PNNL-31226 Rev.1 | NRIC-22-ENG-003 Rev. 1

Fuel Fabrication Capability Assessment in Support of Advanced Reactor Deployments

February 2022

Ali Zbib[a]
Cliff J Yeager[a]
Chad L Painter[a]
David L Blanchard[a]
Mark Nutt[a]
Jeff Katalenich[a]
Bruce McNamara[a]
Stephen Grabinski[b]

[a] Pacific Northwest National Laboratory
[b] Idaho National Laboratory

Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy.
INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC.

DISCLAIMER

Executive Summary

More than 30 U.S. companies are designing a variety of advanced reactor concepts, and several companies are planning to demonstrate their reactor designs in the mid-2020s to late 2030s time frame. In 2020, the U.S. Department of Energy (DOE) announced a series of awards under the Advanced Reactor Demonstration Program (ARDP) to accelerate the successful deployment of 10 of these reactors under three pathways. TerraPower and X-energy were awarded grants under the Advanced Reactor Demonstration Program to deploy their respective Natrium reactor and Xe-100 reactor designs in the next 7–10 years. These demonstrations are in addition to several parallel programs, including the U.S. Department of Defense's (DoD's) interest in the development of microreactors, and interest of the National Aeronautics and Space Administration in space nuclear power and propulsion.

The National Reactor Innovation Center's (NRIC's) mission is to accelerate the demonstration and deployment of advanced reactors; NRIC is partnering with several reactor developers and harnessing the world-class capabilities of the U.S. National Laboratory system to deliver on its mission. Several of these reactor designs will require advanced fuel forms that are not commercially available today, including metal fuel, molten salt fuel, TRi-structural ISOtropic (TRISO) particle fuel, and uranium nitride fuel. Recognizing that there may be potential gaps in the laboratory-scale process development and pilot-scale first-of-a-kind (FOAK) production of these fuel forms leading to delivery of the FOAK cores, NRIC commissioned this study to look at the challenges that need to be overcome for successful deliveries, including the evaluation of existing facilities and the potential need for a new fuel fabrication facility.

While there are feedstock availability, technical, licensing, and logistical challenges that must be overcome to enable the successful deliveries of the first nuclear cores in support of future advanced reactor deployments, this report identified four major challenges/barriers:

1. Nuclear fuel fabrication facilities are expensive to start up and difficult to justify for building a one-off first core load of fuel. A gap in demand for a given fuel form is to be expected after a successful demonstration of a reactor design and before a design is commercially accepted and deployed by a utility; this makes it more difficult for fuel fabricators to justify these investments until there are strong business signals pointing toward a stable market.
2. Establishing a plan for acquiring the high-assay, low-enriched uranium (HALEU) feedstock will be necessary to make sure special nuclear material (SNM) is available to fabricate the first core loads of nuclear fuel.
3. There is no industrial-scale deconversion processing capability to transform HALEU UF_6 gas into the feedstock materials (e.g., oxide, metal, nitrate solution) needed to manufacture the different fuel forms today.
4. There is a lack of licensed transport packages needed to safely move materials and final products.

An informal survey of the various reactor designs was performed as part of this study, to assess their plans for acquiring the first core load of nuclear fuel. Fuel fabricators and HALEU feedstock suppliers were surveyed to establish a better understanding of existing and planned capabilities to support advanced reactor demonstrations. Comparing the needs of the advanced reactor community and what is known about existing and planned capabilities allowed the team to identify the gaps and challenges and establish a need for a new fuel fabrication facility. The facility will be referred to as the Center for Advanced Reactor Fuel Fabrication (CARFF). It should be noted that during the course of this study, one advanced reactor developer made the following comments with regard to such a concept:

> "A user fuel fabrication facility provides a tremendous advantage to advanced reactors…eliminates the costly, time-consuming step of designing and constructing a specialty fuel fabrication facility…avoids the lengthy and costly NRC engagement and review cycle, solely to demonstrate the viability of an advanced reactor technology."
>
> "A fuel fabrication user facility eliminates the majority of the capital investment associated with reactor demonstration-scale fuel production and enables reactor operations that may subsequently result in both reactor orders as well as the capital investment required to construct commercial fuel fabrication facilities."

The informal survey provided an understanding of the specific fuel types, number of vendors, and existing fuel fabrication plans, which resulted in estimates of the throughput and requirements for a CARFF. The study focused on reactor concepts that require uranium-based fuels (up to 20 wt% ^{235}U) and excluded both Pu-based and thorium-based fuels or those that were planning to consume spent nuclear fuel, since the facility requirements for handling Pu-based fuels are drastically different.

Ideally, the CARFF would support pilot-scale fabrication of uranium-based metallic, molten salt, TRISO, nitride, and oxide fuels and would most likely be needed for metallic and molten salt fuels. While TerraPower is currently working industry partners to establish a metal fuel manufacturing capability and Oklo Inc. is working with Idaho National Laboratory (INL) to build their first core, developers using metallic fuels on a longer development timeline would likely benefit from the CARFF. The CARFF would support fabrication of fluoride salts as coolant or fuel, but fabrication of chloride salts would likely be excluded given the desire for a Pu-based fuel salt (although at least one chloride salt fast reactor developer has announced plans to start up on HALEU). It is unlikely that the CARFF would be needed for fabricating TRISO fuels, because commercial TRISO fuel manufacturing capabilities are already being established. However, the CARFF may be useful for prototyping and demonstrating advanced TRISO compacts envisioned by some reactor developers. The CARFF would be capable of assisting with the fabrication of oxide fuels enriched beyond 5%, but oxide fuel is considered unlikely in this context, given that necessary modifications to existing fuel fabrication facilities are relatively small for enrichments ranging from 5 to 8%. Fabrication of uranium nitride fuels would be supported if commercial or government interest in this fuel form is identified.

The CARFF would be classified as a DOE Hazard Category 2 and Safeguards Category IV facility, is assumed to have three separate bays capable of accommodating three independent pilot-scale fuel fabrication lines, with appropriate partitions between bays and in shared spaces to protect the developers' intellectual property. The bays would accommodate installation of the developers' modular process skids: a chemical area provided with nuclear-grade ventilation to accommodate harsh processing chemicals and unencapsulated HALEU, and a mechanical area to handle mild chemical processes and encapsulated HALEU. An additional area would house "clean" support areas and provide for office space. The facility would be able to process HALEU in the form of oxides, metals, and salts, at a total assumed throughput of 2,400 kg of HALEU per month and would be equipped with sufficient storage vault capacity, assumed to be 2,400 kg of HALEU. Analytical and radiological chemistry laboratory capabilities and cryogen/inert gas storage and supply systems would be required. The ability to handle low-level solid and liquid waste streams, gaseous effluents from thermal and chemical processing, and toxic gases from molten salt production would be required. The throughput of 2,400 kg of HALEU is based on approximately 18-month fuel fabrication campaigns and three separate vendors (two large reactor cores and one smaller one) working in the facility. A longer fabrication schedule and/or smaller reactor core designs could be assumed to ease this throughput requirement. Changing the assumption of accommodating three different pilot-scale fuel manufacturing lines operating simultaneously to accommodate either two lines simultaneously or one line at a time would ease the throughput requirement, as well as the cost, construction schedule, and size requirements of the CARFF.

In this study, the following four existing DOE facilities were evaluated against a set of requirements that were developed for CARFF:

1. The Fuels and Materials Examination Facility (FMEF) on the Hanford Site in Washington
2. The Radioactive Liquid Waste Treatment Facility at the Materials and Fuels Complex on the INL site – MFC-798 RLWTF
3. The Fuel Processing Restoration Facility (CPP-691) on the INL site – FPR
4. The Mixed Oxide Fuel Fabrication Facility on the Savannah River Site – MFFF.

Of these four facilities, the FMEF, met the basic requirements for the envisioned fuel fabrication facility. A rough, order-of-magnitude (ROM) cost of $100–150 million was estimated to restart the FMEF for nuclear operations. The FMEF is a large facility that can accommodate multiple missions. Since the facility was initially designed to fabricate Pu-based fuels; however, it was deemed too large, and likely too expensive, to restart for the sole purpose described in this report, it may be advantageous to consider it in a future study focused on fabricating Pu-based fuels, supporting reactor developers' intent on using spent nuclear fuel as their initial feedstock, or restarting for multiple-mission purposes. The other three facilities were deemed not to meet the set of requirements in one or more ways, but could still be considered if conditions or needs change. Repurposing a suitable existing facility is expected to be faster than building a new facility.

Building a new, purpose-built fuel fabrication development facility may be an economical alternative to converting existing space in an existing facility that was designed for another specific purpose. A ROM for such a new facility, set up on a DOE site, is on the order of $100–250 million, based on a recent comparable commercial facility cost estimate and on Pacific Northwest National Laboratory facility engineers' experience with setting up radiological developmental facilities. Such a facility is expected to take 4–5 years to establish once funding is available. This approach is likely more time-consuming than retrofitting a suitable existing facility.

To address the four major challenges, the authors propose the following eight recommendations:

Recommendation 1a: Analyze whether there is a CD-0 mission need for the Center for Advanced Reactor Fuel Fabrication per DOE Order 413.3B. Initiate the preconceptual planning, mission-validation independent review, mission need statement document, and independent cost review for a new Center for Advanced Reactor Fuel Fabrication (CARFF)—either a new facility or restart of an existing facility that meets the basic requirements. This will determine whether there is a mission need and address CD-0 requirements for a capital acquisition per DOE Order 413.3B.

Recommendation 1b: Fuel fabrication PFDs and ASTM standards. Develop fuel fabrication process flow diagrams (PFDs) for each of the major fuel forms. Survey existing ASTM standards associated with the various material specifications and identify gaps where new ASTM standards should be developed.

Recommendation 2a: A central deconversion facility. Evaluate the need for and identify potential private-public frameworks to set up a central deconversion facility that deconverts UF_6 into its common feed material for the different fuel forms.

Recommendation 2b: Colocation of front-end processes. Consider colocating as many front-end processes as possible in the development of the fuel supply chain for advanced reactors. Particular consideration should be given to colocating a central deconversion facility with one of the HALEU enrichment sites. In addition to significant cost reductions associated with pooled resources, transportation cost of HALEU materials would be minimized.

Recommendation 3a: Government purchase of HALEU. The U.S. government should consider purchasing 60 MTU of HALEU UF_6, which could then be sold to the advanced reactor community as needed at some agreed-to fair market price. In addition, the guaranteed purchase of a stock of HALEU will strengthen the commercial case for establishing both the enrichment and deconversion capabilities in the U.S.

Recommendation 3b: Reallocation of highly enriched uranium (HEU) for downblending. Enrichment is the long-term solution. In the short term, some HEU could be reallocated for downblending to HALEU; this would be a choice only made by DOE leadership considering the multiple mission and priority needs.

Recommendation 3c: Reserving HEU downblend for users requiring unobligated fuel. The U.S. government should consider reserving HEU downblend capability for users and programs that must use unobligated fuel.

Recommendation 4a: HALEU Transportation. DOE should consider sponsoring a commercial effort to design, license, and purchase a minimum number of HALEU certified transportation packages. Custodianship for these packages could be assigned to either a commercial vendor or a national laboratory ensuring proper maintenance, service intervals, and managing shipping needs. Additional criticality benchmarks may be needed to support new packages' licensing efforts.

Acknowledgments

The authors of this report and the National Reactor Innovation Center would like to acknowledge the contribution of several industry partners that participated in the informal survey including TerraPower, Oklo, Elysium, ThorCon, Flibe, Ultra Safe Nuclear Corporation, Moltex Energy, Kairos Power, BWX Technologies, Inc., Framatome, Lightbridge Corporation, Materion Corporation, Centrus Energy, and Urenco USA.

CONTENTS

FIGURES

TABLES

Acronyms

ACP	American Centrifuge Plant
ARDP	Advanced Reactor Demonstration Program
BWXT	BWX Technologies, Inc.
CARFF	Center for Advanced Reactor Fuel Fabrication
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
FFTF	Fast Flux Test Facility
FHR	fluoride salt-cooled high-temperature reactor
FLiBe	lithium fluoride (LiF) and beryllium fluoride (BeF_2)
FMEF	Fuels and Materials Examination Facility
FOAK	first of a kind
FPR	Fuel Processing Restoration Facility
GAIN	Gateway for Accelerated Innovation in Nuclear
GNF	Global Nuclear Fuel
GT5	greater than 5% enriched uranium
HALEU	high-assay, low-enriched uranium
HEPA	high efficiency particulate air
HEU	highly enriched uranium
HTGR	high-temperature gas-cooled reactor
HVAC	heating, ventilating, and air conditioning
IMSR	Integral Molten Salt Reactor
INL	Idaho National Laboratory
LEU	low-enriched uranium
LFTR	liquid-fluoride thorium reactor
LWR	light water reactor
MCFR	molten chloride fast reactor
MCSFR	molten chloride salt fast reactor
MFC	Materials and Fuels Complex
MFFB	MOX Fuel Fabrication Building

MFFF	Mixed Oxide Fuel Fabrication Facility
MMR	micro modular reactor
MNPP	mobile nuclear power plant
MOX	mixed uranium-plutonium oxide
MSRE	Molten Salt Reactor Experiment
MT	metric ton; 1,000 kilograms
MTU	metric tons of uranium
NASA	National Aeronautics and Space Administration
NDE	nondestructive examination
NEI	Nuclear Energy Institute
NNSA	U.S. DOE National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
NRIC	U.S. National Reactor Innovation Center
R&D	research and development
RLWTF	Radioactive Liquid Waste Treatment Facility
ROM	rough, order-of-magnitude
SAF	Secure Automated Fabrication
SCO	U.S. Department of Defense Strategic Capabilities Office
SFR	sodium fast reactor
SMR	small modular reactor
SNM	special nuclear material
SWU	separative work unit
TREAT	Transient Reactor Test (facility)
TRISO	tri-structural isotropic (fuel)
TRL	Technology Readiness Level
UCO	uranium oxycarbide
USNC	Ultra Safe Nuclear Corporation
UUSA	Urenco USA
VTR	Versatile Test Reactor

Fuel Fabrication Capability Assessment in Support of Advanced Reactor Deployments

1. Introduction

In the late 2020s and early 2030s, several reactor types using different types of advanced fuel are expected to be demonstrated. In October 2020, the Advanced Reactor Demonstration Program (ARDP) announced two $80M awards to TerraPower and X-energy to demonstrate their reactor concepts (the Natrium reactor and the Xe-100, respectively) within the next 7–10 years in partnership with the U.S. National Reactor Innovation Center (NRIC) and several national laboratories (DOE 2020a). These awards were made under the "demonstration" pathway of ARDP, one of three pathways. Awards for five reactor concepts were announced under the "risk reduction" pathway, with the objective of solving technical, operational, and regulatory challenges to support demonstration of these reactors within 10–14 years. Three awards were announced under the "advanced reactor concepts" pathway to solidify concepts for potential demonstrations in the 2030s. Other programs, including one under the U.S. Department of Defense (DoD), are pursuing development of microreactor concepts (DoD 2020).

This short list of advanced reactors is in addition to more than 20 other advanced reactors under development in the U.S. today, most of which will require advanced nuclear fuels of varying forms—metal fuel, molten salt fuel, TRi-structural ISOtropic (TRISO) particle fuel, and uranium nitride—that are not commercially available today. In addition, evolutionary nuclear fuel designs and advanced ceramic fuel forms are also being developed to improve both the safety and economics of the existing fleet of light water reactors (LWRs). Several of these concepts will require advanced fuels with fissile content above 5% low-enriched uranium (LEU) and approaching 20%, i.e., high-assay, low-enriched uranium (HALEU). Plutonium-bearing fuels are also under consideration as part of an effort to reuse spent LWR fuel and reduce its associated long-term radiotoxicity.

Advanced fuel research and fuel fabrication technology development has been performed at various U.S. national laboratories in the past, often in partnerships with fuel suppliers. However, fuel fabrication at the national laboratories has been done on research-level quantities of fuel, typically in quantities to support irradiation in test reactors or for irradiation of lead test rods or assemblies for use in commercial reactors. The fuel vendors then pursue production-level fuel manufacturing once a new evolutionary fuel is sufficiently tested. The need for fabrication of research-level quantities of various fuel forms in the national laboratories complex will grow as the efforts to deploy advanced reactors accelerate. In addition, the fabrication of HALEU fuels will require commercial entities to be licensed by the U.S. Nuclear Regulatory Commission (NRC) to handle at least Category II special nuclear materials (SNM) and the fabrication of Pu-bearing fuel may require facilities to be licensed as Category I facilities. There are a limited number of facilities that can handle Category I and II SNM, and they are either limited in capacity or not intended for commercial-scale production. In a letter to the U.S. Secretary of Energy, the Nuclear Energy Institute (NEI) highlighted the need for HALEU to support advanced reactor deployment and stated that the required commercial investment in a domestic HALEU infrastructure is hampered by market uncertainty (NEI 2018). And finally, several advanced fuel forms (e.g., molten fuel salts and nitride fuels) have not previously been fabricated in the large batches required to fuel a prototype or demonstration reactor.

To enable future advanced reactor demonstrations and deployments, an infrastructure to fabricate the first-of-a-kind (FOAK) advanced fuels, and then characterize and disposition that fuel after operation, must be identified.

This study is intended to capture the range of fuel production capabilities and fuel cycle processes that will enable the demonstration and deployment of advanced reactor concepts, then analyze options for delivering those capabilities. It will focus on reactor concepts that require uranium-based fuels (up to 20 wt% ^{235}U) and exclude Pu-based and thorium-based fuels or those that use spent nuclear fuel, since the facility requirements for these fuel types are drastically different. Once a need is established, the study will review available infrastructure and identify any gaps in meeting the required fuel fabrication mission.

Several facilities exist within the U.S. Department of Energy (DOE) national laboratory complex that may be capable of satisfying some of these general requirements. An assessment of how existing facilities may be used, or whether new facilities are needed, will be included.

2. Scope and Objectives

The assessment looked at projected needs for fuel fabrication that would enable successful deployment of advanced reactors. A brief overview of the advanced reactor market landscape is provided, followed by descriptions of recent awards, different DOE, DoD, and National Aeronautics and Space Administration (NASA) programs, licensing status of the different designs, fuel forms, initial core size, and projected deployment dates. Then, different fuel form needs are projected and prioritized. While the study does not review the needs for a critical feedstock infrastructure at the extensive level of detail it warrants, this review includes what is known about critical feedstock plans and infrastructure (e.g., HALEU enrichment, deconversion, etc.). Pu-based fuels are discussed, but because manufacturing them adds complexity and political challenges, this assessment focuses on uranium-based fuels.

A detailed assessment of fabrication processes for six different fuel forms will follow:

- ceramic fuel
- metal fuel
- chloride molten salt fuel
- fluoride molten salt fuel
- TRISO fuel
- uranium nitride fuel.

An informal survey of the various reactor concepts under development, a short description of their fuel type and initial core size, status of the fuel development process and associated Technology Readiness Level (TRL) (GAO 2020), development needs to achieve laboratory-, pilot-, and demonstration-scale production, and required support functions are summarized in Appendix A. Figure 1 is an illustration of the process used to identify the various gaps that exist in manufacturing the first core to support deployment of advanced reactors.

