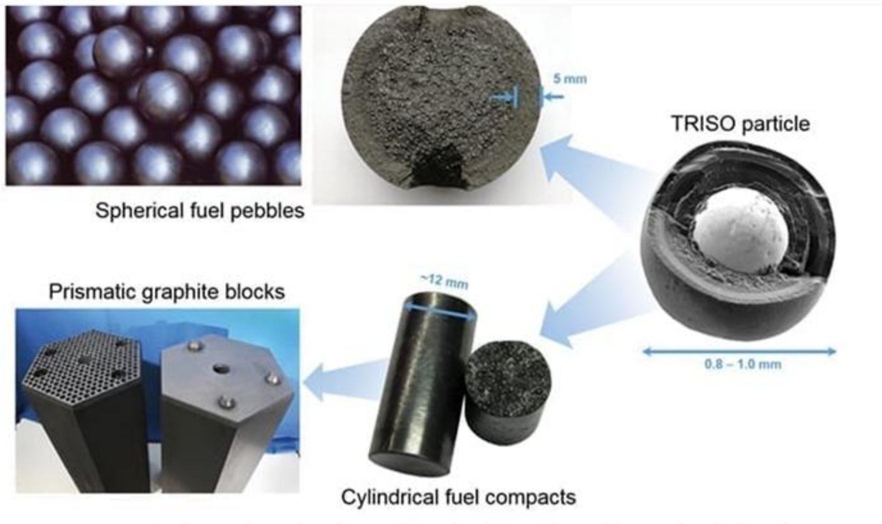


Figure D1-3.8. TRISO-enabled fuel forms for GCRs.

D1-3.1.3. Basic Information from 2012 AFC-CBD and 2017 AFC-CBR Updates.

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 UO2 or UCO kernel fuel could also be used with a molten-salt coolant, hence the change in this module's title from gas-cooled to high temperature. The gas-cooled reactor itself is still covered in Module R-3, and a reactor module (R-8) has been added for solid-fueled molten-salt cooled reactors (i.e., fluoride-salt reactors [FHRs]).

- For economic reasons the utility ESKOM and the South African government have abandoned their ambitious 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. Department of Energy (DOE) has slowed down its NGNP (Next Generation Nuclear Plant) research, development, and demonstration program, for which the demonstration plant was to have been 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 (AGR) is still underway at some national laboratories (ORNL and Idaho National Laboratory [INL]). There is also a small joint effort with Russia on the use of Pu-loaded TRISO fuels for disposition of plutonium from military programs. (A 2021 note: the United States-Russian Federation [or U.S.-RF] Pu-disposition program has been cancelled.)

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 first-of-a-kind (FOAK) plant, a 2,100 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 HALEU as ceramic TRISO fuel particles. 300,000 such TRISO-loaded graphite spheres, each approximately the size of a billiard ball, per year are required for the reactor core. Available cost information on this facility is analyzed in Section D1-3.6 (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 Gen IV work deals with the reactors and possible process heat applications rather than with the fuel manufacturing process.

D1-3.2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

Two GCR Fuel Concepts. All of the above discussed coated particle fuel concepts, however, have a common front-end fuel production technology. The fissile material, enriched uranium, U-233, or plutonium, in the form of an oxide (UO2 or PuO2) or other ceramic forms (e.g., UCO), exists as tiny 200 to >500 micron microspheres or kernels, which are coated with layers of mechanically tough and highly refractory coatings of porous carbon, silicon carbide, and pyrolytic 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. In the back-end fabrication steps thousands of these particles are then imbedded in a graphite, ceramic, or other matrix that forms the pebble or cylindrical compacts or other geometric forms. For early large MHTGRs such as those designed by GA the cylindrical compacts were inserted in a prismatic hexagonal block. For TRISO-based 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 HEU at >90% U-235. For nonproliferation reasons, all U.S. non-military reactor designs have backed off to low-enriched uranium (LEU) enrichments in the range 8 to 19.9% U-235 (Kramer 2020). The fuel for all the above concepts is often referred to as coated particle fuel as opposed to homogeneous pellet or cast alloy fuel for other reactor concepts. Note vibrocompacted fuel [VIPAC] might use uncoated microspherical particle fuel where only kernels of various sizes are packed in a tube. (See Fuel Fabrication Module D1-5.) GA's earlier reactor designs included some fertile natural uranium TRISO particles in their design and in the past has incorporated thorium in the form of thoria (ThO2) fertile particles. This was done for the now decommissioned Fort St. Vrain MHTGR near Platteville, CO.

Status of Industry. Unlike for LWR fuel, no large-scale (tens to hundreds of MTU/yr) coated particle fuel manufacturing capability exists in the United States (or in the world for that matter). Because there is no fleet of electricity-producing or industrial heat-producing reactors of a design requiring TRISO fuel, this fact is not surprising. (The United Kingdom has an aging fleet of lower-temperature CO2-cooled advanced GCRs using stainless steel clad UO2 fuel that are not candidates for further deployment.) All the world's existing high-temperature GCR projects had their fuel produced in pilot scale facilities of at most a few MTU/yr. A U.S. commercial MHTGR, Fort St. Vrain, was operated for several years near Platteville, Colorado. Its fuel was produced in a pilot scale facility operated by GA at Sorrento Valley near San Diego, California. Pebble bed fuel pilot lines in China and originally 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. NFI is now teaming with U.S. company X-energy to assist in the production of TRISO-based annular fuel compacts (WNN 2020b). 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. GA Technologies of San Diego, California, has decided to pursue only the reactor part of this fuel cycle.

If TRISO-based reactor technology is to be deployed for large-scale electricity generation, heat-production, or specialized military and space applications, a large-scale particle fuel production facility will need to be built to support the fuel needs for multiple constructors and operators of such advanced technologies. In terms of heavy metal or uranium throughput, commercial TRISO fuel production facilities are likely to be significantly smaller (tens to low hundreds of MTU/yr) than the world’s major LWR fuel fabrication facilities which are 500 to 2,000 MTU in production capacity. This is partially because the U-235 enrichment of proposed HALEU TRISO fuel is at least two to five times 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 UO2 in the form of pellets. However, for GCR, FHR, or microreactor fuel, much of the total fuel assembly weight will be machined or formed graphite or other matrix materials such as silicon carbide. The TRISO fissile mass is dispersed within defined locations within the matrix material.

From 1988–1992, U.S. 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 MHTGR modules at the INL.[1] These steam cycle MHTGR modules were to use 93.5% U-235 weapons-grade HEU 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.

After the end of the Cold War, GA (GA Technologies 1994) proposed the GT-MHR as a plutonium-dispositioning reactor both in the United States and Russia. (The same particle fuel concept can be used with PuO2 or other plutonium compound ceramic kernels.) GA was 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 was ever presented. The GT-MHR uranium burner was at the time 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 was gleaned from conference papers, and some of this is discussed in the economics sections below.

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

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

There is today, however, considerable new developmental work taking place in the area of TRISO fuels. Figure D1-3.2 listed several reactor concepts and TRISO development efforts that are being supported in some form by DOE and its national laboratories. 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 ORNL 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.

Table D1-3.1 lists the three major corporate TRISO fuel developers in the United States, their locations, and the reactor programs they hope to support with fuel. Also listed are the reference citations for trade process articles that describe recent new developments in more detail:

Table D1-3.1. Current 2021 TRISO fuel developers in the United States with plans for significant capacity to support reactor builds or new accident tolerant fuel concepts for existing plants.

Company	Development or Production Locations	Reactor Development Projects Presently Supported	Comments	Citations for References in Section D1-3.10
BWX Technologies (BWXT)	Lynchburg, VA	DOD microreactors, Transformational Challenge Reactor (ORNL)	Existing Lynchburg facility has Category I and II capability. Hundreds of kgU/yr planned.	(WNN 2019a) (WNN 2019c) (WNN 2019e) (WNN 2020a) (WNN 2020c) WNN 2020e) (Wald 2019) (Patel 2021) (Simmons 2020)
X-Energy partnered with Global Nuclear Fuels and CENTRUS	Oak Ridge, TN Wilmington, NC	XE-100 Modular GCR	Existing Global Nuclear Fuel (GNF) facility readily adaptable to Category II HALEU production.	(WNN 2019b) (WNN 2019c) (Wald 2019) (WNN 2020b) (Patel 2021) (McClure 2018) (Business Wire 2018)
Ultra Safe Nuclear Corporation (USNC)	Salt Lake City, UT (under construction)	LWRs using Fully Encapsulated Ceramic Fuel, Micro-Modular Reactor for remote locations		(Patel 2021) (Patel 2021) (WNN 2020d)

GCR Fuel Fabrication Processes. 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 D1-3.9 shows a generic TRISO fuel fabrication process being considered by the Advanced Fuel Cycle Initiative Fuels Working Group for mixed oxide TRISO fuels which could have other actinide components in addition to uranium. The basic process for U-only fuel is basically the same except for health, safety, and environmental (HS&E)-driven process containment requirements. Production of the ceramic UO2 or UCO kernel is a crucial step in the process. 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 a uranyl nitrate hexahydrate (UNH) must be produced from the UF6. 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. In the **external gelation** process used outside of the U.S. uniform UNH solution drops of the desired size are formed and then contacted with ammonia to form gel-spheres (gel-precipitation process). The United States uses an **internal gelation** process because it produces more highly spherical particles and can be used for UCO, UCx, and UN fuels. Internal gelation includes the addition of urea and hexamethylenetetramine (HMTA) to chilled UNH. The droplets are formed (either above or within) a warm, immiscible forming fluid that causes the droplets to spheroidize and, as they warm, the urea and HMTA decompose to release ammonia, which gels the UNH. These gels are washed to remove forming fluid residues (if needed) and washed with ammonia water to ensure complete gelation For both the external and internal gelation processes washed gel-spheres are 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 overcoated with resonated-graphite powder and pressed 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. To meet the requirement for quality control for TRISO particles in a reactor core, the defective particle fraction must be kept very low. This is true, especially for modern vented confinement reactor designs, 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. Figure D1-3.9 shows a schematic for TRISO-X production presented to the NRC in 2018.

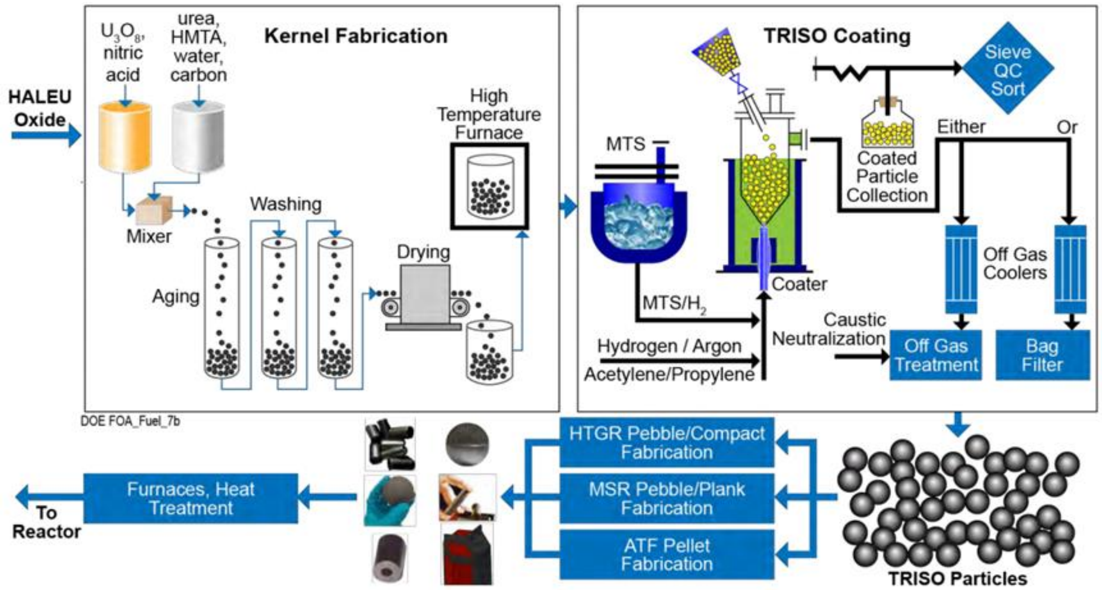


Figure D1-3.9. X-Energy TRISO-X production schematic (Pappano 2018).