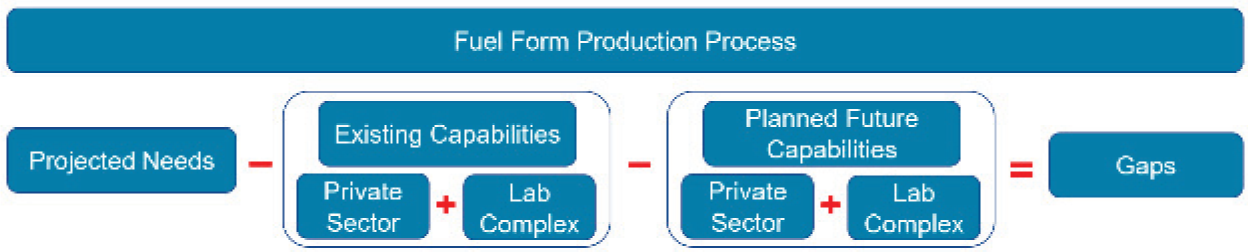

Figure 1. Fuel Form Production Processes Gap Assessment

Based on identified needs and gaps for the different fuels needed, a set of requirements was developed for a future Center for Advanced Reactor Fuel Fabrication (CARFF) facility that would be licensed for HALEU and operated as a type of user facility. These requirements include facility size, design capacities, storage requirements, SNM storage and vault requirements, physical security requirements, surveillance, containment, nuclear material monitoring, hazards and safeguards requirements, analytical/metrology support, and waste treatment and off-gas system requirements. In addition, a series of advantageous/added value features that would enhance the value proposition for such a facility would, include hot cells, waste treatment, and potentially spent fuel reprocessing capabilities if Pu-based fuels were to be considered. The objective is to identify potential requirements for a facility that could act as a user-type facility hosting three separate pilot-scale fuel fabrication lines enabling the successful fueling and deployment of advanced reactors, while providing shared support capabilities (e.g., analytical labs, metrology/nondestructive examination [NDE] capabilities, SNM storage, etc.)

The final step in the study was a review of existing DOE facilities that could be restarted or repurposed into a user-type facility that could support future advanced fuel fabrication campaigns. Four facilities were selected as potentially viable candidates for the scope of this study, while recognizing that the list of candidate facilities is not all-inclusive:

1. The Fuels and Materials Examination Facility (FMEF) on the Hanford Site in Washington
2. The Radioactive Liquid Waste Treatment Facility at the Materials and Fuels Complex on the Idaho National Laboratory (INL) site – MFC-798 RLWTF
3. The Fuel Processing Restoration Facility (CPP-691) on the INL site – FPR
4. The Mixed Oxide Fuel Fabrication Facility on the Savannah River Site – MFFF

The study concludes with recommendations on actions the DOE can take to facilitate fabricating the first core loads of nuclear fuel in support of advanced reactor deployments, the results from a review of existing DOE facilities, the viability of restarting one such facility, and an estimate of cost to build a new facility.

In addition to information gathered from DOE sources, recent news announcements, publications, and publicly available information, the study includes perspective from several reactor developers, fuel vendors, and fuel feedstock suppliers. This allowed the team to better understand the projected needs, future plans, existing capability gaps, and value of a proposed user facility. Several requests were sent out and discussions and meetings were held with responders (listed below) to describe the scope and the ask:

- Reactor developers: TerraPower, Oklo, Elysium, ThorCon, Flibe, Ultra Safe Nuclear Corporation (USNC), and BWX Technologies, Inc. (BWXT), and Moltex Energy

- Fuel vendors/developers: Framatome, BWXT, Global Nuclear Fuel, Westinghouse, and Lightbridge
- Fuel feedstock suppliers: Centrus Energy and Urenco USA., Cameco, Orano Canada.

3. Background

A recent informal survey of advanced reactor developers reveals more than 30 U.S. companies—mostly new start-ups—currently working to develop and deploy advanced power reactors based on different technology approaches (e.g., gas cooled, metal cooled, and salt cooled; thermal or fast spectrum). In most cases, each reactor technology uses a different fuel form (e.g., oxide, metal, nitride, molten salt, or TRISO) and within the groups of similar technologies are slight variations in fuel designs. Many of these fuels are envisioned to be fabricated using HALEU feedstock, while others will utilize plutonium extracted from spent LWR fuel or ^{233}U bred from fertile thorium.

A listing of reactor design companies is provided in Table 1, which includes the intended fuel type. Several historical and notable reports have also provided such listings (Smith 2020; DOE 2014; IAEA 2020); however, the advanced reactor landscape is rapidly changing in response to concerns related to global carbon emissions, proliferation, government funding in support of advanced nuclear technology, aspirational plans for lunar basing and space exploration, and energy security for remote military bases. The authors anticipate that this list will continue to evolve.

A number of these companies have received public funds to support the advancement of their design concepts, while others are being funded solely by private interests. Several of the companies have actively been engaging in licensing discussions with the NRC; in particular, NuScale, GE, and Oklo have submitted their design certification applications seeking regulatory approval of their advanced reactor designs. Moreover, other advanced designs have been considered as part of an industry-led Licensing Modernization Project (42 USC 2019), in which the NRC is working to develop a technology-inclusive, risk-informed, and performance-based licensing methodology for non-LWR–based advanced reactors. Within the listing, there is a wide range of TRLs, design maturity levels, and established testing infrastructure.

Table 1. U.S. Advanced Reactor Design Companies

Company	Reactor Name	Reactor Type	MWt	Spectrum	Coolant Type	Temp (°C)	^{235}U (wt%)	Fuel Type
Advanced Reactor Concepts	ARC-100	Commercial FOAK	260	Fast	Sodium	470	13.5	U-10Zr Metal Alloy
Alpha Tech					Fluoride Salt			Fluoride Based Fuel Salt
Atomos	Nuclear Space Propulsion	NTP system						
Bechtel, GE Hitachi Nuclear Energy, and TerraPower	Versatile Test Reactor (VTR)	Test Reactor	300	Fast	Sodium	500	15	U-20Pu-10Zr Metal Alloy
BWXT	Mobile Nuclear Power Plant (MNPP)	MNPP	(1-10 MWe)	Thermal				TRISO
BWXT	BANR	Commercial FOAK	(1-10 MWe)	Thermal				TRISO
Columbia Basin Consulting	CBCG LFR	Commercial FOAK	250	Fast	Lead Bismuth	500		UO_2 then Metal
Elysium	Molten Chloride Salt Fast Reactor (MCSFR)	Commercial FOAK	110-2700	Fast	Chloride Salt	660		U Pu Na K Cl
Flibe Energy	Liquid Fluoride Thorium Reactor (LFTR)	Commercial FOAK	600	Thermal	Fluoride Salt	650		$2LiF_2$-BeF_2-$(^{233}U)F_4$
Flibe Energy	Demonstration Reactor	Demonstration	60	Thermal	Fluoride Salt	650		$2LiF_2$-BeF_2-$(^{233}U)F_4$
Flibe Energy	Test Reactor in Zipper at INL	Test Reactor	0.5	Thermal	Fluoride Salt	650		$2LiF_2$-BeF_2-$(^{233}U)F_4$
GE Hitachi, USA*	BWRX-300	Commercial FOAK	937.5	Thermal	Light Water	287		UO_2
GE Hitachi, USA*	PRISM	Commercial FOAK	471	Fast	Sodium	500	15	U-26Pu-10Zr Metal Alloy
General Atomics	EM2	Commercial FOAK	500	Fast	Helium Gas	850		
General Atomics	Fast Modular Reactor (FMR)	Demonstration	111	Fast	Helium Gas	850		
General Atomics	Mobile Microreactor	Microreactor (MNPP)						TRISO
Global Energy Research Associates	GERA small modular reactor (SMR)	Commercial FOAK	764	Thermal				Gaseous Pu based
HOLOSGen	HOLOSGen	Microreactor	6-30	Thermal	Helium Gas	760	12	TRISO
Holtec	SMR-160	Commercial FOAK	500	Thermal	Light Water	315		UO_2
Hybrid Power Technologies, LLC	HPR	Commercial FOAK		Thermal	Helium Gas			TRISO
Hydromine	LFR-AS-200	Demonstration	475	Fast	Lead Bismuth	500	19	UO_2-PuO_2
Kairos Power	Hermes	Test Reactor		Thermal	Fluoride Salt	650		TRISO
Kairos Power*	KP-X	Commercial FOAK	320	Thermal	Fluoride Salt	650		TRISO

Company	Reactor Name	Reactor Type	MWt	Spectrum	Coolant Type	Temp (°C)	^{235}U (wt%)	Fuel Type
MicroNuclear LLC	MSNB							
Moltex Energy (Canada)	Stable Salt Reactor – Wasteburner (SSR-W)	Commercial FOAK	375	Fast	Chloride Salt	700	Pu	NaCl PuCl + Actinides
Muons	Mu*Star	Commercial FOAK	500	Thermal	Fluoride Salt	750		Fluoride Based Fuel Salt
Niowave	Niowave molten chloride fast reactor (MCFR)	Demonstration	10	Hybrid	Lead Bismuth			
NuGen LLC	NuGen Engine	Microreactor	(1-3 MWe)	Fast	Helium Gas			TRISO
NuScale*	NuScale Power Module™	Commercial FOAK	(60-684 MWe)	Thermal	Light Water	315	4.95	UO_2
Oklo*	Aurora	Microreactor	4	Fast	Sodium	640		U-10Zr Metal Alloy
Radiant	Radiant	Microreactor	(1.2 MWe)					TRISO
Space Nuclear Power Corp.	Kilopower	Microreactor	4-40 kWt	Fast	Na Heat Pipes	800		U-7.6Mo
StarCore	StarCore	Commercial FOAK	50	Thermal	Helium Gas		15	TRISO
TerraPower, USA	Traveling Wave Reactor–Prototype (TWR-P)	Demonstration	1,475	Fast	Sodium	500	15.75	U-10Zr Metal Alloy
TerraPower and GE	Natrium	Demonstration	820	Fast	Sodium	500	15.75	U-10Zr Metal Alloy
TerraPower, USA	MCFR	Commercial FOAK		Fast	Chloride Salt		U Pu	U Pu Na K Cl
Terrestrial USA	Integral Molten Salt Reactor (IMSR®)	Commercial FOAK	415	Thermal	Fluoride Salt	700	4.95	$LiF-BeF_2-ZrF4-UF_4$
ThorCon	The Do-able MSR	Commercial FOAK	1114	Thermal	Fluoride Salt	700	19.75	UF_4 and ThF_4
ThorCon	Do-able Prototype	Demonstration		Thermal		700	19.75	
Ultra Safe Nuclear Corporation	MMR Energy System	Microreactor	15	Thermal	Helium	630	19.75	TRISO FCM™ Fuel
Ultra Safe Nuclear Technologies	Nuclear Space Propulsion	NTP system	1	Thermal	Helium	630	19.75	TRISO FCM™ Fuel
Westinghouse	SMR	Commercial FOAK	725	Thermal	Water cooled	340		UO_2
Westinghouse	defense-eVinci	Microreactor (MNPP)	(1-10 MWe)	Thermal	Na Heat Pipes	600	19.75	TRISO
Westinghouse*	eVinci	Microreactor	12.5	Thermal	Na Heat Pipes	600	19.75	Not yet determined
Westinghouse	Lead Fast Reactor (LFR)	Demonstration	1,023	Fast	Lead	650		UO_2 then nitride
X-energy*	Xe-100	Commercial FOAK	200	Thermal	Helium	750	15.5	TRISO

Company	Reactor Name	Reactor Type	MWt	Spectrum	Coolant Type	Temp (°C)	^{235}U (wt%)	Fuel Type
X-energy	Xe-Mobile	Microreactor (MNPP)	(1-10 MWe)	Thermal	Helium	750	15.5	TRISO
* Vendors submitted Design Certification Application to the U.S. NRC or engaged in Licensing Modernization Project				Key:	ARDP Awards			
					DoD Strategic Capabilities Office Project			
					NRC Interactions			

3.1 Commercial Advanced Power Reactors

In October 2020, the DOE announced it selected two advanced reactor developers as part of the ARDP—TerraPower and X-energy, LLC. Each company has now entered a public-private partnership with the goal to demonstrate their respective advanced reactors in seven years. The TerraPower design will be a metal-fueled, sodium-cooled fast reactor and the X-energy design will be a TRISO-fueled, gas-cooled, thermal spectrum reactor.

These awards were made under the demonstration pathway of ARDP, one of three pathways. Awards for five reactor concepts were announced under the risk reduction pathways with the objective of solving technical, operational and regulatory challenges to support demonstration of these reactors within 10–14 years, and three awards were announced under the advanced reactor concepts pathway to solidify concepts for potential demonstrations in the mid-2030s.

Through DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) initiative, which seeks to accelerate the commercialization of advanced nuclear power reactors, 39 companies have received awards and access to technical support from DOE laboratories as well as regulatory advice from the U.S. NRC. A number of these companies have created significant engineering teams and invested in testing facilities.

These advanced reactor concepts range from microreactor sized reactors (1–50 MWe), to small modular reactor (SMRs) (50–300 MWe modules), all the way up to large reactors (300 MWe and above) targeting different market segments; the resulting variation in core size between reactors requiring a given fuel form will significantly affect the parameters of their pilot-scale fuel fabrication processes.

With more than 30 U.S. companies developing varying Gen III+ and Gen IV reactor concepts,[a] which have varying reactor core sizes and fuel forms and a wide range of maturity levels or TRLs, it would not be practical for this assessment to review fuel form fabrication requirements and needs for each one of those designs. Many of these reactors are at an early conceptual design stage and very limited information on their fuel fabrication process is available.

Many of the start-ups leading those efforts have been awarded support in response to Industry Funding Opportunity Announcements, ARPA-E, DOE Office of Nuclear Energy GAIN vouchers, and recently ARDP risk reduction awards (pathway 2, TRL 4 or higher) and Advanced Reactor Concepts 2020 awards (pathway 3, TRL 3 or higher) to advance their technologies. A representative subset of applicable reactors was selected under each of those fuel forms, to describe the fuel form requirements and needs. This selection is informed in part by recent and past awards, and the developers' level of interaction with the NRC. Table 2 lists the reactors discussed here that recently received awards under the ARDP announcements, while Table 3 lists

[a] Generation III+ reactors incorporate major advancements developed during the lifetime of the currently deployed light water reactor designs.

Generation IV designs are still under development. They aim for efficiency, safety, and proliferation resistance with less waste.

More information is available at

https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx.

ones that have submitted license applications to the NRC. These reactors will use four of the six fuel forms assessed in this report (metal, oxide, TRISO, and chloride salts fuel forms).

Table 2. Reactors Receiving 2020 ARDP Awards

Company	Reactor	Reactor Type	Reactor Size	Fuel Type	Award
TerraPower	Natrium	Sodium-cooled fast reactor with molten salt energy storage system	345 MWe	U-10Zr Metal Alloy	ARDP Demos
X-energy	Xe-100	High-temperature gas reactor	320 MWe (4 modules, 80 MWe each)	TRISO	ARDP Demos
Kairos Power	KP-FHR	Fluoride salt-cooled high-temperature reactor	140 MWe	TRISO	ARDP Risk Reduction
Westinghouse	eVinci	Heat pipe-cooled microreactors	2–3.5 MWe	TRISO	ARDP Risk Reduction
BWXT	BANR	High-temperature gas-cooled microreactor		TRISO	ARDP Risk Reduction
Holtec International	SMR-160	Advanced LWR SMR	160 MWe	Oxide (UO_2)	ARDP Risk Reduction
Southern Company/ TerraPower	MCFR	Molten chloride salt reactor	1200 MWe	Chloride salt	ARDP Risk Reduction
Advanced Reactor Concepts	Advanced Sodium-Cooled Reactor Facility	Sodium-cooled fast reactor	100 MWe	U-10Zr Metal Alloy	ARDP Concept Development
General Atomics	Fast Modular Reactor (FMR)	Helium-cooled fast reactor	50 MWe	-	ARDP Concept Development
MIT	Modular Integrated Gas High Temperature Reactor (MIGHTR)	Helium-cooled thermal reactor, graphite moderated	230 MWt	TRISO	ARDP Concept Development

Table 3. Reactors with licensing applications submitted

Company	Reactor	Reactor Type	Reactor Size	Fuel Type	Licensing Stage
NuScale	NuScale SMR	LWR SMR	600–720 MWe	Oxide (UO_2)	Design Certification Application approved, 8/2020
Oklo	Aurora	Sodium-cooled fast reactor	~1.5 MWe	U-10Zr Metal Alloy	Combined license application submitted 3/2020

3.2 DoD and NASA Funded Programs

In recent years, interest in nuclear technology by both DoD and NASA has been renewed. In 2020, the DoD's Strategic Capabilities Office (SCO) launched Project Pele to demonstrate a nuclear energy capability that could be deployed to large forward military bases to minimize concerns related to security and cost of fuel resupply. In March 2020, SCO awarded three contracts—to BWXT, Westinghouse Government Services, and X-energy—for preliminary design of a 1–5 MWe mobile microreactor as part of a competitive effort, with plans for a future down-selection for construction of a demonstration reactor. The SCO project specified a TRISO-fueled core.

NASA, with help from the U.S. National Nuclear Security Administration's (NNSA's) Office of Safety, Infrastructure, and Operations, built a highly enriched uranium (HEU)-fueled reactor system, referred to as Kilopower Reactor Using Stirling Technology (KRUSTY), to demonstrate safety and operability. The KRUSTY test took place at NNSA's Nevada National Security Site with a vision toward powering human outposts on the Moon and Mars. While KRUSTY used a U-10Mo alloy fuel, other advanced fuels are also being evaluated for space reactors. Furthermore, NASA is evaluating the trade-offs between lunar surface energy concepts and the need for nuclear thermal propulsion to enable human travel to Mars and deep space. Their evaluations consider commonalities with other reactor designs, such as those under development by DoD, and whether a HALEU-fueled reactor will meet technical requirements. Recently issued Space Policy Directive-6 (85 FR 83923) regarding the national strategy for space nuclear power and propulsion, established policy that the use of HEU in space nuclear power and propulsion systems should be limited to applications for which the mission would not be viable with other nuclear fuels or nonnuclear power sources. A request for proposals for industry-led development of both space reactors and nuclear propulsion are expected in 2021.

4. Descriptions of Problems

While there are significant technical, research, and logistical challenges that need to be overcome for successful deliveries of the first cores in support of advanced reactor deployment plans, there are four major challenges that need to be addressed to enable accelerated deployment:

- Nuclear fuel fabrication facilities are expensive to start up and difficult to justify for building a one-off core load of fuel. Until the technology is successfully demonstrated and electric utility companies begin placing orders for power reactors, industry will find it difficult to justify the expense of building a new fabrication facility.
- Establishing a plan for acquiring the HALEU feedstock will be necessary to make sure SNM is available to fabricate the first core loads of nuclear fuel. The only two domestic sources of industrial-scale levels of HALEU are enrichment or downblending of HEU. A new U.S. enrichment capability to make HALEU UF_6 has recently been licensed but with limited capacity. The existing excess HEU inventory has many competing uses and therefore allocation of HEU feedstocks for downblending to HALEU in support of the advanced reactor community is very limited.
- Additionally, there is no industrial-scale deconversion processing capability to transform HALEU UF_6 gas into the feedstock materials (e.g., oxide, metal, nitrate solution) needed to manufacture the different fuel forms today.
- The lack of licensed transport packages needed to safely move materials and final products.

4.1 Lack of Economical and Practical Ability to Fabricate Fuel

While there are several important challenges that the advanced reactor developers will need to overcome (e.g., private investment to support design, developing, and testing activities; cost and uncertainty of licensing a new reactor technology; and public acceptance), one of the more daunting challenges will be to fabricate the new advanced fuels that will be needed to start up a FOAK demonstration, pilot plant, or both. As reported by the NRC (NRC 2020), there are three licensed commercial nuclear fuel fabrication plants in the U.S.: Global Nuclear Fuel-Americas in Wilmington, North Carolina; Westinghouse Columbia Fuel Fabrication Facility in Columbia, South Carolina; and Framatome, Inc., in Richland, Washington. All three of these facilities fabricate LEU oxide fuels common to LWR technology. The NRC has established three classification categories for nuclear fuel fabrication facilities, according to the type of SNM housed and their strategic significance:

- NRC Category I: High strategic significance
- NRC Category II: Moderate strategic significance
- NRC Category III: Low strategic significance.

All three of the commercially licensed fuel fabrication facilities are classified as NRC Category III Fuel Facilities and are restricted to processing SNM of low strategic significance as defined in 10 CFR Part 74.4, "Definitions" (i.e., less than 10.0 wt% ^{235}U). Currently, there are no licensed Category II fuel fabrication facilities in the U.S. capable of processing SNM of moderate strategic significance (i.e., more than 10.0 wt% ^{235}U but less than 20%) and the very limited Category I fuel manufacturing facilities are set up to produce HEU fuels for military purposes.

In today's advanced reactor design community, with a few exceptions, none of the advanced concepts are being designed to use LEU oxide fuels—and herein lies the problem: how to fund the cost of an advanced reactor design, development, testing, and licensing program while also having to design, build, license, and shake down a new innovative fuel fabrication line, which in many cases will require HALEU feedstock materials and produce novel metal, salt, nitride, and/or TRISO particle fuel. Moreover, in many ways, the return on investment of a new fuel fabrication facility will not be realized until many years after the initial demonstration/pilot reactor plant is fully operational and has satisfied some sort of safety, reliability, and profitability criteria. Therefore, building a new fuel manufacturing facility and letting it sit idle for several years is not likely for many start-up companies.

4.2 Lack of HALEU Enrichment Capability

Another major gap identified is in the uranium (HALEU) supply chain needed to support large-scale deployment of advanced reactors. Many of the advanced reactor design concepts are based on the use of HALEU fuel so as to achieve either smaller sized cores or longer fuel cycles—both these attributes, in theory, will improve the long-term economics of a new nuclear power plant. The problem today is that no domestic HALEU supply exists and the only option for producing HALEU today is by downblending excess HEU material, which is in short supply and high demand.

Furthermore, it is unlikely that the private sector will invest in the needed modifications to existing equipment and facilities, as well as pursue the licensing necessary, to establish the capacity that will be required to supply the feedstocks for the advanced reactor community without a substantial market for HALEU fuel. This very challenging, chicken-and-egg problem will be a significant hurdle to deployment of advanced reactors. The reactor developers that need

HALEU feedstock for their advanced reactors will find it challenging to obtain it until the necessary infrastructure is in place. The necessary infrastructure will require a market demand signal from utilities that see these future reactors as commercially and economically viable. The first to market will undoubtedly be faced with a very steep infrastructure cost to create a new HALEU enrichment manufacturing capability for supply of UF_6 gas. There are two potential suppliers of enrichment services: Urenco USA and Centrus, and they have taken steps to assess the needs of the advanced reactors community and the required facility upgrades to support those needs. In Fiscal Year (FY) 2020, the DOE awarded a cost share contract with Centrus to partially fund demonstration of their AC-100M centrifuge technology to produce 19.75% enriched uranium hexafluoride gas. DOE continues its program to make available small quantities of HALEU from limited DOE uranium inventories and from HALEU production in the short term and to support the private sector in its design and build-out of commercial HALEU production capability in the U.S. in the long term. These efforts are further described in Section 5.2 and Appendix B.

4.3 Lack of HALEU Deconversion Capability

After natural uranium feedstock is converted to UF_6, the latter is enriched to as much as 20 wt% ^{235}U. The gap discussed here is in the "deconversion" step in which the HALEU is chemically transformed into various feed materials used to fabricate the nuclear fuel. Deconversion products include uranium metal, uranium oxides (UO_2 and U_3O_8), uranyl nitrate solution, and UF_4. Processes for these transformations are reasonably well known, but for the following reasons, technology does not exist for processing HALEU materials in the U.S. today:

- For processes used in NRC Category III (uranium at less than 5% enrichment) fuel processing facilities, nuclear safety constraints would make deconversion equipment too large for 20% enriched uranium. Scaling down the equipment presents technical challenges.
- The equipment and capacities currently used in the NRC Category I facilities for processing HEU are far too small to meet the needs of the advanced reactor fuel fabricators.
- Further, no one today possesses the full range of the needed processes, regardless of scale.
- Finally, there is no currently NRC-licensed Category II facility in the U.S., and NRC regulations and requirements are not well defined for this type of facility.

Thus, the process equipment must be completely redesigned to support HALEU processing, and process development and demonstration testing is needed before production of reload quantities of these deconversion products is possible.

4.4 Lack of Storage/Shipping Containers for HALEU Materials

Uranium in various forms must be collected, shipped, and stored in suitable containers and shipping overpacks (if necessary). The forms include all chemical permutations mentioned in this report: uranium hexafluoride (UF_6); uranium oxides (UO_2 and U_3O_8); uranium tetrafluoride (UF_4); and uranium metal. There are currently no NRC-licensed, high-capacity packages available for these materials when enriched between 5% and 20%. The German company Daher is currently working with Urenco to design and license a transportation and storage package for 1600 kg HALEU UF_6. Challenges include ensuring subcriticality during transport and water ingress protections in an accident scenario (Jarrel 2018). This will be an expensive, multiyear activity. The uncertainties involved in licensing and the number of future packages needed make the colocation of enrichment and deconversion processes quite attractive. Licensing packages for the materials other than UF_6 should be less expensive and time-consuming.

Additionally, DoD activities are currently underway to make sure some future, but limited, HALEU transportation capability exists in support of their projects.

5. Suggested Solutions

This section suggests solutions to the challenges identified in Section 4. Four solutions are discussed for the four challenges discussed respectively: (1) a DOE-funded fuel fabrication development facility, (2) accelerating the creation of a HALEU UF_6 enrichment capability, (3) addressing the deconversion facility gap, and (4) addressing the SNM transportation gap.

5.1 DOE-Funded Fuel Fabrication Development Facility

One solution to this problem could be for the DOE to consider establishing a "Pilot Scale" fuel manufacturing plant. A pilot-scale plant is often built by manufacturing companies to accomplish the following:

1. Learn more about a specific process to make decisions regarding new technologies or improve processes and plant configurations.
2. Develop a better understanding of safety-related issues.
3. Collect large amounts of process data to aid in process/product improvements.
4. Explore new processing methods and/or test out new materials.
5. Evaluate/understand manufacturing costs and drivers.

Pilot plants are typically limited in their production capacity and are by design very flexible and easily reconfigured. These initial manufacturing plants are meant to expose potential problems so that possible solutions can be engineered and tested before continuing to scale up or transfer technology to a full-scale commercial operation. For example, an advanced-fuel pilot manufacturing plant might be limited in its capacity and throughput so as to fabricate the initial start-up core of fuel over a two- to three-year period.

Much the way that advanced reactor designers have adopted modular design concepts to reduce on-site construction costs, manufacturing organizations have sought far less expensive and faster alternatives to traditional "stick-built" process systems built on site. Thus, advanced manufacturing has adopted "modular process skids" that offer both robustness and flexibility that traditional stick-built process capabilities are unable to offer. Modular process skids have enabled advanced manufacturers to get their product to market faster and with less expense, especially with a new product line for which the manufacturer may not have fully worked out all the process difficulties.

Definition of a Modular Process Skid – a self-contained processing capability that has been assembled into some sort of frame (module) that can be easily transported to a manufacturing site and integrated into an existing facility and process line. Modular process skids can contain individual process steps or entire processing lines, which may include casting, blending, solvent recovery, centrifuge, and small-scale distillation.

Using modular process skids for various types of fuel fabrication process steps and/or inspections in a pilot fuel manufacturing facility will help create a very flexible, easily reconfigurable, and more user-friendly facility.

An example of an existing user-type facility is the Applied Process Engineering Laboratory (APEL), which is owned and operated by Energy Northwest in Richland, WA, and is financed using a combination of community funds and grants provided by the DOE. The 90,000 sq. ft. facility includes high bays, wet laboratories, and office space, allowing new business start-ups and entrepreneurs to lease space while also accessing nearby university and national laboratory staff. Moreover, the new start-ups can access advanced scientific instrumentation, which is often cost prohibitive for a new start-up but essential to innovate new materials and demonstrate new processes. The APEL facility offers opportunities for collaboration and cross-fertilization of ideas, in a setting where proper security and access are managed and proprietary information is protected.

5.1.1 Fuel Fabrication Facility Requirements

The requirements for a proposed pilot-scale advanced fuel fabrication facility are estimated assuming the facility will support primarily uranium fuel fabrication, and assuming accommodation of up to three different pilot-scale fuel manufacturing lines operating simultaneously. It is assumed that the facility would be capable of receiving and processing uranium enriched up to 20 wt% in ^{235}U. It is assumed that the fabrication of metal fuel forms would be supported and that the fabrication of molten salt as either coolant or fuel form could be supported if the salts were produced and shipped to the reactor under inert atmosphere. It is assumed that a fuel salt would be brought to criticality at the reactor by addition of fissile isotope(s). As discussed in the TRISO Fuels Summary section of Appendix A, the fuel fabrication facility would support vendors who wish to stand up their own TRISO capabilities independently of commercial fuel fabricators, and/or those who prefer to incorporate commercially acquired TRISO particles into custom compacts specific to reactor designs. Advanced oxide fuel forms will likely be supplied by commercial vendors, as discussed in the Oxide Fuels section of Appendix A, but the facility could certainly support such a fabrication line if needed.

Accommodation of fuels that incorporate transuranics (e.g., plutonium) and/or spent fuel is not considered an effective use of the proposed facility. The reasons are discussed in more detail in Appendix A and Appendix B. Briefly, there are currently plans to use existing facilities for such fuels. These facilities are already configured and approved for the more complex processes and requirements involved. Inclusion of transuranics and/or spent fuel would greatly increase the size, requirements, and cost of building such a facility. Additionally, support for such fuels appears to be needed at a later date than for the uranium-based fuels. A more cost-effective approach to supporting the greatest number of advanced fuel types would likely be a facility (with a different set of requirements) specifically for these more complex fuels.

A summary of the basic requirements developed for this evaluation and some additional capabilities is provided below. Additional detail is provided in Appendix C. The basic layout (floor dimensions, ceiling heights, etc.) and electrical service estimates to meet the assumed requirements are based on comparable commercial fuel fabrication facility designs and proposals recently produced for another program.

If DOE were to decide to pursue the construction of the CARFF, it would most likely be managed per the requirements established in DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*. The conceptual design phase would establish detailed requirements, analyze alternatives, and develop a conceptual design. The requirements and capabilities presented below were developed to provide an understanding of what a CARFF could look like and a rough, order-of-magnitude (ROM) cost estimate.

5.1.1.1 Size and Capacity

- Minimum 22,500 sq. ft. for radiochemical operations: fume hoods, glove boxes, etc.

  - Three floors, with 50 ft overall height to allow gravity feed for chemical processing
  - 375,000 cu ft ventilated volume, at 44,000 SCFM
  - Ventilation configured for quick connect/disconnect of up to six inertable glove boxes, 5' deep by 10' long by 8' high
- Ventilation configured for quick connect/disconnect of up to twelve 3' deep by 8' long fume hoods
- Minimum 60,000 sq. ft. of mechanical assembly space, for activities such as rod loading and bundle storage; 40 ft ceiling height; 10-ton crane
- Minimum 45,000 sq. ft. of clean administrative space for vendors and facility support functions, including offices, control room, shop, change rooms, etc.
- Electrical service of approximately 4000 kVA normal plus 1000 kVA standby/emergency, and a 1000 kVA standby/emergency diesel generator.

5.1.1.2 SNM Type, Physical Form, and Throughput

- The ability to process HALEU in the form of oxides, metals, and/or salts at a throughput of up to 2,400 kg of HALEU per month. This throughput is based on assumptions of approximately 18-month fuel fabrication campaigns and three separate vendors (two large reactor cores and one smaller one) working in the facility. The 18-month schedule is based on the fuel fabrication schedule shown in Table 5 of Appendix A, which reflects a notional timeline for fabricating a Natrium-like core (worst case based on core size). By the time the facility is constructed, licensed, and made ready, the fuel campaign will have about 18 months to complete an entire core load of fuel. Certainly, a longer fabrication schedule and/or smaller reactor core designs could be assumed to ease this throughput requirement. Changing the assumption of accommodating up to three different pilot-scale fuel manufacturing lines operating simultaneously to either accommodating two lines simultaneously or one line at a time would ease the throughput requirement as well.

5.1.1.3 Analytical, Measurement, and NDE Capability

- Analytical and radiological chemistry laboratory including advanced electron microscopy instruments that are sensitive to magnetic fields, vibrations, barometric pressure changes, and temperature variations
- Metrology laboratory where both temperature and humidity fluctuations are minimized to support measurement accuracy and reduce measurement uncertainty
- Optical microscopy laboratory with cutting and wet polishing capability.

5.1.1.4 SNM Storage Vaults

- Sufficient vault storage for up to 2,400 kg of HALEU metal.

5.1.1.5 SNM Shipping and Receiving

- The ability to receive up to 1 MT of HALEU in gas, oxide, or metal form, per day
- Sufficient UF_6 canister storage area for 3.5 MT of UF_6, which is equivalent to about three large transportation packages
- 10-ton lift that can transfer payloads between building interior and loading dock.

5.1.1.6 Cryogen/Inert Gas Storage and Supply

- Two 3000-gal capacity tanks for cryogen storage, with boil-off capture and distribution system to building interior for inerting of gloveboxes.

5.1.1.7 Waste Streams and Off-Gas Systems

- The ability to handle low-level solid wastes from routine radiochemical operations
- The ability to handle low-level liquid effluents from cleaning, sampling, and dissolution to support wet chemistry, polishing of optical microscopy specimens, and process waste management
- The ability to handle gaseous effluents resulting from thermal heat treatments, analytical chemistry dissolution, and possibly waste management
- The ability to handle toxic gases resulting from molten salt production, such as HF.

5.1.1.8 Safeguards and Hazard Categories

- DOE Safeguards (Material Control and Accountability) Category IV, assuming processing of only uranium enriched below 20% in ^{235}U. (Processing of material with more than 10% ^{233}U would require a higher category facility).
  - DOE Hazard Category 2 or 3, as determined in a reviewed and approved Documented Safety Analysis.

This facility is expected to be owned and regulated by DOE. For comparison purposes, it would likely be an NRC Category II facility, assuming processing of uranium enriched below 20% in ^{235}U. Processing of any significant quantity of ^{233}U in addition to ^{235}U would require an NRC Category I designation.

5.1.1.9 Seismic

- The seismic category requirement must be determined by analysis of the largest credible earthquake that could occur given the regional geology of the facility location and the resulting maximum surface accelerations at the facility.

5.1.2 Advantageous/Value Added Capabilities

The requirements described in the previous section are specific to each fuel manufacturing facility; however, various additional requirements could also be considered as part of an overall set of criteria and would provide certain advantages. These additional capabilities are described in the following subsections.

5.1.2.1 Hot Cell Capabilities

The likelihood that any new nuclear fuel will experience no performance problems after being irradiated in an advanced reactor (which itself has little operating experience) is small. Therefore, it would be beneficial to have hot cell capabilities either as part of the fuel manufacturing facility or located nearby. The hot cells allow scientists to perform post-irradiation examination and study the performance of irradiated nuclear fuels and materials without exposure to high levels of radiation. Such hot cells typically house an array of cutting, puncturing, and polishing capabilities that can create test specimens from larger fuel elements/assemblies. The irradiated specimens can then be further examined using an array of both nondestructive and destructive instruments capable of measuring irradiated materials' thermophysical properties, chemical composition, burnup, oxide thickness, etc. In addition, purpose-built equipment can be used to subject irradiated fuel to simulated accident conditions to establish the necessary technical basis for safety analyses. More stringent facility safeguards and hazard categories would likely be necessary to work with irradiated fuels.

5.1.2.2 Scrap Recovery and Waste Treatment Capabilities

Any nuclear fuel manufacturing process will generate scrap and rejected product. The chemical processing capability necessary to recover, purify, and reclaim uranium scrap and rejected fuel is highly desirable even though it adds to the facility's size, complexity, and cost. More importantly, recovery and recycle may be necessary for environmental and waste management reasons.

It may be possible to package and ship scrap and rejected product to existing facilities (e.g., the Y-12 National Security Complex and BWXT Nuclear Fuel Services) for recovery and reclamation. However, it might be worthwhile to assess the financial benefit of housing a scrap recovery and waste treatment capability within the fuel manufacturing facility.

5.1.2.3 Reprocessing Capabilities

It might be worth considering the benefits and drawbacks of establishing a fuel reprocessing center that can handle, process, and dispose of the array of irradiated nuclear fuels that will result from the advanced reactor start-ups. More stringent facility safeguards and hazard categories would likely be necessary to stand up a reprocessing capability.

5.1.3 DOE Facilities

5.1.3.1 Summary of Relevant Studies

In 2008, an evaluation of existing DOE facilities was performed to gain a better understanding as to whether these might be deployed to advance the near-term programmatic objectives of the Advanced Fuel Cycle Initiative (INL 2008). The scope of the 2008 evaluation focused on the candidate facilities' ability to produce lead test assemblies for an advanced burner reactor. This choice of representative fuel type required that the fuel fabrication facility have an NRC Safeguards Category of I, a large reprocessing capability, and significant atmosphere-inerting capabilities.

The evaluation rejected 22 facilities at Argonne National Laboratory, Hanford/Pacific Northwest National Laboratory (PNNL), SRNL/Savannah River Site, INL, LANL, and Oak Ridge National Laboratory based on their insufficient size (<1000 sq ft). After this down-selection, seven remaining fuel reprocessing facilities were evaluated. Five of the sites were rejected because their facilities were not rated to store and handle DOE Safeguards Category I levels of material (as of 2008). In each case, a new advanced burner reactor fuel fabrication facility would in effect have to be built on these sites to supplement the existing reprocessing capability.

For this current evaluation, since only HALEU materials are being considered, the Safeguards Category I requirement would be relaxed. There were (in 2008) and are issues for which significant investment would be required to upgrade the candidate facilities. These include

- lack of a minimum inertable process space required for metal or salt processing,
- updated safeguards systems,
- issues with facility age,

- newly required seismic and environmental studies,
- cleanup of heavy radiological contamination,
- the potential prohibition of new construction on contaminated DOE sites,
- effects of an encroaching public,

and possibly others. In the current evaluation, it is agreed that the costs are too high to warrant further discussion of fuel fabrication within the existing facilities set, except for those recommended by the 2008 evaluation at INL and at the FMEF site at Hanford.

5.1.3.2 The Fuels and Materials Examination Facility at the Hanford Site in WA – FMEF

The FMEF is a DOE facility located near the Fast Flux Test Facility (FFTF) in the 400 Area of the Hanford Site (controlled area) in Washington State. The FMEF, shown in Figure 2, was built during the late 1970s and early 1980s as a major addition to the DOE's breeder reactor technology development program.