D1-3.3. PICTURES AND DIAGRAMS

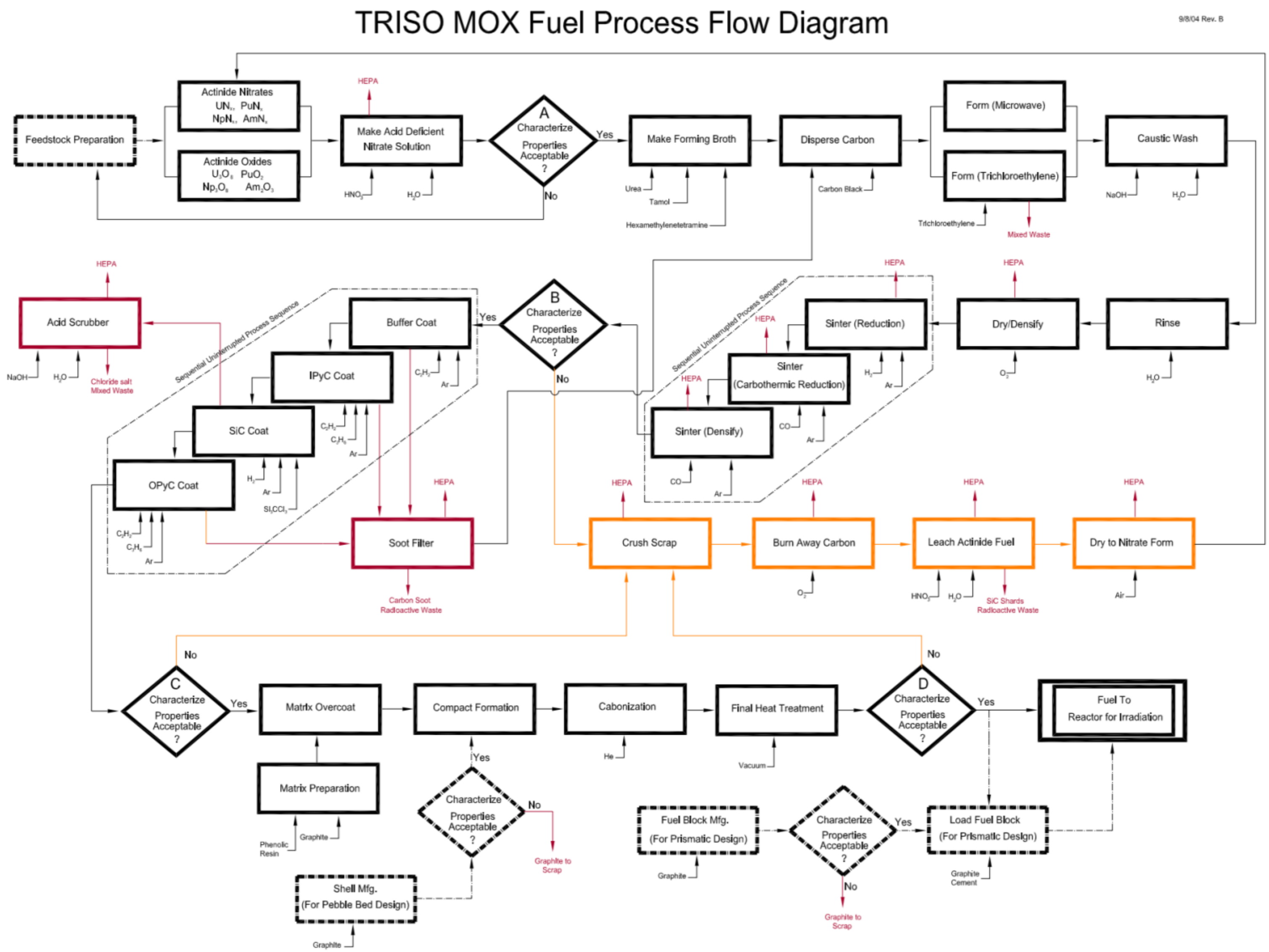


Figure D1-3.10. TRISO MOX fuel process flow diagram (Shaber 2004).

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 HALEUF6 coming from a new centrifuge enrichment plant or from blended U.S. or Russian EUF6 derived from surplus virgin HEU. HEU arising from the reprocessing of government research reactor, such as EBR-II (Patterson 2019), or arising from the reprocessing of military production reactor or naval reactor fuel could also be used if sufficiently clean: for introduction into a contact-handling fuel fabrication facility. The concern for clean is not just radiological. There are also chemical impurity specifications as excessive impurities will attack the TRISO coating layers, especially the silicon carbide, and result in in-pile, TRISO particle failures.

The security and safety implications for storing and transporting HALEU TRISO-based are just starting to be examined from a technical and regulatory standpoint (McKirgan 2020). It may be desirable to co-locate HALEU enrichment capacity with the front-end steps of TRISO fuel fabrication. HALEU enrichment and its interfacing aspect with other fuel cycle steps will be the subject of a future AFC-CBR Module C update.

Back-end interface. Irradiated blocks and pebbles are the fuel forms that exit a GCR fuel fabrication facility. Special storage/transport packages will need to be designed to store, 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 (Forsberg 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 where the matrix and block material such as graphite must be removed. The Generation IV Roadmap (GIF-004-00 2002) for gas-cooled systems discusses research and development issues with reprocessing and other aspects of this technology. In a recent Radwaste Solutions article a strategy for the handling of TRISO-based SNF from a solid-fuel molten-salt-cooled reactor is presented (Vergari et al. 2021)

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 and the use of multiple shifts. The size of an optimal automated TRISO particle fabrication line will be determined by the market, which hopefully will include many reactor types and vendors.

In the cost-related sections below a unit cost ($/kgU) versus capacity (MTU/yr) relationship will be derived by analogy from the 1978 NASAP study (Olsen et al. 1979). This will be useful for selecting a WIT unit cost range for HALEU TRISO produced in an Nth-of-a-kind (NOAK), NRC Category II facility of 100 MTU/yr capacity. A plant this size could provide fuel for several fleets of microreactors, SMRs, and some FCM-accident tolerant fuel (ATF) burning LWRs.

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

D1-3.6.1. 2009 AFC-CBR Cost Data.

Cost and Pricing of GCR Fuel Fabrication. The fabrication cost of TRISO-based GCR fuel is most useful if it can be expressed in $/kgU or $/kgHM and not include the ore, natural U3O8 to UF6, and enrichment components. In the literature, it is hardly ever expressed in this fabrication-only way, so in the cases below the fabrication-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 USD, this 3 MTU/yr NRC Category I HEU fuel fabrication plant, based on unpublished Fluor-Daniel study, would have cost $355 million and have annual operating costs of $22.6 million/yr. This operations cost does not include the ore, conversion, uranium enrichment separative work units (SWU) or UF6 to UO3 or UNH conversion needed to supply HEU feed material (UO2 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 kgHEU 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) HEU in a Category I facility 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 (i.e., HALEU) and increased the fuel burnup, thermodynamic efficiency, and electrical capacity of the reactor, which will drive down the per kWh unit fuel cycle cost component of the LCOE (levelized cost of electricity).

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(deuterium-tritium) targets for inertial confinement (a.k.a., laser) 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 design, 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 D1-3.2 as follows, (Note: ore, SWU, graphite, conversion from UF6, etc., add approximately $5,900/kgU to the stand-alone particle fabrication cost, based on 2002 USD unit costs for ore, conversion, and SWU):

Table D1-3.2. Fabrication costs as a function of TRISO particle cost (2002 USD).

Reference: Particle Cost (U.S. cents/particle)	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.)
20	$2,540,000	$573,000	$2,560,000	$579,000
1	127,000	28,700	147,000	34,700
0.1	12,700	2,870	33,000	8,850
0.003	382	860	20,700	6,070

Today’s 2009 USD 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 TRISO, and <25% of particles containing natural uranium TRISO.

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 USD; this would be ~$16,000 per block in 2009 USD. 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 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/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 (EEDB) code of accounts level only. All the costs are in 1992 constant USD. The data from this study were input by this section's author to the Power Generation Cost model, G4-ECONS (Williams 2007), 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 2008 constant USD using a construction index similar to the Handy-Whitman Utility Construction Index.

The reactor core for each MPBR module consists of 360,000 round, billiard-ball-sized pebbles with 7g (expressed as uranium) of 8% U-235 enriched UO2 (HALEUOX) in each. The UO2 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 (or 0.1 cents per TRISO microsphere) in 1992 USD including all front-end fuel cycle steps. The author of this section assumes that this has risen to $28 in 2009 USD. 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 unit cost, in the opinion of the analyst for this report, is very optimistic given the complexity of GCR fuel fabrication. Such a TRISO fuel production plant would have to be highly automated.

Facility Cost Projections. The author of this report located some fuel fabrication facility cost projections for both the South African PBMR (IAEA 2001; Nuclear Engineering International 2005; Platts 2005) and GA GT-MHR (GA Technologies 1994) concepts. Both of these costs were for fuel fab facilities to be located outside the United States, either in South Africa or Russia. The GT-MHR data were for a plant producing PuO2 TRISO fuel for use in the joint U.S.-RF Plutonium Disposition Program. Table D1-3.3 shows the fissile loading, throughput, and cost projections for each of these facilities. Based on experience in the United States with other nuclear facilities, these cost projections would likely be considerably higher for similar facilities located in the United States or Western Europe.

ESKOM of South Africa at one time (May 2005) announced (Nuclear Engineering International 2005; Platts 2005) the award of a $20 million design and construction contract for a 270,000 sphere (pebble fuel assembly) per year HALEU (8% U-235) pilot plant to support their PBMR project. If this ~2.4 MTU/yr plant operated for 10 years and the capital cost is distributed over the uranium processed (9 g U per pebble), the capital component of the unit cost comes to ~$825/yr. The operating cost anticipated for this pilot plant was not given, but it is anticipated that a staff of 50 will be required. At an $80,000/yr loaded average staffing cost about $4 million/yr would be required. Spread over the 2 MTU/yr, this is an additional $2,000/kgU. As PBMR orders come in, South Africa will add additional production capacity to this pilot facility. This staffing operations and maintenance (O&M) component cost is felt to be much more realistic than the $20 million capital cost for what will be a very complex process facility.

Table D1-3.3. Data for projected ESKOM and GA TRISO fuel fabrication facilities.

ESKOM Pebble-Bed Modular Reactor (PBMR)	for Uranium Fuel:	GA Modular Helium Reactor (GT-MHR) U or Pu burner	for Uranium or Plutonium fuel as noted:
		TRISO Particles per Cylindrical compact	4230
TRISO Particles per Sphere (Pebble)	~15000	Compacts in Full Core of one 286MWe GT-MHR module	3102120
Spheres in Full Core of one 117MWe module	~360000	Average enrichment of U in initial core	10.31%
New Spheres introduced annually per module	~122000	Total U mass of initial core for one GT-MHR module (MTU)	4681
Grams of U in one sphere	9	Average 235 enrichment of U in annual GT-MHR reload	15.46%
Ave U-235 Enrichment of TRISO fuel	8.0%	Total U mass of annual MHTGR reload for 1 module (MTU)	2262
		Total Pu mass of initial core for one GT-MHR module (MTPu)	634
Uranium loading of full core (MTU) for 1 module	3.24	Total Pu mass of annual reload for one GT-MHR module (MTPu)	262
Make-up Uranium required per year to fuel one module (MTU)	1.10	Projected Yr 2000 US$ cost in Russia (Seversk) for Pu-TRISO FFF supporting 4 GT-MHR modules (Nth of kind plant) [$M]	126
		Annual throughput of Pu-TRISO FFF [kg Pu/yr]	1048
Proposed prod'n capacity of initial ESKOM fuel fab plant based	12.6	Annual operations cost for Pu-TRISO FFF in Russia ($M/yr)	28.4
on 1.4 million spheres/yr (MTU/yr)		Capital cost per unit of capacity ($/kgPu/yr)	120229
Estimated capital cost of ESKOM fuel plant based on	23	Operations cost per kgPu processed [$/kgPu]	27099
nth-of-kind cost of $2M/reactor supported ($M)		Unit cost using 10 year amortization at 4% annual discount rate (in $/kgPu) [in Russia]	41922
Capital cost per unit of capacity ($/kgU/yr)	1825		
		Projected Fuel cycle contribution to electricity cost	13
ESKOM Projected Fuel cycle contribution to 16.7 mills/kwh	4.0	(mills/kwh) from nth of a kind Pu-burning plant	
electricity cost (South African conditions; nth of a kind)			
[Information from IAEA-TECDOC-1198 (Feb 2001)]		**[Information from General Atomics Reports]**	