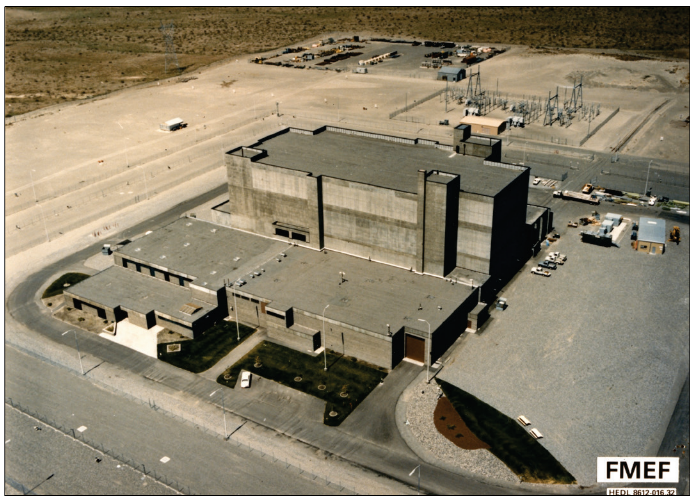

Figure 2. Fuels and Materials Examination Facility at Hanford

The FMEF was designed and constructed to have fuel development, fabrication, and examination capabilities in support of the FFTF and other reactors in the liquid metal fast breeder reactor program. It was to be equipped to receive SNM in powder form and prepare feedstock, analyze fuels and fuel materials, fabricate test fuel pins, and develop fuel manufacturing processes, equipment, and handling systems that meet established safeguards, security, safety, and environmental criteria. In addition, the facility was to be equipped to receive, clean, nondestructively examine, and disassemble irradiated fuels, materials, and core components from fast flux test facilities and other liquid metal fast breeder reactors, nondestructively and destructively examine individual fuel, blanket, and absorber pins, and reassemble selected fuel assemblies or other material for additional irradiation after nondestructive examination. It is a modern structure designed to meet present-day requirements for seismic and high wind conditions. No operation with radioactive material ever took place in the FMEF; it is a clean facility. FMEF was placed in layup in the late 1990s; the facility is unoccupied.

Given that the facility's original intended purpose was to develop, fabricate, and characterize nuclear fuel for multiple reactors in the liquid metal fast breeder program, the facility meets the basic requirements presented in Section 5.1.1.

It is a Safety Class I nuclear facility (Stradley et al. 1985). Details of the FMEF design and safety analysis can be found in the Fuel Cycle Plant Final Safety Analysis Report (Larson et al. 1986). It was designed to ERDA 6301 for missions that required enhanced safeguards and security. It is a security Category I facility, designed and constructed for processing and storing Category I quantities of nuclear material.

FMEF has approximately 188,000 ft^2 of operational space, including a process building, a fuel fabrication area, a truck bay, and an entry wing that accommodate up to 25,000 ft^2 of office space and administrative support areas. The facility's size exceeds those set in Section 5.1.1.1. A more detailed description of the facility's floor plan is provided in Appendix E.

There are five different and significant heating, ventilating, and air-conditioning (HVAC) systems (and minor exhausters on uninterruptible power system battery bank rooms) to the Process Building, Entry Wing, Fuel Assembly Area, Emergency Equipment Wing, and Mechanical Equipment Wing. All cells, enclosures, gloveboxes, and open-faced hoods are exhausted by the HVAC system. The Fuel Assembly Area and Process Building HVAC systems have multiple levels of high efficiency particulate air (HEPA) filtration and have recirculation capability for multiple air changes (8) per hour. The Process Building HVAC has three 200 hp exhaust fans (80,000 cfm with two fans running), three supply fans, and six large recirculation fans to accommodate original mission air flows. Cooling is provided by two 350-ton water-cooled chillers and 1800 gallons per minute of glycol/water circulating through fan coil units.

The facility receives its electric power from redundant 115 kV power lines, each supplied from a separate portion of the Bonneville Power Administration's power grid. This is transformed to supply power at 13.8 kV to the main 400 Area substation. Conversion of this power to 480 V for facility use occurs in two redundant transformer facilities located just north of the Process Building. In the event of a power failure, two on-site 900 kW gas turbine generators are available to provide redundant power to vital loads. Fuel capacity is enough for 24 hours of continuous operation. An uninterruptible power system is also provided. It comprises two 150 kVA systems with lead-calcium batteries that can supply power for one-half hour at full load. Other on-site services that support the FMEF are security, fire protection, maintenance, warehousing, sanitary and fire water supply, and process and sanitary water disposal systems.

While the facility could meet the requirements for an advanced fuel fabrication facility, its large size, its safety and security classification, and the fact that it has been dormant for almost two decades may mean it is too large and expensive to restart solely for the mission described in this assessment. To assess the cost of restoring FMEF to support full-time, nonnuclear/nonradioactive operations, PNNL contracted with a team of specialists experienced with Hanford's abandoned structures who have direct background with this facility. This team performed a tabletop review (no facility historical records were accessed and no walkdowns were conducted) of reactivating systems at FMEF allowing full-time occupancy. The review yielded a ROM cost estimate of $12.5 M (including 50% contingency) with an execution schedule of 12 to 24 months. Restarting the facility for nuclear operations would be significantly more expensive. The estimated cost of $75 million (Heath and Race 2019) to restart the Transient Reactor Test (TREAT) facility provides a reasonable ROM estimate of what it could cost to restart the FMEF for nuclear operations. While the facilities and safety bases differ, they are both nuclear facilities that contain SNM. Many of the steps that were needed to restart the TREAT facility would be required to restart the FMEF for nuclear operations (See Heath and Race 2019 for what needed to be accomplished to restart the TREAT facility). Adding a contingency to account for the longer time that the FMEF has been dormant brings the ROM estimate to $100–150 million. The option of retrofitting an existing facility such as FMEF is expected to be quicker than building a new facility. If timing is important, this may be a factor in weighing the options.

If the FMEF is deemed too expensive to restart for the purpose described in this report, it may be advantageous to (1) expand its purposes to include fabrication of Pu-based fuels or that use spent nuclear fuel, since the requirements for these fuel types are drastically different and would require a facility like FMEF, or (2) consider a restart for multiple-mission purposes.

5.1.3.3 The Radioactive Liquid Waste Treatment Facility at INL's Materials and Fuels Complex – (MFC-798 RLWTF)

The RLWTF (Figure 3) was previously used to treat radioactive liquid wastes from the Hot Fuels Examination Facility, Fuel Conditioning Facility, and other facilities at the Materials and Fuels Complex (MFC). RLWTF is no longer used for that purpose, and the dedicated liquid waste treatment piping, components, tanks, ventilation, control panels, and equipment are being removed via an associated deactivation and decommissioning project. Primary attributes of and considerations for use of the RLWTF building (MFC-798) include the following:

- RLWTF is a two-story, 5000 ft^2 building that was purpose-built in 1983 for treating radioactive liquid wastes.
- The building has no current mission but has been considered for HALEU fuel fabrication.
- The building should be suitable for Hazard Category 2 operations based upon the known seismic design, with associated nuclear/criticality safety analysis and minor facility modifications as required.
- Some of the legacy equipment within the building would be useful for a fuel fabrication mission. The exhaust stack, blowers, and HEPA filters are all in good condition and can be reused. The main electrical supply lines and switchgear would be reused.
- The two-story, compartmentalized design and small size of this facility likely limit its use to a dedicated smaller-quantity fuel fabrication mission. More efficient use of the building could be enabled by space reconfiguration or limited building extensions.

Figure 3. Radioactive Liquid Waste Treatment Facility

While RLWTF is not large enough to meet the mission of CARFF, the option of retrofitting a smaller existing facility such as RLWTF for a smaller mission would be quicker than building a new facility. If timing is important, this may be a factor in weighing the options.

5.1.3.4 Fuel Processing Restoration Facility at INL's Idaho Nuclear Technology and Engineering Center (INTEC) – (FPR; CPP-691)

The Fuel Processing Restoration (FPR) facility (Figure 4) was built starting in 1986 to house state-of-the-art HEU extraction and denitration capabilities needed to replace the existing 1950s-vintage spent nuclear fuel processing capability and increase annual throughput. As such, it is built primarily around tall, heavily shielded, adjoining hot cells. It is a large, rectangular, reinforced concrete structure with overall dimensions of approximately 215 by 245 feet, with about 170,000 ft^2 of floor space. Construction was phased out in 1992–1993, leaving a structurally complete facility with an interior that was completed to a lesser degree. While the exterior of the building was completed, permanently installed utility and life safety systems (e.g., electricity, lighting, ventilation, water, fire protection, etc.) were not.

Figure 4. Fuel Processing Restoration Facility

While this is a large, robust facility, the original hot-cell–based operations for which this facility was primarily designed could prove somewhat inefficient to adapt to contact-handled glovebox/hood fuel fabrication lines. The incomplete nature of the facility interior could simplify modification for future missions, but completion of the facility's utility and life safety systems has been projected to require tens of millions of dollars. FPR is also currently managed under the DOE Office of Environmental Management mission, so use of this building would likely require a DOE interoffice agreement that could present additional potential challenges and cost-sharing implications for management and operation of this facility at its Idaho Nuclear Technology and Engineering Center cleanup location.

The building has two above-grade stories for a total height of 50 ft above grade, and three below-grade stories for a total depth of 45 ft below grade. The building has a central high-roofed section with two lower-roof wings to the north and south of the building. The upper above-grade level (also called the second floor) is located beneath the southern portion of the central structure at the same elevation as the north and south low-roof wings. There is also a mezzanine level between the first and second floors near the southern end of the central structure. The second floor and mezzanine levels consist of generally open space.

The first level of FPR covers the full facility footprint at ground level. It comprises various nondescript partitioned rooms and includes a large generator supported on concrete pads near the southwest corner of the building. This level contains several doors and openings for personnel and equipment access.

The three below-grade levels house corridors, maintenance, storage, and equipment rooms. Numerous three-story-tall concrete hot cells span the height of these basement levels near the northern end of the central building. The basement levels extend over the full building length in the east–west direction but cover only a portion of the total building footprint in the north–south direction.

Below grade, the FPR Facility comprises reinforced concrete footings, reinforced concrete slabs, and reinforced concrete walls. Above grade, the facility has a steel superstructure with roof-level diaphragms (including steel joists and bracing), steel columns, girders, and cross-braces. The above-grade structure also has reinforced concrete shear walls, and elevated reinforced concrete slabs on metal decking.

The steel superstructure columns also support crane rails for a 50-ton bridge crane at an elevation between the second floor and high roof near the northern side of the central structure. Steel bracing is provided directly beneath the roof level for redundancy to prevent the roof from collapsing in the event of the failure of a crane column.

This is a large, robust facility that could likely support the mission, and should be considered, but it is not laid out for the current needs and building a new purpose-built fuel fabrication facility may be more economical. However, the option of retrofitting an existing facility such as FPR is expected to quicker than building a new facility. If timing is important, this may be a factor in weighing the options.

5.1.3.5 The Mixed Oxide Fuel Fabrication Facility on the Savannah River Site – MFFF

The Mixed Oxide Fuel Fabrication Facility (MFFF, now the Savannah River Pit Production Facility) was started in 2007 as part of a U.S. agreement with Russia to eliminate excess weapons-grade plutonium by converting it into mixed uranium-plutonium oxide (MOX) fuel, which in turn would be used to fuel commercial LWRs. The project was terminated in 2018. The MFFF consisted of numerous buildings; however, the primary building was the MOX Fuel Fabrication Building (MFFB). The MFFB housed the aqueous polishing area, the MOX fuel processing area, and the shipping and receiving area. The MFFB has three different levels and more than 400,000 square feet of space. The exterior walls and roof were designed and constructed to resist hazards of credible anthropogenic and natural phenomena.

In 2020, the NNSA issued a final environmental impact statement (DOE 2020c) in support of repurposing the MFFF to produce a minimum of 50 war reserve plutonium pits per year at the Savannah River Site for supplying the nuclear weapons stockpile. Such a mission would involve internal modifications and installation of manufacturing and support equipment directly associated with the pit production mission. In the event that MFFF is slated for a new pit production mission, the security requirements necessary for such a mission would make it impractical to consider its use as a user-type fuel manufacturing facility for the advanced reactor community.

5.1.3.6 New Facility

A new, purpose-built fuel fabrication development facility is an economical alternative to converting existing space in an existing facility that was designed for other purposes. A new facility design can be optimized for the purpose, without having to pay for renovation and modification of an existing (usually hardened) structure. This section of the report describes a system optimized for the purpose of providing the infrastructure needed by advanced reactor fuel developers.

The basic requirements for such a facility are described in Section 5.1.1. It would house three parallel "bays" for developers to use independently of each other. Appropriate partitions between bays and in shared spaces would protect the developers' intellectual property. All bays are essentially identical, equipped for easy placement of the developers' process equipment on skids in one of two process areas.

The first process area is the "chemical area," provided with nuclear-grade ventilation to accommodate harsh process chemicals and unencapsulated HALEU. It should have a 50' × 50' floor area and a 50' ceiling height. Metal platforms could be included to provide up to three floors of process area, allowing gravity flow of materials if desired. This area would also have ventilation to support glove boxes and fume hoods as needed for the particular developer.

The second process area is the "mechanical area" that allows handling of encapsulated uranium and mild chemicals similar to the rod and bundle fabrication areas in a conventional fuel fab shop. This area should be 20,000 square feet (50' × 400') with a 30' ceiling. It would include shipping container loadout as needed as well.

An additional area would house "clean" support areas, including change rooms, offices, lunchrooms, maintenance/machine shops, analytical laboratory, etc. An area with at least 15,000 square feet per bay is suggested.

A ROM cost for such a new facility, set up on a DOE site, is $100–250 million. This cost is based on a recent comparable commercial facility cost estimate and on PNNL facility engineers' experience with setting up development facilities at PNNL. Such a facility is expected to take 4–5 years to establish once funding is available.

5.2 Accelerate Creation of a HALEU UF_6 Enrichment Capability

Obtaining enriched uranium feedstock and nuclear fuel-related components can be a significant challenge. These are certainly long lead items and require advanced planning, qualification of sub suppliers, and capital for building/licensing new HALEU enrichment infrastructure and transportation packaging. With regard to HALEU enrichment, the U.S. does not currently possess an industry scale enrichment capability to manufacture UF_6 at the enrichments (up to 20%) needed to enable the deployment of many of the advanced nuclear power reactors.

The flow diagram in Figure 5 shows the relationship between enriched uranium product (as UF_6), the necessary deconversion processes, and the various fuel fabrication processes, which thereafter become exclusive to the different types of fuel needed for advanced reactors. The green boxes are capabilities that already exist commercially, but for which the level of enrichment that can be handled is limited by licensing and criticality safety constraints. The blue boxes show conversion fuel cycle steps that used to be performed in the U.S. at an industrial scale but no longer exist. The purple boxes signify the fuel fabrication processes that are unique to each of the major types of reactor fuels. Each specific reactor design may require unique fuel fabrication processes within major fuel types as a result of their different designs. The plutonium processing is depicted very simplistically in orange and would itself require a rather large and complex infrastructure to support large-scale production. Historically, attempts to process plutonium in the U.S. have not been successful because of policy issues, fears of proliferation, and a myriad of safety/regulatory requirements that increase the cost of handling it. Transportation of these materials between fuel cycle facilities is also challenging and must be factored into any new fuel fabrication effort.

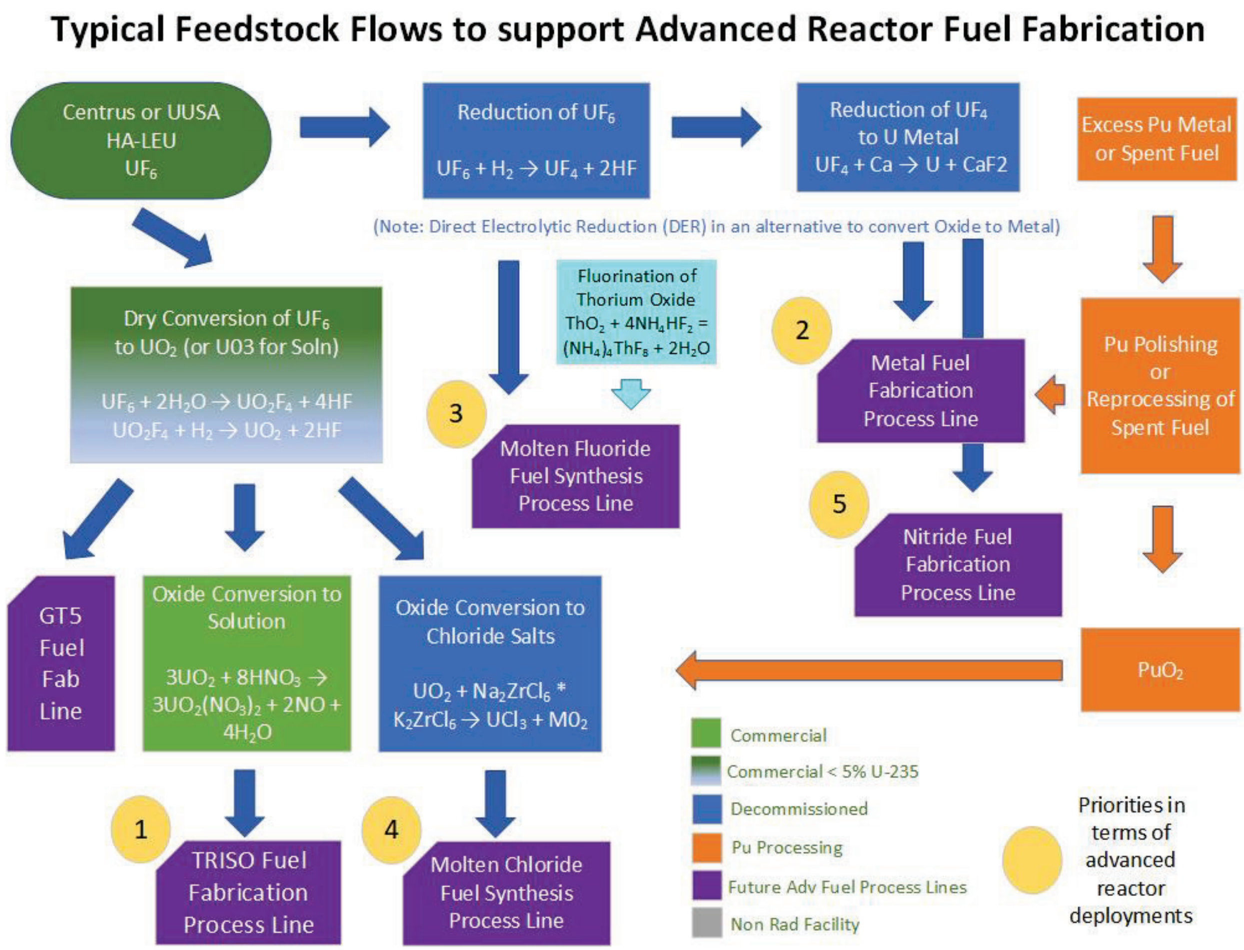

Figure 5. Typical Feedstock Flows to Support Advanced Reactor Fuel Fabrication Needs (UF_6 Feed)

Currently, the U.S. has two licensed suppliers of enrichment services: Urenco USA and Centrus. Informal discussions with both companies indicate that strong market drivers will be needed before private investments are made in establishing and licensing a new HALEU enrichment capability. Other potential commercial interests in future HALEU enrichment might also emerge, given sufficient business interest. A more extensive discussion of domestic enrichment capabilities is presented in Appendix B.