Uranium-Plutonium TRISO. Because of the need for gloveboxes and more nuclear safety controls for plutonium fuels in a Category I facility, the costs associated with the use of plutonium TRISO fuels are likely to be an order of magnitude higher than for 19.75% U-235 LEU TRISO from a Category II facility on a per kilogram (heavy metal) basis.

G4-ECONS Calculation of TRISO Unit Cost. Because of the high process complexity (and not radiological considerations) it is likely that the lowest unit cost for HALEU TRISO fuel will be on the order of that (the high unit cost) for commercial MOX fuel (i.e., around $5,000/kgHM if the SRS-MFFF projected costs are included in the MOX database in this case). Using some data from the MIT/UC/OSU study cited previously and the G4-ECONS Fuel Cycle Facility economics model (Williams 2008), one can deduce what the capital cost of TRISO plant might be for a given production capacity. Figure D1-3.11 shows the breakdown of the unit cost and a capital cost for a TRISO facility of capacity 50 MTU/yr. This fabrication cost would be about $35 per MPBR pebble for spheres containing 7 grams of 8% U-235 UO2. The overnight cost for the facility would be around $2 billion. This plant could supply fuel for ~6,500 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 desription	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		
Specific Capital Cost	**$43**	**$/kgHM/yr**	
Int During Constr as % of Overn't Cost	**7.9%**		

Levelized & Annualized Cost Components:

	$M (US) /yr	$/kgU	
Capital	140.4	**3511.12**	
O&M (Production)	55.0	**1375.00**	
D&D Fund	1.5	**37.63**	
Total	**196.9**	**4923.75**	**"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 D1-3.11. Breakdown of unit and capital cost for a TRISO facility (from 2009 AFC-CBR).

D1-3.6.2. 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, 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 preconceptual 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. A high 1978 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 UO2 fuel at that time should give a good indication of the technical complexity of manufacturing these fuels even today. Table D1-3.4 shows the unit cost ratios for selected fuels to that for PWR UO2 fuel (i.e., what this module's author calls complexity ratios). It should be noted that in constant 1978 USD 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 USD 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 $2,132/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 dominate fuel fabrication costs more quantitatively for new fuel types since 1979. Most important of these would be regulatory costs such as meeting current nuclear standards, fuel qualification, building safety and security requirements, 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 particle-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 D1-3.4. 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 UO2 fuel from 2012 AFC-CBR Update ($/kgHM)	Calculated Year 2012 USD Unit Cost Using Ratios from ORNL/TM-6522	Remarks on Fuel in Table 18 ORNL/TM-6522
PWR $LEUO_2$	1.00	350	350	High-capacity plant (1,500 MTU/yr); 1979 USD unit cost was 110/kgU or $/kgHM
PWR $(U, Th)O_2$	1.09		382	High-capacity plant (1,000 kgHM/yr)
PWR MOX (U, Pu)	5.27		1,845	MOX plant assumed highly automated with high capacity (1,000 MTHM/yr); remote ops and maintenance
HWR (natural UO_2)	0.59		207	High-capacity plant (1,500 MTU/yr)
HWR (slightly enriched $LEUO_2$)	0.60		210	High-capacity plant (1,500 MTU/yr)
FR MOX (U, Pu)	8.45		2,959	High-capacity plant (1,000 MTHM/yr); remote ops and maintenance
FR metal (U, Pu, Zr)	7.73		2,705	High-capacity plant (1,000 MTHM/yr); remote ops and maintenance
HTGR $LEUO_2$	6.09		2,132	High-capacity plant (500 MTU/yr)
HTGR (MEU, Th) O_2	5.64		1,973	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 U.S. DOE-NE NGNP project. This Chinese 2.1 MTU per year graphite-pebble plant is projected to cost 230 million yuan or about $36 million. It will fuel the two 100 MWe FOAK HTRs under construction at Shidoawan, China. No annual operations cost projections are available for this plant. Table D1-3.5 shows an analysis of the Chinese data from (World Nuclear Organization 2012) and this author's own analysis of operations costs which are used to project the unit cost of TRISO-based graphite HTR fuel.

Table D1-3.5. Unit HTR fuel fabrication costs derived from an 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 $36 million capital cost to obtain the capital component of the unit fabrication cost. (This is the method used in G4-ECONS for reactor economics). 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 D1-3.3 and Table D1-3.4 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 (Idaho National Laboratory 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 form was prismatic and assumed to cost from $10,600 to $26,500 per kgU from a small capacity dedicated plant.

The following Table D1-3.6 summarizes HTR fuel fabrication cost data from the above and other recent sources. It was used to select the 2012 AFC-CBR WIT unit cost range.:

Table D1-3.6. 2012 AFC-CBD Update what-it-takes HTR fuel fabrication unit costs from various sources (constant 2012 USD).

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.1979) Handy-Whitman escalation only (LEUO2 kernels from high-capacity plant) MHTGR TRISO (D1-17)	N/A	2,132	N/A
HTR Pebble Fuel with $LEUO_2$ 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 (Idaho National Laboratory 2012)	10,600	N/A	26,500
Personal communications from unnamed fuels experts (range only)	5,000	N/A	20,000

A few recent unnamed 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 as with UO2 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.