Urenco USA (UUSA), a wholly owned subsidiary of the European company Urenco, operates an enrichment facility in Eunice, NM. The facility receives natural UF_6 feedstock from Canada and other global suppliers and uses centrifuge enrichment technology to increase the concentration of the fissionable ^{235}U isotope from natural uranium to a maximum of 5.5 wt% ^{235}U. The enrichment capacity at UUSA is approximately 4.9 million separative work units (SWU) per year. This capacity is roughly equivalent to 25% of the annual demand for uranium enrichment services by the U.S. fleet of LWRs. Urenco has stated that they can meet HALEU demand in one of two ways, depending on demand signals from industry (and government). If the HALEU demand is low but sufficient, they can invest some millions of dollars to convert some of their existing centrifuges to HALEU production. This will necessitate an NRC license amendment and partitioning off some of their existing facility to handle Category II SNM as defined by the NRC. The alternative is to expand the capacity of the existing plant by adding more centrifuges. Investment needed for this alternative is on the order of hundreds of millions of dollars.

In FY 2020, the DOE awarded a cost share contract with Centrus to partially fund demonstration of their AC-100M centrifuge technology to produce 19.75% enriched uranium hexafluoride gas. Once the new centrifuges are installed and the license amendment is completed, the American Centrifuge Plant (ACP) will be limited to about 900 kgU of HALEU and have a production capacity of approximately 5,500 SWU each year. However, the demonstration facility is not of a scale to be commercially viable or meet the HALEU requirements of the advanced reactor community. Therefore, if the ACP is to become a valid supplier of HALEU enrichment services, it will be critical to sustain and grow the capability in order to establish a HALEU production capability to meet demonstration reactor fuel requirements in early-stage development. It is necessary as well to demonstrate the long-term reliability of the AC-100 M centrifuges and the commercial viability of the ACP.

Downblending HEU to produce LEU has been done commercially at the BWXT Nuclear Fuel Services, Inc. (BWXT NFS), which is located in Erwin, TN. BWXT NFS is the only domestic commercial NRC-licensed Category I nuclear fuel facility and is capable of downblending metric-ton quantities of HEU. Modifications of vessels for criticality safety reasons would need to be done to produce HALEU feedstocks. Downblending HEU to HALEU would result in a uranium nitrate solution, which could be transformed into an oxide powder. With the proper investments, commercial capabilities to convert uranium nitrate to uranium metal via an intermediate UF_4 salt could be established.

Note: Existing HEU inventory has many competing uses (e.g., research reactors, medical isotopes, naval reactors, and DoD users); therefore, allocation of HEU feedstocks for downblending to HALEU in support of advanced reactor deployments would be a choice only made by DOE leadership considering multiple missions and priorities.

If downblending existing HEU stockpiles to support the deployment of advanced reactors is not feasible, then DOE might consider procuring 40–60 MTU of HALEU and creating incentives to establish deconversion capabilities. The resultant products could then be sold to the advanced reactor community as needed at some agreed-to, fair market price. One approach to accomplish this could be to work with Congress to extend/modify the American Nuclear Infrastructure Act of 2020 to include this new feedstock material as part of the national strategic uranium stockpile.

The guaranteed purchase of a stock of HALEU could strengthen the commercial case for establishing both the enrichment and deconversion capability in the U.S.

5.3 Deconversion Capability

Filling the "deconversion gap" presents both a technical and economic challenge. From a technical perspective, while the processes were well understood in the past, there will be a learning period to create commercial-scale processes. From an economic standpoint, it may not be optimum or feasible for every advanced reactor vendor to pay to redevelop the technology and build new facilities to deconvert UF_6 to meet the requirements for their specific feed material. Doing so would pose a very large hurdle, particularly for smaller start-ups. A potential option is to establish a central deconversion operation that would convert UF_6 from the enrichment facility into four products, as indicated in Figure 6.

As mentioned earlier, deploying this capability will require two steps: (1) development and demonstration of the HALEU processes and equipment, and (2) building an appropriately sized production scale facility. It is estimated that the latter must be in production by late 2024 to support the two ARDP recipients. Since it is unlikely that a government-sponsored facility could meet this demanding schedule, it is likely that a commercial entity would need to take on both activities, and supplemental funding by DOE could help.

Development and demonstration may best be accomplished at an existing, licensed facility using natural uranium; this is estimated to take 2–3 years. Building the facility could be started in parallel with development and demonstration, and would depend on results from that first step by the detailed design stage so that the facility would be ready to begin production in 4–5 years. To reduce the various risks associated with shipping HALEU UF_6 and because there is (currently) no NRC Category II fuel fabrication facility, there may be benefits in colocating the deconversion facility with the HALEU enrichment facility.

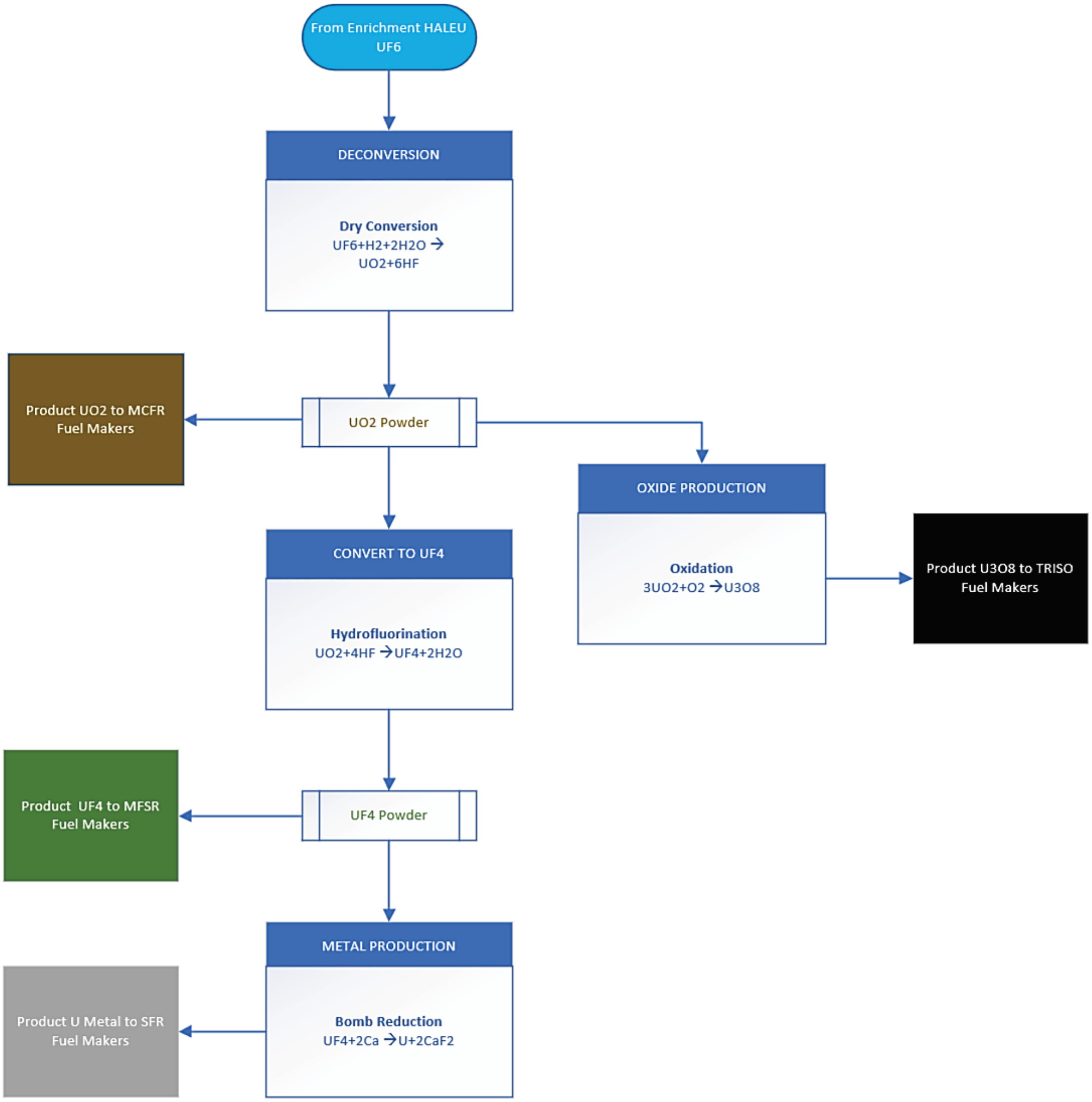

Figure 6. Deconversion Facility Material Flow Diagram

5.4 Suggested Solution for Transport of HALEU Materials

DOE should consider sponsoring a commercial effort to design, license, and purchase a minimum number of HALEU certified transportation packages for the various materials described in Section 4.4. Custodianship for these packages could be assigned to either a commercial vendor or a national laboratory ensuring proper maintenance, service intervals, and managing shipping needs. DOE has previously invested in the evaluation of available HALEU UO_2 criticality benchmarks (Eidelpes 2019); however, additional criticality benchmarks may be needed to support new packages' licensing efforts. Transportation packaging becomes less important if the deconversion plant is colocated with the enrichment facility. In any case, DOE support for the development and deployment of HALEU shipping containers would be a useful contribution to advanced reactor development.

6. Conclusion and Recommendations

The fact that more than 30 U.S. companies are designing a variety of advanced reactor types evidences significant commercial and U.S. government interest in commercializing these new technologies. Today's advanced reactor technologies promise enhanced safety, improved economics, and allowance for nonelectric applications (e.g., desalination, energy storage, and high-temperature process heat). Moreover, nuclear power has already been proven to enhance grid resilience, reduce long-term volatility in electricity costs, and provide carbon-free electricity generation.

Each of the advanced reactor designs has its own distinct fuel design. The advanced fuels include oxides, metals, TRISO-based particle fuels, salts, and nitrides. Most will be fabricated using HALEU, but several include plutonium.

In this report, an informal survey of the various reactor designs was performed to assess designers' plans for acquiring their first core load of nuclear fuel. Comprehension of the specific fuel types, number of vendors, and existing fuel fabrication plans allowed requirements to be defined for a new fuel fabrication facility: the Center for Advanced Reactor Fuel Fabrication (CARFF).

With regard to each of the specific fuel types, the following conclusions were drawn:

- HALEU oxide fuels – Although a new advanced fuel fabrication user-type facility would be capable of assisting a potential GT5 (greater than 5% enrichment) fabricator, it is considered unlikely to be so utilized given that modifications to existing fuel fabrication facilities are relatively small for enrichments ranging from 5 to 8%.
- HALEU metal fuels – TerraPower is currently working with the commercial industry to establish a metal fuel manufacturing capability, and Oklo is working with INL to build their first core. Developers that have longer-term plans would benefit from a new advanced fuel fabrication user-type facility, and from a cost, staffing, and capability viewpoint, sharing such infrastructure would make considerable sense.
- HALEU TRISO fuels – It is unlikely that the CARFF would be needed for fabricating TRISO fuels to support near-term deployments because commercial TRISO fuel manufacturing capabilities are already being established. However, the CARFF may be useful for prototyping and demonstrating advanced TRISO compacts, envisioned by some reactor developers, or to support vendors who wish to stand up their own capabilities independently of commercial TRISO fuel fabricators.
- Fluoride salt fuels – Use of a new, advanced fuel fabrication user-type facility to support deployment of advanced fluoride salt reactors may be very beneficial to the molten salt reactor (MSR) community.
- Chloride salt fuels – The vision of a new, advanced fuel fabrication user-type facility that is set up specifically for HALEU may not meet the needs of advanced chloride salt reactor developers, given their need for a plutonium-based fuel salt.
- Nitride fuels – The open literature did not yield much information related to commercial advanced reactor companies pursuing reactor designs based on use of uranium nitride fuels.

The pending NASA announcements for nuclear space power and space propulsion may motivate development of nitride-fueled designs.

Technical, research, and logistical challenges remain before delivery of the first advanced reactor cores. This report identified four major challenges:

1. Nuclear fuel fabrication facilities are expensive to start up; it would be difficult to justify building one to produce a single core load of fuel. A gap in demand for a given fuel form is to be expected after a successful demonstration of a reactor design and before a design is commercially deployed. This makes it more difficult for fuel fabricators to justify these investments until there are strong business signals pointing toward a stable market.
2. A plan is needed to acquire the HALEU feedstock to make sure SNM is available for fabricating the first core loads of nuclear fuel. The DOE recognizes this and has efforts underway to address this issue.
3. There is currently no industrial-scale deconversion processing capability to transform HALEU UF_6 gas into the feedstock materials (e.g., oxide, metal, nitrate solution) needed to manufacture the different fuel forms.
4. Licensed transport packages are needed to safely move materials and final products.

An NRC Category II facility is envisioned; this concept assumes three bays that could accommodate three independent fuel fabrication efforts; appropriate partitions would be established between bays and in shared spaces to protect the developers' intellectual property. The bays would be essentially identical. Each would be equipped for easy placement of the developers' process equipment on skids in one of two process areas: a chemical area provided with nuclear-grade ventilation to accommodate harsh process chemicals and unencapsulated HALEU, and a mechanical area to handle mild chemical processes and encapsulated HALEU. An additional area would house "clean" support areas. Changing the assumption from accommodating three different pilot-scale fuel manufacturing lines operating simultaneously to accommodating either two lines simultaneously or one line at a time would ease the throughput requirement, as well as the cost, construction schedule, and size requirements of the CARFF.

As part of this study, four facilities within the DOE national laboratory complex were evaluated to be potentially restarted or reconfigured as a fuel fabrication facility:

1. The Fuels and Materials Examination Facility (FMEF) on the Hanford Site in Washington
2. The Radioactive Liquid Waste Treatment Facility at the Materials and Fuels Complex on the INL site – MFC-798 RLWTF
3. The Fuel Processing Restoration Facility (CPP-691) on the INL site – FPR
4. The Mixed Oxide Fuel Fabrication Facility on the Savannah River Site – MFFF

Of these four facilities, the FMEF met the basic requirements for the envisioned fuel fabrication facility. A rough, order of magnitude (ROM) cost of $100–150 million was estimated to restart the FMEF for nuclear operations. The FMEF is a large facility that can accommodate multiple missions. The facility was initially designed to fabricate Pu-based fuels; however, it was deemed too large, and likely too expensive, to restart for the sole purpose described in this report. Thus, it may be advantageous to consider it in a future study focused on fabricating Pu-based fuels, supporting reactor developers intent on using spent nuclear fuel as their initial feedstock, or restarting for multiple-mission purposes. The other three facilities were deemed to not meet the set of requirements in one or more ways but could still be considered if conditions or needs change. Repurposing a suitable existing facility is expected to be faster than building a new facility.

Building a new, purpose-built fuel fabrication development facility may be an economical alternative to converting existing space in an existing facility that was designed for another specific purpose. A ROM cost for such a new facility, set up on a DOE site, is on the order of $100–250 million, based on a recent comparable commercial facility cost estimate and on PNNL facility engineers' experience with setting up radiological developmental facilities. Such a facility is expected to take 4–5 years to establish once funding is available.

To address the four major challenges, the authors propose the following eight recommendations:

Recommendation 1a: Analyze whether there is a CD-0 mission need for the Center for Advanced Reactor Fuel Fabrication per DOE Order 413.3B. Initiate the preconceptual planning, mission-validation independent review, mission need statement document, and independent cost review for a new Center for Advanced Reactor Fuel Fabrication (CARFF)—either a new facility or restart of an existing facility that meets the basic requirements. This will determine whether there is a mission need and address CD-0 requirements for a capital acquisition per DOE Order 413.3B.

Recommendation 1b: Fuel fabrication PFDs and ASTM standards. Develop fuel fabrication process flow diagrams (PFDs) for each of the major fuel forms. Survey existing ASTM standards associated with the various material specifications and identify gaps where new ASTM standards should be developed.

Recommendation 2a: A central deconversion facility. Evaluate the need for and identify potential private-public frameworks to set up a central deconversion facility that deconverts UF_6 into its common feed material for the different fuel forms.

Recommendation 2b: Colocation of front-end processes. Consider colocating as many front-end processes as possible in the development of the fuel supply chain for advanced reactors. Particular consideration should be given to colocating a central deconversion facility with one of the HALEU enrichment sites. In addition to significant cost reductions associated with pooled resources, transportation cost of HALEU materials would be minimized.

Recommendation 3a: Government purchase of HALEU. The U.S. government should consider purchasing 60 MTU of HALEU UF_6, which could then be sold to the advanced reactor community as needed at some agreed-to fair market price. In addition, the guaranteed purchase of a stock of HALEU will strengthen the commercial case for establishing both the enrichment and deconversion capabilities in the U.S.

Recommendation 3b: Reallocation of highly enriched uranium (HEU) for downblending. Enrichment is the long-term solution. In the short term, some HEU could be reallocated for downblending to HALEU; this would be a choice only made by DOE leadership considering the multiple mission and priority needs.

Recommendation 3c: Reserving HEU downblend for users requiring unobligated fuel. The U.S. government should consider reserving HEU downblend capability for users and programs that must use unobligated fuel.

Recommendation 4a: HALEU Transportation. DOE should consider sponsoring a commercial effort to design, license, and purchase a minimum number of HALEU certified transportation packages. Custodianship for these packages could be assigned to either a commercial vendor or a national laboratory ensuring proper maintenance, service intervals, and managing shipping needs. Additional criticality benchmarks may be needed to support new packages' licensing efforts

7. References

42 USC. 2019. *Nuclear Energy Innovation and Modernization Act*. Public Law 115-439, §103, Advanced Nuclear Reactor Program. Accessed February 2, 2021, at https://www.congress.gov/115/plaws/publ439/PLAW-115publ439.pdf.

DOD – U.S. Department of Defense. 2020. *DOD Awards Contracts for Development of a Mobile Microreactor*. Accessed January 26, 2021, at https://www.defense.gov/Newsroom/Releases/Release/Article/2105863/dod-awards-contracts-for-development-of-a-mobile-microreactor/

DOE – U.S. Department of Energy. 2014. Advanced Reactor Concepts Technical Review Panel Public Report: Evaluation and Recommendation for Future R&D on Seven Advanced Reactor Concepts, Conducted March through June 2014. Washington, D.C. Accessed January 25, 2021, at. https://www.energy.gov/sites/prod/files/2014/12/f19/Advance%20Reactor%20Concepts%20Technical%20Review%20Panel%20Public%20Report.pdf.

DOE – U.S. Department of Energy. 2020a. *U.S. Department of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program*. Accessed January 26, 2021, at https://www.energy.gov/ne/articles/us-department-energy-announces-160-million-first-awards-under-advanced-reactor.

DOE – U.S. Department of Energy. 2020b. *Energy Department Green Lights Critical Decision 1 for Versatile Test Reactor Project*. Accessed January 26, 2021, at https://www.energy.gov/ne/articles/energy-department-green-lights-critical-decision-1-versatile-test-reactor-project#:~:text=WASHINGTON%2C%20D.C.%20%E2%80%93%20The%20U.S.%20Department,nuclear%20energy%20and%20other%20technologies.