D1-3.6.3. 2017 AFC-CBR Cost Data

No new cost data was developed in the period 2013–2017, and the 2017 WIT data presented below in Section D1-3.8 is merely an escalation-only increase in unit cost from the 2012 values.

D1-3.6.4. New 2021 Cost Data for this Update

General Comment. Compared to standard LWR fuel, TRISO and other advanced ceramic fuels have the advantages of longer in-core residence times, higher burnup, use of higher temperatures for increased thermodynamic efficiency of the reactor, and inherent safety due to the much higher melting point and lack of possible cladding fuel chemical reactions. This should be true of GCRS, FHRs, and even LWRs that use ATFs with ceramic fully encapsulated fuel. A recent research article (Carlson et al. 2020) does a very complete economic analysis comparing fueling a NuScale 160 MW(th) Small LWR with high burnup, but higher unit cost HALEU fuel as opposed to conventional UOX LWR fuel achieving lower burnup. The figure of merit for comparison is the LCOE (a.k.a., LUEC). One must face the fact that TRISO particle fuel will be more expensive to fabricate on a per kilogram of U basis, but that the fuel cycle component of the $/kw(th) or $/kw(e) figure of merit may not be affected in the same manner because the reactor will use far less fuel (uranium) on an annualized basis. One must also be concerned about the additional ore, enrichment (SWUs), andU3O8 to UF6 conversion required for HALEU on a per kilogram basis. The use of less fuel per unit of energy, however, will offset the per kgU cost increases in these items. In the sections below the intent is to examine only the unit cost of TRISO production and where possible its formation into fuel assemblies for various reactor concepts.

NASAP Studies. One of the late 1970s NASAP documents (Olsen et al. 1979) did an extensive analysis of large monolithic MHTGR fuel cycles with both once-through use and recycle of TRISO-based fuel. Most of these fuel cycles (Table 16 in the ORNL/TM-6522 document cited above) made extensive use of thorium oxide as BISO particle fuel in the fuel assembly along with enriched UO2 TRISO to enable the breeding and subsequent burn of U-233. The unit fuel fabrication cost given in this report did not break down the unit cost between uranium and thorium-based particle fuel. For this reason, case OT-1, which was all-uranium contact-handled fuel at 10% U-235, was chosen as the best case for any comparison. Production of graphite block type fuel with imbedded TRISO was estimated at $530/kgU for a 520 MTU/yr plant capable of supporting eighty 1,000 MWe once-through MHTGRs. Based on the NASAP-based methodology described in all the contact-handled cylindrical metal clad fuels (Modules D1-1, D1-2, D1-4, D1-5, D1-6, and D1-7) one can estimate what this unit cost would amount to in today's USD and under today's regulatory and project financing environment. In Module D1-1 (LWR UOX) it was found that the 1978 USD unit cost for LWR UOX (in Table 12 of ORNL/TM-6522) of $100/kgU for a 520 MTU/yr facility would increase to the mean WIT value of $400/kgU in 2020 constant USD. This factor of 4 increase includes inflation, escalation endemic to nuclear projects, a more robust building meeting today's Category III standards, and the beneficial effects of a longer assumed plant life and lower interest rates for government-backed financing. Applying this same factor of 4 to the NASAP TRISO unit cost of $530/kgU would result in a 2020 USD unit cost of $2,120/kgU. If the same percentage uncertainty bounds of -40% and +50% of the PWR UOX unit fabrication cost mean are applied to TRISO, a low and high unit cost of $1,272/kgU and $3,180/kgU respectively results. Table D1-3.7 summarizes these results:

Table D1-3.7. MHTGR TRISO unit cost range based on late 1970s NASAP study.

All costs in 2020 USD >>	Low ($/kgU)	Mid ($.kgU)	High ($/kgU)
MHTGR all 10% U-235 TRISO imbedded in graphite compacts (NASAP GA-type design assumed)	1,272	2,120	3,180

Note no extensive analysis or verification of the NASAP MHTGR fuel cycle studies was undertaken. This contrasts with the cylindrical contact-handled fuels discussed in other D1-X fuel cycle modules. Such further study of the NASAP assumed TRISO production flowsheet and reference fabrication plant design would be worthwhile as a future Systems Analysis and Integration (SA&I) activity.

FHR Fuel Fabrication Study by Georgia Institute of Technology. Georgia Tech student, Christopher Kingsbury, developed *Fuel Cycle Cost and Fabrication Model for Fluoride-Salt High-Temperature Reactor (FHR) "Plank" Fuel Design Optimization* as a master's thesis (Kingsbury 2015). The base reactor technology chosen for study was the ORNL-developed one described in Module R-8, "Solid-fueled Molten Salt Reactor," of the 2017 AFC-CBR (Dixon et al. 2017). Diagrams of the core configuration and plank design are in both the Kingsbury and AFC-CBR documents and are not repeated here. Development of a model for optimizing the fuel cost as a function of (1) the HALEU U-235 enrichment and (2) the packing fraction of the TRISO particles imbedded in the graphite planks, was a major part of this thesis. TRISO fabrication costs were separated from the graphite molding and particle imbedding costs. TRISO costs were based on a very wide range of costs per coated particle similar to the method used in Table D1-3.2 for the gas-cooled GT-MHR. Figure D1-3.12 from Kingsbury's thesis shows the per kgU cost ranges for the various components of plank manufacture for a plank with a 30% TRISO packing fraction. The TRISO fabrication cost is the most uncertain parameter. The SA&I author of this report suggests the mid-case range (Figure D1-3.12) of $1,700/kgU to $9,000/kgU for TRISO production is reasonable.

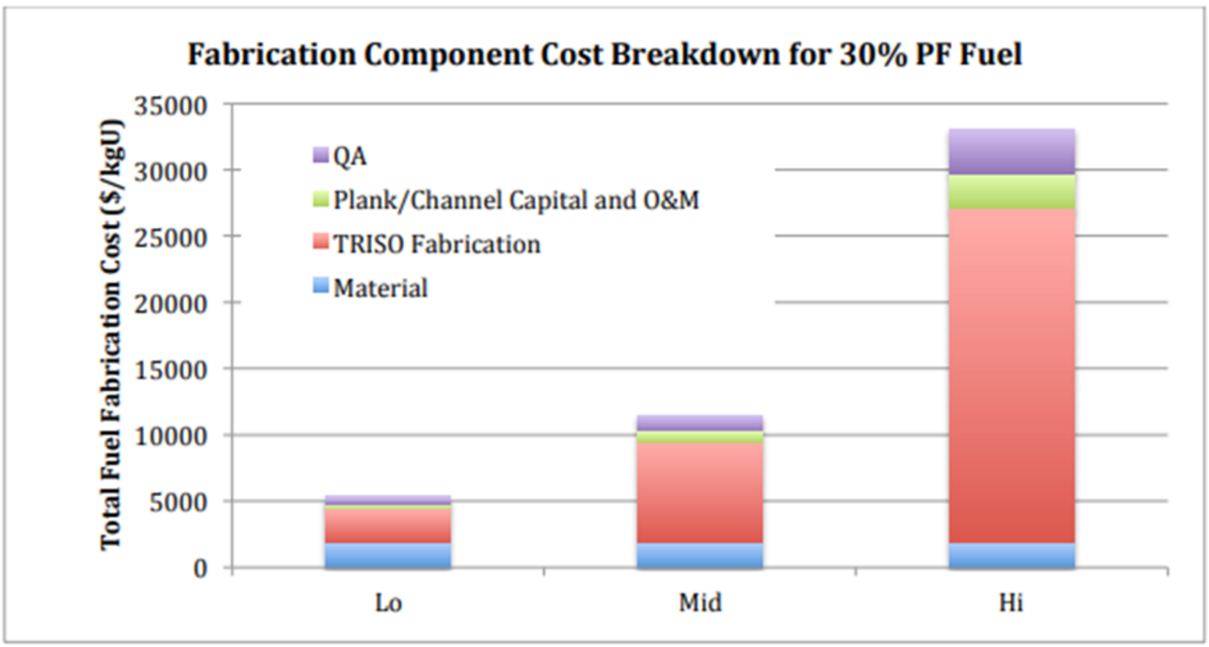


Figure D1-3.12. Breakdown of plank fuel fabrication cost from Kingsbury thesis (Kingsbury 2015).

This document provides a useful modeling framework, and further study of the model details and input assumptions would be useful for further SA&I economic analysis of TRISO fuel options.

HOLOS-GEN Studies. HOLOS-GEN of College Park, MD is developing transportable microreactor designs capable of providing heat or electricity to military operations in remote battlefield locations (Vitali et al. 2018; Fillipone et al. 2017). (Use of nuclear energy would decrease the need for large, diesel fuel supply lines requiring attack- vulnerable vehicle convoys.) The fuel would consist of TRISO imbedded in manufactured fuel cartridges as shown in Figure D1-3.4. A 2018 feasibility and cost study (Allen et al. 2018) projected a cost range of $12 million to $26 million for the fuel cartridges required for a 30 MWth microreactor needing 3,500 kg of U; a unit cost range of $3,400/kgU to $7,400/kgU results. The contribution of actual TRISO particle fuel manufacture to this overall fuel cost was not given.

Metal Fuel Fabrication Cost Studies in AFC-CBR Module D1-6A. The following Figure D1-3.13 is extracted from Module D1-6A and shows the unit fabrication costs for U-metal alloy HALEU fuel prepared in both Category I (10% U-235 and below) and Category II (>10% and <20% U-235) fuel fabrication facilities. The ranges for contact-handled metal-cast U-Zr fuel are 400 to 1,200 $/kg for Category III HALEU, sometimes called LWR-"LEU-plus," and 1,200 to 3,000 $/kgU for the more stringent Category II facility.

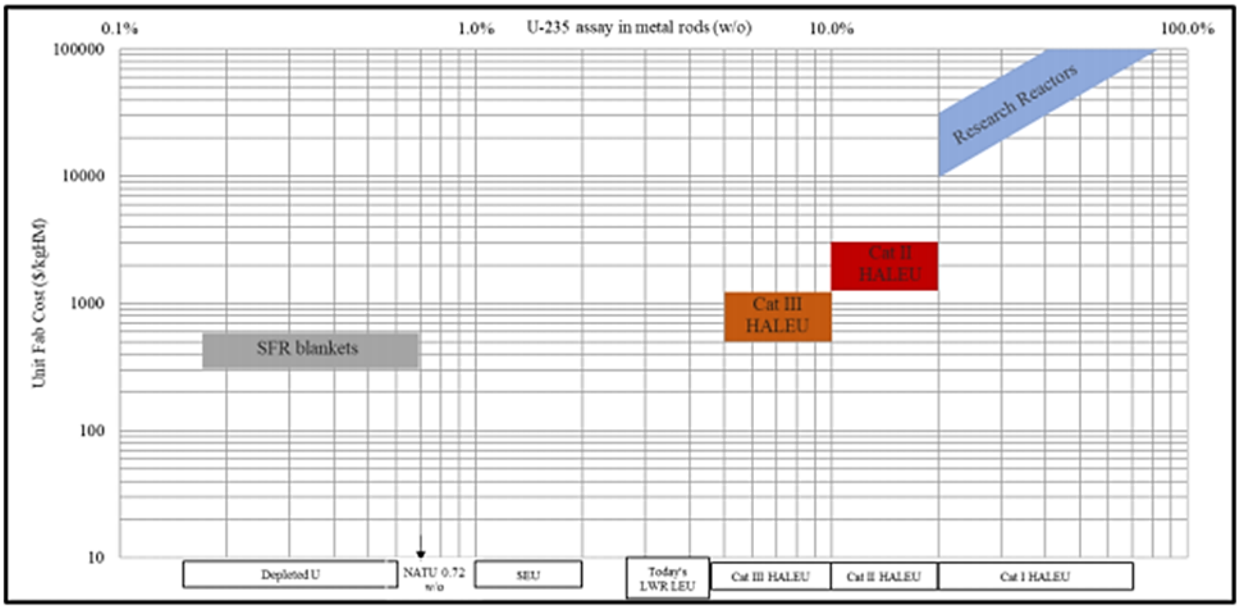


Figure D1-3.13. Unit fabrication cost versus U-235 enrichment for uranium metal-based fuels.