DOE – U.S. Department of Energy. 2020c. *Final Environmental Impact Statement for Plutonium Pit Production at the Savannah River Site in South Carolina*. DOE/EIS-0541, U.S. Department of Energy, Washington, DC. Accessed April 22, 2021, at https://www.energy.gov/nepa/downloads/doeeis-0541-final-environmental-impact-statement.

DOE 6430.1. 1983. General Design Criteria Manual. DOE Order 6430.1, U.S. Department of Energy, Washington, DC. Accessed March 12, 2021, at https://www.directives.doe.gov/directives-documents/6400-series/6430.1-BOrder-ch01-09/@@images/file

Eidelpes E, JJ Jarrell, HE Adkins, BM Hom, JM Scaglione, RA Hall, and BD Brickner. 2019. *UO_2 HALEU Transportation Package Evaluation and Recommendations*. INL/EXT-19-56333, Rev. 0, Idaho National Laboratory, Idaho Falls, Idaho. Accessed April 22, 2021, at https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_20375.pdf.

ERDA Manual Appendix 6301, *General Design Criteria, Engineering Handbook*. U.S. Energy Research and Development Administration, Division of Construction.

GAO – Government Accountability Office. 2020. *Technology Readiness Assessment Guide*. GAO-20-48G, U.S. Government Accountability Office, Washington, DC. Available at https://www.gao.gov/products/gao-20-48g.

Heath BK and CC Race. 2019. "TREAT Restart Project." *Nuclear Technology* 205:10, 1369-1377. DOI: 10.1080/00295450.2019.1589853. Accessed March 12, 2021, at https://www.tandfonline.com/doi/full/10.1080/00295450.2019.1589853.

IAEA – International Atomic Energy Agency. 2020. *The Advanced Reactor Information System (ARIS) Database*. Vienna, Austria. Accessed November 2020 at https://aris.iaea.org/.

INL – Idaho National Laboratory. 2008. *Evaluation of Existing Department of Energy (DOE) Facilities to Support the Advanced Fuel Cycle Facility (AFCF) Mission*. GNEP-AFCF-PMO-AI-EA-2008-000271, Revision 1. Idaho National Laboratory, Idaho Falls, Idaho.

Jarrel J. 2018. *A Proposed Path Forward for Transportation of High-Assay Low-Enriched Uranium*. INL/EXT-18-51518, Idaho National Laboratory, Idaho Falls, ID. Accessed March 31, 2021, at https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_19856.pdf.

Larson GF, AB Webb, MW Benecke, IL Metcalf, RK Hulvey, WI Clark, and RC Reinmann. 1986. *Fuel Cycle Plant Final Safety Analysis Report*. HEDL-TC-2679, Hanford Engineering Development Laboratory, Richland, Washington.

NEI – Nuclear Energy Institute. 2018. *Addressing the Challenges with Establishing the Infrastructure for the front-end of the Fuel Cycle for Advanced Reactors*. (NEI White Paper).Washington, DC, January 2018. Accessed January 25, 2021, at https://www.nrc.gov/docs/ML1810/ML18103A250.pdf.

NRC – U.S. Nuclear Regulatory Commission. 2020. *Fuel Fabrication*. Accessed January 27, 2021, at https://www.nrc.gov/materials/fuel-cycle-fac/fuel-fab.html.

NuScale. n.d. *Technology Overview: How the NuScale Module Works*. Accessed January 26, 2021, at https://www.nuscalepower.com/technology/technology-overview

Smith NV. 2020. *Assessment Gap National Lab Capabilities to Enable Demonstration Reactors* INL/EXT-20-59834, National Reactor Innovation Center, Idaho Falls, Idaho. Accessed January 25, 2021, at https://inldigitallibrary.inl.gov/sites/STI/STI/Sort_26793.pdf#search=Assessment%20Gap%20National%20Lab%20Capabilities%20to%20Enable%20Demonstration%20Reactors.

Stradley J, H Yook, E Gerber, R Lerch, and L Rice. 1985. *SAT-BRET-FMEF: A Developmental LMR Fuel Cycle Facility*. Presented at the American Nuclear Society Annual Meeting, June 9, 1985. Accessed March 12, 2021, at https://www.osti.gov/servlets/purl/5332413.

UN – United Nations. 1970. *Treaty on the Non-Proliferation of Nuclear Weapons (NPT)*. Accessed January 25, 2021, at https://www.un.org/disarmament/wmd/nuclear/npt/.

Waksman J. 2020. Project *Pele: Overview Mobile Nuclear Power For Future DoD Needs*. Accessed January 28, 2021, at https://ric.nrc.gov/docs/abstracts/waksmanj-th34-hv.pdf.

DOE Order 413.3B. 2010. "Program and Project Management for the Acquisition of Capital Assets." U.S. Department of Energy, Washington, D.C. Accessed March 24, 2021, at https://www.directives.doe.gov/directives-documents/400-series/0413.3-BOrder-b.

85 FR 83923. December 20, 2020. "Posting of the Presidential Policy Directive 6 (Space Policy), 'National Strategy for Space Nuclear Power and Propulsion.'" *Federal Register*, U.S. Department of Energy. Accessed March 31, 2021 at https://www.federalregister.gov/documents/2020/12/23/2020-28457/posting-of-the-presidential-policy-directive-6-space-policy-national-strategy-for-space-nuclear.

Appendix A

Fuel Forms

Nuclear fission is the process whereby a fissile atom splits into two or more lighter atoms. During this process, an enormous amount of energy is released. Energy in the form of heat is generated during each fission event; the more fission events, the more heat generated. In a commercial power reactor, steady-state power is achieved by sustaining a fission chain reaction in the nuclear fuel. In a chain reaction, neutrons released in one fission event produce at least one additional fission. The fission event, in turn, produces more neutrons, and the process repeats. In a nuclear power reactor, the fission chain-reaction process is carefully controlled, and safety systems are designed to shut down the chain reaction in the event of an emergency.

The only naturally occurring fissile isotope is ^{235}U. Natural uranium, which is made up mostly of ^{238}U, contains 0.7 wt% ^{235}U. In addition to the fissile ^{235}U atom, there are two other synthetic fissile isotopes that can be produced in a nuclear reactor's core and used as fuel, thereby extending the finite supply of ^{235}U–^{239}Pu and ^{233}U. Plutonium-239 is the result of fissioning an atom of ^{235}U, which releases, on average, roughly 2.5 neutrons. While one of these neutrons is needed to sustain the chain reaction, the other can be absorbed in nearby ^{238}U atoms to produce ^{239}Pu. Another isotope, ^{233}U, is produced when the excess neutron is absorbed by ^{232}Th. Thorium is three to four times more abundant in the world than uranium; the U.S. is ranked second with respect to thorium reserves in the world, and fourteenth for uranium.

The various types of nuclear reactor designs have been categorized according to several schemes. Perhaps the most common classification is based on the energy level of the neutron spectrum, whereby two types of reactors have been developed. The first type is a thermal reactor, which is designed to use thermal fission neutrons to sustain the chain reaction. Fission neutrons emerge with high energy levels, and in a thermal reactor are slowed down (a process referred to as moderation) using materials that are associated with low atomic weights (e.g., water and graphite). Slower neutrons are more likely to collide with a fissile atom and induce fission. Most of the currently deployed commercial power reactors (i.e., pressurized water reactors and boiling water reactors) are thermal reactors. The second type of reactor is a fast reactor. Fast reactors are designed to sustain their fission chain by using fast neutrons. Because fast neutrons often are less likely to cause a fission event, the neutron population is significantly higher. However, the benefit of a fast reactor is that more surplus neutrons are generated during each fission, which allows for the production of additional synthetic fission material.

Another popular classification scheme for reactors is by coolant type. Many of today's commercial reactors are cooled using water and are referred to as light water reactors. But other designs are cooled by gas (e.g., helium or carbon dioxide gas), molten metal (e.g., lead or sodium), or molten salts.

For the purpose of this report, the advanced reactor designs will be grouped and analyzed based on the type of fuel that they are designed to use. The goal is to summarize and group the various advanced reactor designs by fuel type and then project their future fuel needs and resources. The following nuclear fuel types will be described:

- oxide
- metal

- tri-structural isotropic (TRISO) particle fuel
- molten fluoride salts
- molten chloride salts
- nitride.

One very significant challenge to the advanced reactor community is fuel supply. As stated previously, nuclear fuel fabrication facilities are expensive to start up and difficult to justify for building a one-off core load of fuel. Until the technology is successfully demonstrated and electric utility companies begin placing orders for power reactors, the industry may be challenged to justify the expense of building a new fabrication facility. A flexible and intermediate pilot-scale facility could be set up in a way that accommodates the variety of advanced fuel forms.

Additionally, establishing a realistic plan for acquiring the high-assay, low-enriched uranium (HALEU) feedstock will be necessary to make sure special nuclear material (SNM) is available to fabricate the nuclear fuel. DOE is aware of this challenge and has a program in place to begin building the HALEU supply. The domestic enrichment capability and important considerations are also described in this section.

The following subsections are organized by fuel type. Analysts assumed that the near-term deployments would drive several key fuel fabrication facility requirements, such as vault storage for SNM, throughput requirements, and support functions. Throughput requirements will drive facility size.

Oxide Fuels

The leading advanced reactor designs that would employ uranium dioxide (UO_2) fuel all use conventional low-enriched uranium (LEU) (<5% enriched). This enables them to fabricate their fuel (or have someone do it for them) in a conventional U.S. Nuclear Regulatory Commission (NRC) Category III facility. The reactor companies are likely to contract with an existing light water reactor (LWR) fuel fabricator to build their fuel for them, obviating the need for the reactor company to develop and demonstrate their fuel fabrication technology in the proposed DOE facility.

The nuclear fuel industry, for various economic reasons, is considering using fuel with enrichments between 5% and 10% in conventional, existing LWRs. This level of enrichment, known variously as LEU+, or GT5, is made from otherwise conventional UO_2-based fuel. Although the material is not HALEU, it is above U.S. fabricators' regulatory limit of 5% enrichment, and so at a minimum requires extensive reanalysis and relicensing. New facilities are likely to be built if reactor operators request a significant amount of GT5 fuel from fabricators. For purposes of clarity and because GT5 is not considered for use in advanced reactors, GT5 fuel is not discussed in this report. Although the DOE development facility certainly would be capable of assisting a potential GT5 fabricator, it is considered unlikely to be so utilized.

Metal Fuels

Two of the leading commercial metal-fueled reactor candidates to be deployed in the near term are

- Natrium (TerraPower and GE Hitachi Nuclear Energy); large sodium fast reactor (SFR)
- Aurora (Oklo); a small SFR

What is known of these two reactor fuel designs will serve as the basis for the typical generic reactor types described below.

A third, the Versatile Test Reactor (U.S. Department of Energy) falls outside consideration because it will use plutonium alloy fuel and plans for manufacturing its fuel are already underway.

Even though no specific advanced reactor is associated with the innovative Lightbridge Fuel™ design, their metal fuel will also be discussed in this section for completeness.

Large Metal-Fueled SFR

Table 4. Sodium-Cooled Fast Reactor

Reactor type	Pool-type, sodium-cooled, fast neutron spectrum reactor
Fuel type	Sodium-bonded U-10Zr alloy metal in HT-9 cladding Enrichment: 15.75%
Fuel description	Core: 17.6 MTU; 200 fuel assemblies Assembly: 4.7 m long, hexagonal HT-9 duct containing 217 fuel pins. Fuel Pins: 8.2 mm OD HT-9 cladding, 3.5 m long; active fuel height 1 m; slug diameter of 6 mm
Estimate of materials needs for first core	3,100 ft of HT-9 duct 724,000 ft of HT-9 cladding (+ 9,000 ft of bar stock for end caps) 17,600 kg of 15.75% enriched uranium metal
Development needs (lab, pilot, demonstration scales)	Laboratory scale: Develop reliable alloying; injection casting Pilot scale: Alloying and injection casting at pilot scale Demonstration: Need integrated process tests to refine and industrialize processing from alloying through final fuel assembly Need to fabricate first core
Demonstration Facility Description	Nameplate Throughput: 20 MTU/yr (~1 year to make first core) Instantaneous rate goal: 1 assembly per 24 h Uranium usage: 110 kgU/day Alloy Usage 130 kg alloy/day Slug production: ~60 x 8" long slugs/hour
Facility size requirements	Scope: Rad area: Melting, alloying, casting, slug treatment, pin loading Non-rad area: Pin assay, wire wrap, bundle assembly, bundle inspection, bundle storage, shipping container load, truck load Floor space - radiological area: 10,000 sq ft with 15' ceiling height Floor space - non-rad: 20,000 sq ft with 40' ceiling height Ventilation: rad area ~2000 scfm room; 500 scfm process Utilities: electric power (480 VAC); water Waste Streams: small mixed waste liquid; dry U contaminated solid waste

Support function needs	Analytical chemistry laboratory (e.g., mass spectrometry for enrichment; impurities in U metal; %Zr for homogeneity, electron backscatter diffraction for crystallography and texture)
	Metrology laboratory
	Nondestructive Examination Methods (e.g., visual, ultrasonic, and x-ray)
	Engineering support
	    Process engineering - maybe
	    Plant and design engineering – probable
	Operations support
	    Process operators – maybe
	    Lifting and rigging – probable
	    Radiation protection – probable
	    Machine shop support – maybe
	    Waste handling and processing - probable
	Safety engineering support:
	    Criticality safety
	    Material control and accountancy and reporting
	Physical security, receiving/shipping, and storage

TerraPower's 820 MWt SFR will include a molten salt energy storage system that will allow the plant to respond to cyclic grid demands, enhance grid stability, and integrate more seamlessly into power grids with high penetrations of renewables. Informal discussions with TerraPower indicate they are engaged in discussions with Global Nuclear Fuel (GNF) to perform the deconversion (i.e., gas to metal processing) as well as to establish a fuel fabrication facility to build their fuel. A hypothetical timeline for fabricating their first core is shown in Table 5 and very much depends upon their ability to obtain the HALEU UF_6.

Another option for TerraPower will be to work directly with ROSATOM State Atomic Energy Corporation in Russia to obtain HALEU metal.

Table 5. Notional Timeline for Fabricating First Core of Metal Alloy Fuel

ID	Task Name	Start	Finish	Duration
1	Fuel Design & Prototyping	10/1/2021	9/27/2024	781d
2	Process Design, Engineering & Procurements	6/3/2022	6/3/2026	1044d
3	Facility Mods, Licensing, & Equipment Install	10/3/2022	3/1/2027	1151d
4	Acquire U Feedstocks & Components	1/3/2023	1/3/2028	1305d
5	Process Qualifications	8/3/2026	2/3/2028	394d
6	Fabricate First Core	9/3/2027	12/14/2028	335d
7	First Core Ready	1/3/2029	1/3/2029	0d

TerraPower requires a supply chain to acquire HT-9 cladding and duct components. Such an effort involves the long lead procurement and qualification of at least several large heats of alloy from a mill that must then be forged into billets and bar stock before being shipped as a feedstock to their cladding tube manufacturer. Several sizes of billet and bar stock product will be necessary to fabricate the necessary cladding tubes, end plugs, duct, and other hardware.

Assuming an 18-month timeline for fabricating Natrium's first core would mean that the facility should be sized to handle approximately 1,200 kg HALEU per month. Assuming that the feedstock supply would be one shipment every 2 months would mean that a laydown area for UF_6 canisters should be capable of storing 3.5 MT of UF_6. It will be assumed that the vaults should be sized to store a two-month supply of metal, which equates to 2,400 kg.

The types of processing capabilities that would be necessary would include the following, which are divided into radiologically controlled versus clean processing areas:

- Radiologically Controlled
  - Alloying and injection casting
  - Analytical and metallurgical lab analyses, inspections, and nondestructive examination
  - Pin fabrication: first end-cap welding, slug and Na charging, second end-cap welding, and Na melt
  - Mixed waste management and disposal for quartz tubes and other waste streams
- Clean-Area Activities
  - Nondestructive assay and nondestructive examination testing of pins, weighing, inspection
  - Wire wrapping
  - Final pin inspection
  - Pin loading into ducts

Small Metal-Fueled SFR

Oklo's Aurora reactor is a compact fast-spectrum microreactor and is intended to be fueled using recycled HALEU in the form of U-10Zr metal alloy. The objective for this design is to demonstrate a small fast reactor, a relatively long-life core, and demonstrate recycle of spent fuel. The design is based upon the significant work done during the U.S. advanced fast reactor development period and relies heavily upon experience gains from EBR-II and the Fast Flux Test Facility. Oklo is the only advanced reactor designer that has submitted a combined license application to the NRC. Table 6 provides information about the Aurora SFR.

Table 6. Aurora Characteristics

Reactor Name	Aurora
Company	Oklo
Reactor type	Sodium-cooled, fast neutron spectrum reactor
Estimate of materials needs for first core	U-10Zr metal slugs with average enrichment of 15.75% Unknown ft of 316 stainless steel ducting Unknown ft of 316 stainless steel cladding (and bar stock for end caps) Estimated to be 4,500 kg of enriched uranium metal obtained from recycled EBR-II fuel

Reactor Name	Aurora
Status of fuel form development (Technology Readiness Level [TRL] for primary steps)	Fabrication of U-alloy slugs: TRL 6 Development of fuel assembly: TRL 6 Fuel performance: TRL 8 (historical)
Development needs (laboratory, pilot, demonstration scales)	Laboratory scale: None Pilot scale: Using existing INL capabilities Demonstration: Need integrated process tests to refine and industrialize processing from alloying through final fuel assembly. Need to fabricate first core.
Support functions needed	Analytical chemistry laboratory Mass spectrometry for enrichment; impurities in U metal; alloy analysis Engineering support Process engineering – TBD Plant and design engineering - TBD Operations support Process operators – probable Radiation protection - probable Safety engineering support: Criticality engineering – probable Radiation protection – probable

Informal discussions with Oklo indicate their plan is to construct and operate a 4 MWt microreactor at INL. Plans for fueling this microreactor include obtaining approximately 4,500 kg of approximately 19.75 wt% ^{235}U from downblending recycled highly enriched uranium (HEU) EBR-II fuel that already resides at the INL site. The irradiated EBR-II fuel will be placed in a molten salt electrorefiner located at INL's Materials and Fuels Complex to recover the enriched uranium and then purified using a vacuum distillation process. During the purification step, depleted uranium will be added to achieve the desired fuel enrichment. Finally, the recycled HALEU metal will be alloyed and recast into fuel slugs of the desired size and metallurgical properties.

Versatile Test Reactor (VTR)

In 2020, the Battelle Energy Alliance announced that they had initiated contract negotiations with a Bechtel National Inc. (BNI)-led team to design and construct the new VTR for DOE. The BNI team includes both TerraPower and GE Hitachi Nuclear Energy. The VTR will provide the U.S. a new capability to perform irradiation testing using much higher neutron energy fluxes than what currently exists today. This new capability will accelerate testing of advanced nuclear fuels, materials, instrumentation, and sensors and allow the DOE to modernize its essential nuclear energy research and development infrastructure. VTR fuel development needs are summarized in Table 7.

Table 7. Versatile Test Reactor Requirements

Reactor Name	Versatile Test Reactor
Company	DOE (subcontracted to Bechtel, GE Hitachi, TerraPower team)
Reactor type	Sodium-cooled, fast neutron spectrum research reactor
Estimate of materials needs for first core	66 Fuel Assemblies, each containing many wire-wrapped fuel pins clad in HT-9. U-20Pu-10Zr metal slugs with average enrichment of 15.00% 760 ft of HT-9 ducting 165,868 ft of HT-9 cladding (+ 5,000 ft of bar stock for end caps) 2,219 kg of enriched uranium metal (~61,500 SWU) 650 kg of Pu
Status of fuel form development (TRL for primary steps)	Fabrication of U-alloy slugs: TRL 6 Development of fuel assembly: TRL 6 Fuel performance: TRL 8 (historical)
Development needs (lab, pilot, demonstration scales)	Laboratory Scale: None Pilot Scale: None Demonstration: Need integrated process tests to refine and industrialize processing from alloying through final fuel assembly Need to fabricate first core
Support functions needed	Analytical Mass spectrometry for enrichment; impurities in U metal; alloy analysis Engineering support Process engineering – TBD Plant and design engineering - TBD Operations support Process operators – probable Radiation protection - probable Safety engineering support: Criticality engineering – probable Radiation protection - probable

While the VTR is in its preliminary design phase, conceptually, the core will be fueled using a U-20Pu-10Zr metallic fuel encased in HT-9 cladding. It is envisioned that the enriched uranium will be acquired from downblending HEU at the Y-12 National Security Complex and the plutonium will come from surplus Pu that has been designated by the National Nuclear Security Administration for dilution and disposal.

The plans for fabricating this fuel are currently under development.

Lightbridge Fuel

Lightbridge has been developing a new, advanced metal fuel for use in existing LWRs. Because metal has much better thermal conductivity than oxides, the Lightbridge concept will perform better thermally than oxide fuel, operate at much lower temperatures, and allow the plant to operate at higher power without significantly affecting safety margins. The opportunity to uprate existing plant power levels has already been proven to reduce electricity costs and carbon emissions.

Lightbridge anticipates using 15–20% HALEU fuel to enable uprating core power levels, which may allow for an overall improvement in a plant's economics. The Lightbridge fuel is centered on a helical, multi-lobe fuel rod design with a U-50Zr alloy core. The combination of increased surface area achieved by the multi-lobe configuration and the use of a metal alloy fuel center significantly enhances thermal performance. The initial cast U-50Zr alloy and its associated processing equipment will be very similar to what is needed to fabricate fuel for the sodium-cooled fast reactors, which is why the fuel form is briefly discussed in this section.

Metal Fuels Summary

A DOE-sponsored, pilot-scale fuel manufacturing plant could support deployment of advanced metal-fueled reactors. New HALEU facilities customized to fabricate a specific metal fuel design and using processes that are fully proven may be costly and may detract from designing, testing, and licensing a new advanced reactor design. Moreover, as discussed previously, the real challenge will be sustaining the capability once the first core load of fuel is fabricated and utilities wait to see how the new reactor will perform before submitting orders for new builds. Therefore, a newly built manufacturing line may sit idle, or only operate at a very limited capacity, for some time. This scenario could pose significant challenges in terms of cost of refueling a single reactor, retaining trained and seasoned staff, and supporting proper retention and maintenance of manufacturing equipment.

While TerraPower is working with the commercial industry to establish their metal fuel manufacturing capability, Oklo is working with INL to build their first core, which is much smaller than a Natrium core, and DOE is currently determining how best to manufacture fuel for the VTR. As a result, timing of a new user facility would need to be more carefully examined. Certainly, support-infrastructure overlap among the three (i.e., TerraPower, Oklo, and VTR) fuel manufacturing campaigns in terms of shipping/receiving, SNM storage and material control and accounting, analytical laboratory capabilities, metrology, and nondestructive examination (NDE). Sharing of these resources could make sense from the viewpoints of cost, staffing, and facility space.

TRISO Fuels

Advanced reactors using TRISO fuels are among those most likely to be demonstrated and deployed in the near term. The envisioned TRISO-fueled reactors are alike in their plans to use HALEU, which helps offset the inherently low fissile density of particle-based fuel. Designs using uranium oxycarbide (referred to as UCO) and uranium nitride kernels are envisioned, with UCO having a higher TRL but lower fissile density than UN. Among the leading TRISO-fueled reactor candidates to be deployed in the near term are these:

- micro high-temperature gas-cooled reactor (HTGR) nuclear power plants (e.g., Project Pele, the BWXT Advanced Nuclear Reactor, and Ultra Safe Nuclear Corporation's (USNC's) MMR Energy System)
- high-temperature molten-salt-cooled reactors (e.g., Kairos Power's Hermes test reactor and KP-1)
- high-temperature gas-cooled reactors >50 MWe (e.g., X-energy's Xe-100).

Many advanced reactor designers plan to use TRISO fuel to enhance performance, proliferation resistance, and safety. The DoD's Project Pele, which currently includes reactors under development by BWXT and X-energy, has baselined TRISO fuel on the basis of safety and nonproliferation because they are interested in mobile nuclear power sources for use at forward-deployed military installations. Additionally, TRISO-based reactors are under development by BWXT, X-energy, Kairos Power, USNC, HolosGen, NuGen, StarCore, Hybrid Power Technologies, and Radiant Nuclear. USNC-Tech (a space-based subsidiary of USNC) also envisions nuclear reactors for space power and propulsion that are based on HALEU TRISO fuel. Near-term demonstration of TRISO-based advanced reactors is supported by recent efforts and plans by industry to establish TRISO fabrication capabilities. Commercial efforts are currently underway by BWXT and X-energy to establish TRISO coated particle fuel fabrication lines.

In 2019, X-energy and GNF announced a collaboration to fabricate TRISO fuel particles in a new facility called TRISO-X. They plan to leverage X-energy's pilot TRISO fuel fabrication facility, recently completed at Oak Ridge, TN, as they design and build the licensed GNF facility in Wilmington, NC. The TRISO-X fuel fabrication facility is designed to be modular, accommodate uranium enriched up to 20%, and be adaptable to multiple fuel forms with a 5 MTU capacity to accommodate future demand. Licensing activities with the NRC are underway for a 10 CFR Part 70 Category II SNM license amendment, and facility construction is anticipated to be complete by the mid-2020s. X-energy and GNF envision producing TRISO fuel for the Xe-100 gas reactor, small mobile nuclear reactors for the DoD, and potentially other TRISO-fueled reactors.

In November 2020, BWXT announced the restart of their TRISO fuel manufacturing line in Lynchburg, Virginia. As noted previously, BWXT is the only company that is currently licensed as an NRC Category 1 fuel facility in the U.S., which enables production of HALEU as a Category II material. The existing TRISO line is capable of producing hundreds of kilograms of TRISO particles annually. BWXT has developed a strategy to expand that capacity to approximately 1 MTU/yr if there is demand. Furthermore, BWXT recently began conceptual design activities to create a new TRISO manufacturing facility, at an existing NRC-licensed site, with a 4 MTU/yr capability expandable to 8 MTU/yr using 1 MTU/yr fabrication modules.

Micro HTGR Nuclear Power Plant

Little public information is available regarding the specific design or development needs for the small mobile nuclear power plant funded through DoD's Project Pele. The following reactor features are known from publicly released reactor requirements (Waksman 2020):

- TRISO fuel form using HALEU
- Output power 1–5 MWe
- Core lifetime exceeding 3 years
- Transportable via truck, rail, ship, and C-17 aircraft.

According to the Project Pele timeline, outdoor mobile testing of the reactor is planned at a DOE facility in 2024 if the reactor is deemed feasible by the end of 2023. Additionally, a memorandum of agreement was signed between the DoD Strategic Capabilities Office (SCO), DOE, and the National Aeronautics and Space Administration (NASA) to jointly develop a commercial-scale TRISO facility to supply terrestrial and space-based TRISO-fueled reactors.

The micro nuclear reactor category includes the Micro Modular Reactor (MMR) Energy System under development by USNC. Seattle-based USNC is developing microreactors for remote terrestrial and space applications. Their MMR Energy System, which is a helium-cooled, graphite-moderated reactor, is designed to produce 5 MWe / 15 MWt for electricity and process heat. USNC reactor designs are based on a common fuel form using HALEU TRISO particles dispersed within a silicon carbide matrix. MMR fuel is rated for 20 years at full power and may be replaced if operation beyond 20 years is desired.

USNC-Power, the Canadian operating unit of USNC, is actively engaged in agreements with the Canadian Nuclear Laboratory, Atomic Energy of Canada (AECL), and Canadian Nuclear Safety Commission to demonstrate their MMR Energy System. The proposed project at Chalk River, Ontario is a partnership between USNC-Power and Ontario Power Generation through jointly owned Global First Power. A Project Host Agreement was signed in 2020, establishing a framework for Global First Power and the Canadian Nuclear Laboratory to address licensing, design, and siting issues as well as enabling the development of a land use agreement at Chalk River. USNC-Power envisions site preparations beginning in 2021 with first power demonstrated in 2026.

USNC-Tech, also located in Seattle, is a subsidiary of USNC developing technologies for space nuclear power and propulsion. USNC-Tech's reactor designs also use HALEU TRISO particles encapsulated in silicon carbide matrix elements. The use of HALEU in their designs for space applications are consistent with new U.S. space policies and nonproliferation norms. Current space reactor designs span a range from 0.01–1 MWe, with larger reactors envisioned for nuclear thermal propulsion.

Table 8 summarizes requirements for microscale reactors.

Table 8. Micro HTGR Nuclear Power Plant Requirements

Reactor Name	Mobile Nuclear Power Plant	Micro Modular Reactor (MMR) Energy System
Company	BWX Technologies, Westinghouse, or X-energy	USNC
Reactor type	1–5 MWe High-Temperature Gas-Cooled Reactor	5 MWe High-Temperature Gas Reactor
Estimate of materials needed for first core	~400 kg HALEU as TRISO fuel by ~2023	2,000–3,000 kg HALEU by 2022
Status of fuel form development (TRL for primary steps)	Fabrication of TRISO particles: TRL 8 Development of fuel elements: TRL 7 Fuel performance: TRL 7	
Fuel development needs (laboratory, pilot, and demonstration scales)	Laboratory Scale: None for uranium oxycarbide (UCO); Continuing for uranium mononitride Pilot Scale: Preparing compacts, particularly if using a SiC matrix Demonstration: Need to fabricate first core	
Support functions needed	Analytical Chemical Laboratory Engineering support Process engineering – probable Plant and design engineering – high-temperature, high-pressure heat exchangers Operations support Process operators – facilities to enable testing of in-core components in prototypical conditions and for low power, low-source-term, proof-of-concept assemblies Radiation protection – probable Safety engineering support: Criticality engineering – probable Radiation protection – probable	

High-Temperature Molten-Salt-Cooled Reactors

Unlike molten salt reactors discussed in later sections of this report, the molten-salt-cooled reactor physically segregates fuel from the molten salt coolant. Use of TRISO fuel in combination with a molten salt coolant enables use of a high-temperature fuel element that is fixed in the core while maintaining low coolant pressure for enhanced, passive safety. The combination may reduce the number of safety systems required as well as the cost associated with a high-pressure containment structure. Requirements for molten-salt-cooled reactors are summarized in Table 9.

Kairos Power is developing a fluoride salt (LiF and BeF_2, called FLiBe)-cooled high-temperature reactor (FHR) using HALEU TRISO fuel. The Hermes non-power demonstration reactor is designed to provide up to 50 MWt and requires approximately 250 kg HALEU at start-up. Hermes is part of the DOE's Advanced Reactor Demonstration Program and planned for construction on the K-33 site in Oak Ridge, TN. The Hermes demonstration reactor will be followed by a commercial-size FHR that is designed to provide 280–320 MWt / 140 MWe and require approximately 1,400 kg of HALEU per pebble-bed core. Approximately 230,000 annular pebbles, each containing about 16,000 TRISO particles, are needed for a single core load. The average pebble residence time is about 500 days, effectively requiring a new core load every 16 months. For the FHR design, FLiBe salt is circulated between the reactor core and an intermediate heat exchanger, which transfers heat to a secondary salt loop and steam generator. Kairos is collaborating with Materion Corporation to develop a reliable and cost-effective supply of lithium fluoride and beryllium fluoride coolant. In December 2020, Kairos announced plans to deploy a test reactor at the East Tennessee Technology Park in Oak Ridge, TN. Construction and 100% power demonstration for Hermes is planned by the late 2020s in the U.S. The Hermes plant would be closely followed by a full-size commercial unit for demonstration and subsequently installed in multiples of four (KP-4).

Table 9. High-Temperature Molten-Salt-Cooled Reactor Requirements

Reactor Name	FHR KP-1
Company	Kairos Power
Reactor type	High-temperature gas-cooled reactor
Estimate of materials needed for first core	~250 kg HALEU by 2024 for initial fuel fabrication
Status of fuel form development (TRL for primary steps)	Fabrication of TRISO particles: TRL 8 Development of fuel assembly: TRL 3 Fuel performance: TRL 3
Fuel development needs (laboratory, pilot, demonstration scales)	Laboratory scale: High-temperature molten salt research and development (R&D); Pilot scale: Fabricate fuel and molten salt coolant Demonstration: Fabricate enough fuel for a small-scale demonstration reactor
Support functions needed	Analytical chemistry laboratory Engineering support Process engineering – The pebble handling system and related system components require significant effort to address criticality requirements Plant and design engineering – probable Operations support Process operators – Need a shipping container to move fresh fuel pebbles Radiation protection – probable Safety engineering support Criticality engineering – More clarity on criticality rules for NRC Category II facilities Radiation protection – probable

High-Temperature Gas-Cooled Reactor Exceeding 50 MWe

HTGRs with power levels exceeding 50 MWe require substantially more TRISO fuel than the microreactors discussed previously. Additionally, these designs require fuel reloads on a regular schedule, in contrast with the lower power systems that have lifetimes of 5–20 years without refueling. Graphite-based prismatic and pebble-bed designs are under consideration and use helium gas as a coolant, with reactor outlet helium temperatures near 750 °C. X-energy's Xe-100 is an example of a TRISO-fueled HTGR with output power above 50 MWe. HTGR requirements are summarized in Table 10.

X-energy is developing both a microreactor HTGR, for Project Pele, and a small modular HTGR, the Xe-100. The Xe-100 reactor is designed to produce 200 MWt / 80 MWe using a pebble-bed core composed of approximately 220,000 pebble compacts containing UCO TRISO particles. It is designed to also provide process heat and support applications such as desalination and hydrogen production. The Xe-100 is helium cooled and has a reactor outlet temperature of 750 °C. A 60 -year reactor lifetime is planned. The reactor is designed for online refueling, but fuel residence time and reload requirements are unknown. X-energy is preparing to submit a license application and plans to demonstrate the Xe-100 reactor by the late 2020s. In October 2020, DOE awarded X-energy $80M to support demonstration of the Xe-100 within seven years. Deployments of four colocated Xe-100 units are envisioned.

Table 10. High-Temperature Gas-Cooled Reactor Exceeding 50 MWe Requirements

Reactor Name	Xe-100
Company	X-energy
Reactor type	High-temperature gas-cooled reactor
Estimate of materials needed for first core	15.5% HALEU 220,000 pebble compacts per core
Status of fuel form development (TRL for primary steps)	Fabrication of TRISO particles: TRL 8 Development of fuel assembly: TRL 7 Fuel performance: TRL 7
Fuel development needs (laboratory, pilot, demonstration scales)	Laboratory scale: None, using Oak Ridge facility Pilot scale: Joint TRISO fabrication facility with GNF in design phase Demonstration: Need to complete design, construct, and operationalize new ~180,000 ft² facility. Need to demonstrate first core.
Support functions needed	Analytical chemistry laboratory Engineering support Process engineering – Plant and design engineering – Operations support Process operators – Radiation protection – Safety engineering support: Criticality engineering – Radiation protection –

TRISO Fuels Summary

Commercial fuel fabricators are clearly taking the lead to deploy TRISO fuel fabrication capabilities, and therefore TRISO fuels are less likely than other HALEU fuel types to benefit from a DOE fuel fabrication user facility. The technical maturity of the TRISO fuel form, its history of irradiation testing and post-irradiation examination, and nascent TRISO fabrication lines operated by BWXT and X-energy/GNF make it more likely that new reactor designs requiring TRISO fuel will have a commercial fuel acquisition pathway. If BWXT and X-energy/GNF expand their commercial TRISO production capacities as envisioned, reactor developers using TRISO fuels are unlikely to require a DOE user facility to acquire fuel for their initial reactor deployments. However, some reactor developers requiring TRISO fuel may find a DOE user facility convenient to either incorporate commercially acquired TRISO particles into custom compacts specific to their reactor designs or to produce their own TRISO fuel independently of BWXT and X-energy/GNF.

Additional R&D on TRISO fuels may be needed over time because new reactor designs use evolutionary TRISO designs that deviate from previously tested fuels and because some envisioned operating conditions differ from past irradiation test conditions. Also, modifications to enhance fuel performance may also be desired and require testing. While potential needs for additional TRISO R&D were envisioned, such work could be accomplished using currently existing facilities.

Molten Fluoride Salt Fuels

Molten fluoride salt, thermal spectrum reactors are considered useful machines for enabling the thorium fuel cycle because of their high conversion ratio of fertile Th to fissile ^{233}U. The thorium fuel cycle has advantages over a uranium fuel cycle in that thorium is three times more abundant than uranium and the overall production of plutonium and actinides per unit of energy produced is lower.

Lithium is often used in the synthesis of reactor fluoride fuel salts (LiF and FLiBe). In nature, Lithium has two stable isotopes, ^{6}Li and ^{7}Li, and is mostly made up of ^{7}Li (92.5%). The very high neutron cross section (~3 barns) of ^{6}Li makes it necessary to isotopically separate and eliminate this isotope. However, domestic production of enriched ^{7}Li ceased in 1963. Today the only sources of enriched ^{7}Li are in Russia and China.

Among the leading molten fluoride salt reactor candidates to be deployed in the near term are three that will be described here:

- Flibe Test Reactor
- ThorCon Prototype
- Terrestrial Integral Molten Salt Reactor (IMSR) (in Canada).

Materion, a supplier of precursor salts and molten salts, is also included. Table 11 summarizes requirements for liquid-fluoride thorium reactors (LFTRs).

Table 11. Liquid-Fluoride Thorium Reactor Requirements

Reactor Name	Liquid-fluoride thorium reactor
Company	Flibe Energy
Reactor type	Molten fluoride salt reactor (thermal spectrum)
Estimate of materials needed for first core	20–30 kg of ^{233}U for initial 500 kWt test reactor Unknown amount of ^{233}U to support a 60 MWt demonstration reactor
Status of fuel form development (TRL for primary steps)	Synthesis of fuel salt: TRL 6 Fuel performance: TRL 5
Fuel development needs (laboratory, pilot, demonstration scales)	Laboratory scale: Pilot scale: Demonstration: Need to complete design, construct, and operationalize a facility for salt synthesis.
Support functions needed	Analytical chemistry laboratory Engineering support Process engineering – Plant and design engineering – Inerted gloveboxes Hazardous gas handling Hazardous gases abatement system Large melter/reactor units Inerted storage and nickel-based transport containers Operations support

Reactor Name	Liquid-fluoride thorium reactor
	Process operators – Radiation protection – Safety engineering support: Criticality engineering – Radiation protection –

Flibe Test Reactor

Flibe Energy's LFTR is a graphite-moderated, thermal spectrum reactor fueled with molten fluoride salts containing both fissile and fertile materials. The objective for this design is the efficient use of thorium as a fertile material, which, in principle, will result in less long-lived high-level waste as compared to LWR technology, be more sustainable in the long term, and allow for extraction of medical isotopes. Informal discussions with Flibe Energy indicate a well-conceived vision for achieving construction and operation of a 600 MWt commercial LFTR power plant through a series of smaller test and demonstration reactor builds.