The SA&I author of this module and Module D1-6A notes that the TRISO manufacturing process is much more complex than for metal fuel and involves far more steps than the casting process for contact-handled U-metal fuel. Quality assurance requirements are also much more stringent for TRISO particles. A range of twice that of metal fuel fabrication is suggested (i.e., $800/kgU to $6,000/kgU for the entire HALEU range).

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 several advanced reactor concepts are being seriously considered for deployment as electricity producers, heat 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 conceptual design and cost 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 already under development.

Readiness Level. In the 1960s this fuel fabrication technology reached the pilot plant level of deployment in the United States to produce 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. but will soon expand to the pilot plant scale (100s of kgU/yr) at other locations.

D1-3.8. COST SUMMARY

2009 AFC-CBD Cost Summary. The 2009 AFC-CBR module cost information is summarized in the What-It-Takes (WIT) cost summary in Table D1-3.8. The summary shows the reference cost basis (constant year 2009 USD), 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 D1-3.8. Cost summary table for GCR TRISO fuel (2009 AFC-CBD).

What-It-Takes 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 2009 AFC-CBR value for 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_2 kernels	If automated process is successful:

2012 AFC-CBR Update Cost Summary. The following set (Table D1-3.9) of WIT values and a corresponding probability distribution is recommended for use in future fuel cycle studies. A triangular distribution is suggested.

Table D1-3.9. Low, nominal, and high suggested HTR fuel fabrication price values in $/kgU (2012 USD).

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

The low end of this range has been lowered from $5,000 (in 2009) 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, significantly higher personnel costs, and possibly use of a Category I facility for handling U-235 assays greater than 20% (HEU).

2017 AFC-CBR Update Unit Cost Summary. Table D1-3.10 merely escalates the 2012 USD amounts above by 9% to 2017 USD and rounds to nearest $100/kgHM. No new cost data was gathered in the period 2012 to 2017.

Table D1-3.10. Low, mode, mean, and high suggested HTR fuel fabrication price values in $/kgU (2017 USD).

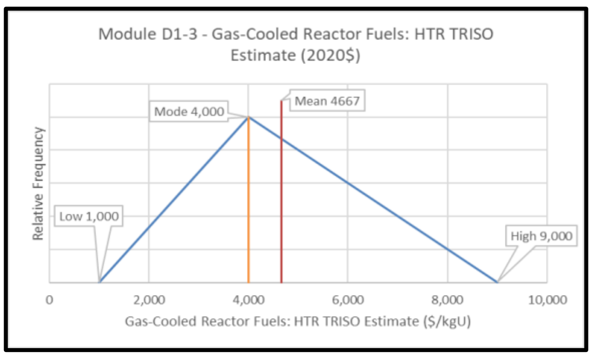
Fuel Type	Low (2017 $/kgU)	Mode (2017 $/kgU)	Mean (2017 $/kgU)	High (2017 $/kgU)
HTR	3,300	10,900	14,500	29,400

D1-3.8.1. 2021 AFC-CBR WIT Unit Fuel Fabrication Cost Values

Table D1-3.11 and Figure D1-3.14. show the new FY 2021 WIT unit fabrication costs in $/kgU for TRISO-based fuel expressed in 2020 USD.

Table D1-3.11. WIT unit cost ranges in 2020 USD for TRISO-based fuels.

Fuel Type	Low (2020 $/kgU)	Mode (2020 $/kgU)	Mean (2020 $/kgU)	High (2020 $/kgU)
TRISO-based for any reactor concept	1,000	4,000	4,667	9,000
Triangular distribution assumed				



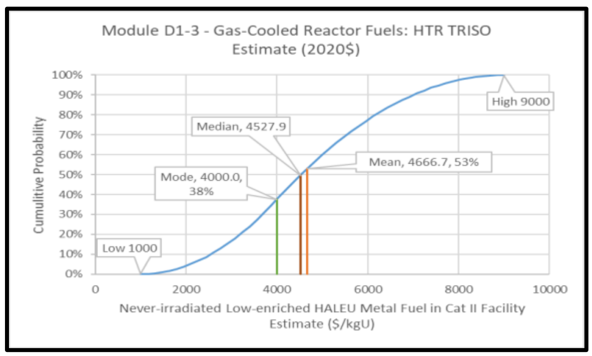


Figure D1-3.14. Probability distribution and cumulative frequency distribution for TRISO-based fuel cost.

The author of this module examined the new unit cost ranges appearing in Section D1-3.6 to arrive at these WIT ranges. The following should be noted:

- The low part of the above range would be for high production capacity (100s of MTU/yr) in a highly automated NOAK TRISO production facility. It probably would be for TRISO particles only and not include production of the shapes in which the TRISO particles are imbedded, such as compacts, planks, or pebbles. Such a facility might service many different reactor-fuel vendors.
- The high range would be for very small (<5 MTU/yr) facilities that are more FOAK than NOAK in nature. Such facilities are the type to be expected in the next 10 years. These higher ranges might include the costs producing the final blocks, planks, pebbles, or other forms that imbed TRISO particles fuel.

- Production of HEU TRISO, which would require a Category I facility, is not included in the above range of unit costs.
- These range has come down from previous years, mainly due to exclusion of HEU, and hopefully significant improvements to the TRISO manufacturing process. Planned use of existing fuel fabrication facility space can also reduce estimated costs, for example X-energy and Global Nuclear Fuel (GNF) plan to use space in the existing GNF LWR fuel fabrication plant in Wilmington NC.

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. Further NASAP-based SA&I studies on TRISO fuel can provide some sensitivity analysis.

D1-3.10. REFERENCES

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