Flibe Energy's current plans include constructing a 500 kWt test reactor, which may be located at INL and housed within the existing Zero Power Physics Reactor building—a DOE Hazard Category 2 nuclear facility. Plans for fueling this first small test reactor include obtaining approximately 20–30 kg of ^{233}U from Oak Ridge National Laboratory's existing inventory and synthesizing it into a fluoride fuel salt at INL's Materials and Fuels Complex. The second step will be to construct a 60 MWt demonstration reactor. This larger demonstration reactor will be capable of generating electricity and will also be fueled using existing ^{233}U stockpiles. It is envisioned that both uranium and thorium fuel salts will be synthesized on site at the new demonstration plant. The demonstration reactor will produce fuel for the FOAK commercial LFTR power plant.

ThorCon Prototype

The 2 × 557 MWt ThorCon reactor is a rather straightforward scale-up of the Molten Salt Reactor Experiment, which was originally built and operated at Oak Ridge National Laboratory in the 1960s. What makes ThorCon unique is adopting modern and proven shipbuilding construction techniques to reduce construction costs and accepting a limited reactor vessel (referred to as a "Can") lifetime to avoid corrosion challenges. The ThorCon plant is to be built in the hull of a barge and deployed in shallow water near the ocean shore or along a river. The barge will need to be accessible to an oceangoing Can ship to exchange fuel-salt casks and reactor Cans. Information describing the ThorCon prototype is collected in Table 12.

Table 12. ThorCon Requirements

Reactor Name	ThorCon
Company	ThorCon US, Inc.
Reactor type	Molten fluoride salt reactor (thermal spectrum)
Estimate of materials needed for first core	27 MT DUF4 to support initial pre-fission testing 4.6 MT HALEU U to support a 2,800 MWt demonstration reactor
Status of fuel form development (TRL for primary steps)	Synthesis of fuel salt: TRL 6 Fuel performance: TRL 5
Fuel development needs (laboratory, pilot, demonstration scales)	Laboratory scale: Pilot scale: Demonstration: Need to complete design, construct, and operationalize a facility for salt synthesis.
Support functions needed	Analytical chemistry I Engineering support

Reactor Name	ThorCon
	Process engineering – Inerted gloveboxes Hazardous gas handling Hazardous gases abatement system Large melter/reactor units Inerted storage and nickel-based transport containers Plant and design engineering – Operations support Process operators – Radiation protection – Safety engineering support: Criticality engineering – Radiation protection –

The first demonstration reactor can be fueled using LEU if HALEU is not available in time, but requires development, testing, and licensing first with LEU, which would then need to be repeated for HALEU. Chemical processes that can simplify the conversion of UF_6 to UF_4 are needed and are currently being evaluated. If HALEU is available, the first demonstration plant would require approximately 920 kg of ^{235}U plus an additional 1,240 kg makeup to last for four years so about 11 MT of HALEU UF_6 would initially be needed.

Based on informal discussions with ThorCon staff, they believe it would be very helpful if the U.S. Government could support and accelerate the licensing efforts to establish a HALEU enrichment capability and license transport containers. This could substantially shorten the schedule from a commercial decision to move forward until HALEU is available in commercial quantities.

Terrestrial Integral Molten Salt Reactor

Terrestrial's 400 MWt Integral Molten Salt Reactor is designed around a small, compact, sealed, thermally moderated reactor core that is periodically replaced. Specifics for the IMSR are provided in Table 13. The first demonstration reactor will be fueled using standard assay LEU tetrafluoride salt; therefore, the existing milling, conversion, and enrichment capabilities are adequate to supply feedstock material in the form of either gas or oxide. Chemical processes that can simplify the conversion of UF_6 to UF_4 are also being evaluated by Terrestrial. Terrestrial was not contacted to provide input to this assessment.

Table 13. Integral Molten Salt Reactor Requirements

Reactor Name	Integral Molten Salt Reactor (IMSR)
Company	Terrestrial Energy
Reactor type	Molten fluoride salt reactor (thermal spectrum)
Estimate of materials needed for first core	
Status of fuel form development (TRL for primary steps)	Synthesis of Fuel Salt: TRL 6 Fuel performance: TRL 5 Laboratory scale: Pilot scale: Demonstration:
Support functions needed	Analytical chemistry laboratory Engineering support Process engineering – Plant and design engineering – Inerted gloveboxes Hazardous gas handling

Reactor Name	Integral Molten Salt Reactor (IMSR)
	Hazardous gases abatement system Large melter/reactor units Inerted storage and nickel-based transport containers Operations support Process operators – Radiation protection – Safety engineering support Criticality engineering – Radiation protection –

Materion

Materion is an advanced materials supplier that recently partnered with Kairos to develop a facility for production of FLiBe salt for advanced reactors.[b] Materion also supplies precursor salts such as beryllium fluoride. During informal discussions, Materion expressed the view that an advanced reactor fuel fabrication facility would provide value to those customers who wish to produce their own molten salt formulations, either independently or in partnership with a precursor salt supplier such as Materion. While not ruling it out for the future, Materion does not currently have capability to provide salt with fissile material or the capacity to manufacture the volumes of thorium-containing material the molten salt reactor (MSR) industry will require. An advanced fuel fabrication facility would allow developers of MSRs to produce subcritical quantities of molten salt fuel for transport to the reactor site. Materion also noted the lack of a stable domestic supply of ^{7}Li.

Molten Fluoride Salt Fuels Summary

Use of a DOE-sponsored pilot-scale fuel manufacturing plant to support deployment of advanced fluoride salt reactors may be very beneficial to the MSR community. The specialized radiological analytical laboratory capabilities—which are expensive to establish and require very uncommon skill sets—that are part of a pilot-scale fuel manufacturing plant would be very useful to support measurements of final salt purity, morphology, enrichment, and homogeneity—all physical attributes that should be verified before loading. Final salt purification steps will be needed to provide proper removal of moisture, oxygen, and other air contaminants just before loading the fresh salt fuel into the reactor vessels. As a result, there would need to be a focus on development and licensing of specially designed fresh fuel transportation packages.

Molten Chloride Salt Fuels

Thermophysical properties associated with molten chloride uranium and plutonium fuels are not entirely well known, nor fully qualified; therefore, more testing of both unirradiated and irradiated properties will be necessary. These reactors will be fast-spectrum reactors taking advantage of the fact that chlorine has a lower moderating power than fluorine, and as a result a fast-spectrum test capability will likely be needed in the future to facilitate testing.

In nature, chlorine has two stable isotopes ^{35}Cl (75.77%) and ^{37}Cl (24.23%). Chlorine-35 has a larger neutron absorption cross section than ^{37}Cl. The ^{36}Cl produced when ^{35}Cl absorbs a neutron has a relatively long half-life (301,000 yr) and one decay path produces stable ^{36}S, which can increase the corrosion potential of the salt mixture. All three of these aspects make chlorine enriched in ^{37}Cl desirable.

---

[b] https://kairospower.com/external_updates/kairos-power-and-materion-partner-to-develop-and-supply-materials-for-advanced-reactor-technology/

The leading molten chloride salt reactor candidates that could potentially be deployed in the near term include

- TerraPower molten chloride fast reactor (MCFR)
- Elysium
- Moltex Energy SSR-W.

The Elysium and Moltex molten chloride reactors being considered will use Pu-based fuels; they are intended to operate at higher overall plant efficiencies and burn spent fuel, excess Pu stockpiles, or both to reduce their associated long-term radiotoxicity and storage requirements. An attractive feature of these reactors is that the HALEU supply is not necessary to enable fueling of these plants, nor would it be necessary to build and operate traditional fuel reprocessing facilities. The TerraPower MCFR is expected to use HALEU.

TerraPower MCFR

In addition to the Natrium reactor, TerraPower is working with Southern Company to develop a large, 3,100 MWt chloride salt fast reactor using HALEU for fuel. A multimillion-dollar test facility is currently planned to start this year (2021) to facilitate component testing using surrogate salts produced by a process that has been reported to have been successfully scaled up. TerraPower intends to use the data generated from the test facility to validate both their thermal hydraulics and safety analysis codes. The plans for acquiring fuel for this reactor have not been made public and the team was unable to contact TerraPower to discuss their planning and assumptions.

Elysium

Elysium is actively developing a molten chloride salt fast reactor (MCSFR). The objective of this design is to burn reactor grade plutonium extracted from spent LWR fuel or surplus weapons-grade plutonium thereby reducing existing stockpiles. The fast spectrum allows for the transmutation of longer-lived transuranic elements into shorter lived products for safer long-term burial. Elysium has adopted modular design concepts to allow for scaling core power between 125 and 2700 MWt. Informal discussions with Elysium indicate a vision to first construct a 125 MWt power module as a demonstration reactor. At first, this module would be licensed to operate at less than 10 MWt. The power level would be increased as operational experience is gained.

Plans for fueling Elysium's first demonstration reactor include acquiring ~1–2 MTU of surplus plutonium from existing DOE stockpiles that have been declared excess as described in (GAO 2019) and having it processed into a suitable chloride fuel salt as part of some type of cooperative effort working with the DOE. To eliminate the need for design and licensing of a new and specialized transportation package, the processing facility would be ideally colocated with the demonstration reactor. A pilot-scale pyroprocessing facility to extract reactor grade plutonium from spent fuel would follow as commercial interest in deployment of an MCSFR develops.

Moltex Energy SSR-W

Moltex, a privately held company based in the United Kingdom and Canada, is developing the 1,250 MWt Stable Salt Reactor – Wasteburner (SSR-W) to utilize the fissile uranium and plutonium that remains in recycled Canada Deuterium Uranium (CANDU) fuel. The SSR-W is a fast-spectrum reactor that uses chloride fuel salt in pins that resemble those used in traditional LWRs. However, the pins are vented to release fission gas into the coolant, which is a molten salt,

$MgCl_2$-NaCl. Moltex is currently planning to initially use natural abundance chlorine for its fuel salt, but does fully appreciate the future benefits of enriched chlorine if an economical enrichment process is demonstrated. Moltex was recently awarded funding from Advanced Research Projects Agency – Energy (ARPA-E) to support further development of their reactor design and intends to build their first demonstration plant at Point LePreau near Saint John, New Brunswick, Canada.

Molten Chloride Salt Fuels Summary

The vision of a DOE-sponsored, pilot-scale fuel fabrication plant as described in this assessment would not support deployment of advanced chloride salt reactors given the need for a plutonium-based fuel salt. As discussed elsewhere, the Pu-based fuels will add another level of complexity to the facility design in terms of handling, shielding, processing, and off-gas systems. However, if a decision were made to either operate or start up the first chloride fueled demonstration reactors using uranium-based fuels, then such a facility would be useful.

Uranium Nitride Fuels

Uranium nitride fuels possess high fissile loading density and can operate at higher temperatures because they have superior strength and thermophysical properties. However, nitride fuels require more complex fuel fabrication processes and necessitate using nitrogen that is isotopically enriched in ^{15}N because ^{14}N has a high neutron capture cross section. There are several approaches that have been explored in terms of fabricating both pelletized fuels and fuel particles. In the open literature, there is not much information related to commercial advanced reactor development companies that are pursuing reactor designs based upon use of uranium nitride fuels. The pending NASA announcements for nuclear space power and space propulsion will surely result in further development of nitride-fueled designs.

References

GAO – U.S. Government Accountability Office. 2019. *Surplus Plutonium Disposition: NNSA's Long-Term Plutonium Oxide Production Plans Are Uncertain*. GAO 20 166, U.S. Government Printing Office, Washington, DC. Accessed January 26, 2021, at https://www.gao.gov/assets/710/702239.pdf.

Waksman J. 2020. *Project Pele: Overview Mobile Nuclear Power For Future DoD Needs*. Accessed January 28, 2021, at https://ric.nrc.gov/docs/abstracts/waksmanj-th34-hv.pdf.

Appendix B

HALEU Supply Issues

Obtaining feedstock and fuel-related components can be a significant challenge. These are certainly long lead-time items and require advanced planning and capital for building the necessary infrastructure. Uranium feedstocks for use in fabricating advanced reactor fuels in the forms of oxides, salts, metals, and tri-structural isotropic (TRISO) kernels all require additional upstream deconversion processing (e.g., uranium hexafluoride [UF_6] conversion to oxides or metals) after the enrichment process. Processing high-assay, low-enriched uranium (HALEU) UF_6 gas into these various feedstocks requires specialized chemical processing capabilities that do not exist in the U.S. today. (The option of downblending Highly enriched uranium [HEU] is discussed below). In addition to the uranium feedstock, a number of the advanced reactors are being designed to burn plutonium and transuranics. If these reactor plans became viable, plutonium processing and handling would become necessary for its use as fuel in advanced reactors. For the reactors that are being designed to use the thorium fuel cycle, thorium salts and ^{233}U feedstock will be needed.

Fuel-related components may include hardware (e.g., cladding, end caps, ducts, and assemblies) or other materials like graphite, silicon carbide, and additional salt constituents. These materials are typically procured from an established supply chain. However, some of these components may be novel and not have an existing supply chain.

The flow diagram in Figure 7 shows the relationship between enriched uranium product (as UF_6), the necessary deconversion processes, and the various fuel fabrication processes, which thereafter become exclusive to the different types of fuel needed for advanced reactors. The green boxes are capabilities that already exist commercially, but for which the level of enrichment that can be handled is limited by licensing and criticality safety constraints. The blue boxes show conversion fuel cycle steps that used to be performed in the U.S. at an industrial scale but no longer exist. The purple boxes signify the fuel fabrication processes that are unique to each of the major types of reactor fuels. Each specific reactor design may require unique fuel fabrication processes within major fuel types as a result of their different designs. The plutonium processing is depicted very simplistically in orange and would itself require a rather large and complex infrastructure to support large-scale production. Historically, attempts to process plutonium in the U.S. have not been successful because of policy issues, fears of proliferation, and a myriad of safety/regulatory requirements that increase the cost of handling it. Transportation of these materials between fuel cycle facilities is also challenging and must be factored into any new fuel fabrication effort.

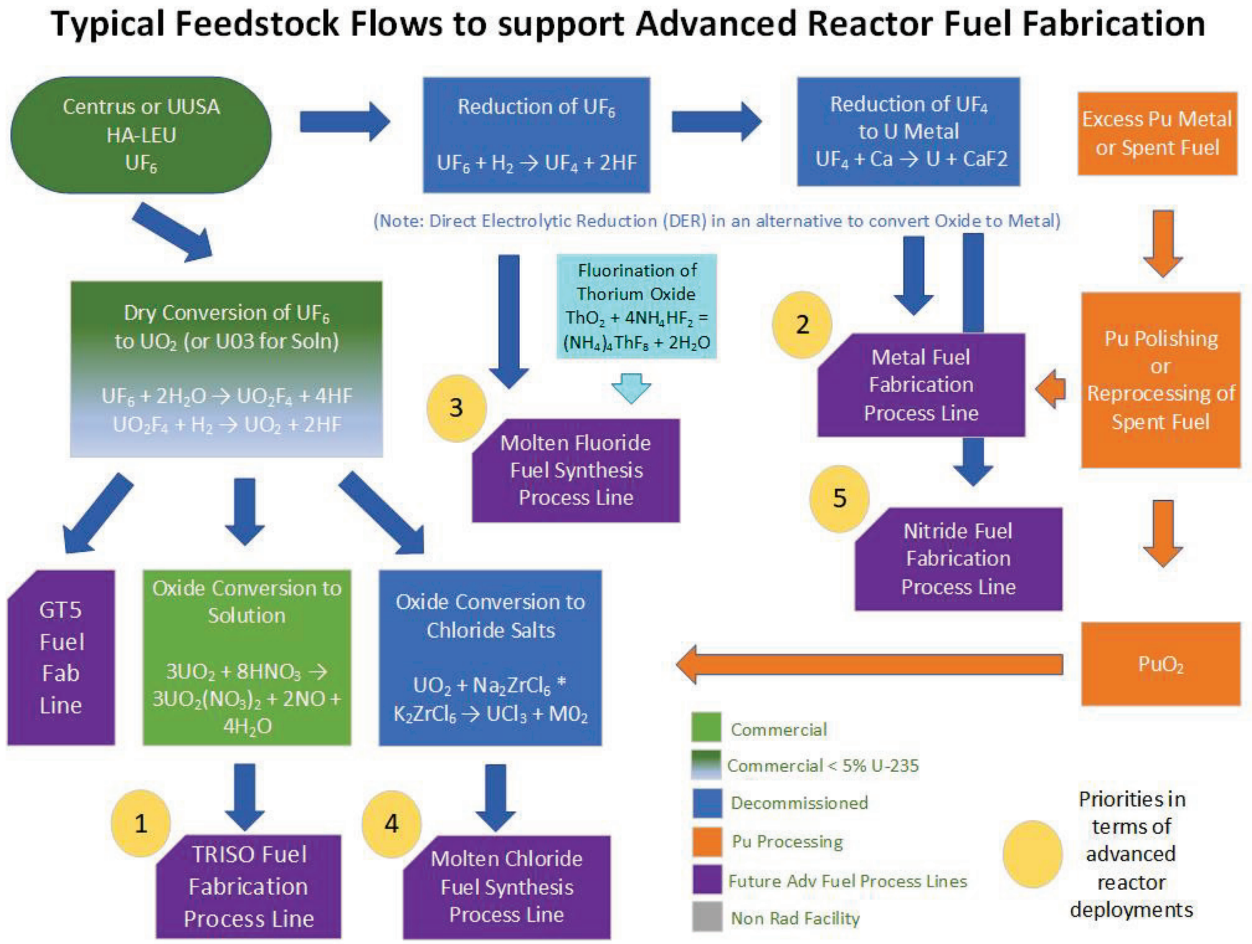

Figure 7. Typical Feedstock Flows to Support Advanced Reactor Fuel Fabrication Needs (UF_6 Feed)

The Fiscal Year 2019 Energy and Water Development Appropriations Act (42 USC 2019) required DOE to submit a plan to Congress to develop HALEU. Two basic options exist: enrich natural or low-enriched uranium hexafluoride (UF_6) to produce HALEU UF_6; the other is to downblend HEU, which normally produces a HALEU uranyl nitrate solution. Although downblending is being done today, the supply of HEU starting material is very limited and none is currently available for downblending to HALEU for advanced reactor applications. The ability to commercially produce HALEU UF_6 does not exist in the U.S. today. Enrichment is the long-term solution, although reallocating some HEU for downblending to HALEU may be possible in some limited situations.

Urenco USA (UUSA), a wholly owned subsidiary of the European company Urenco, operates an enrichment facility in Eunice, NM. The facility receives natural UF_6 feedstock from Canada and other global suppliers and uses centrifuge enrichment technology to increase the concentration of the fissionable ^{235}U isotope from natural uranium to a maximum of 5.5 wt% ^{235}U. The enrichment capacity at UUSA is approximately 4.9 million separative work units (SWU) per year. An SWU is a unit of measure defining the effort required to separate ^{235}U from ^{238}U. This capacity is roughly equivalent to 25% of the annual demand for uranium enrichment services by our domestic fleet of light water reactors.

Urenco indicated that they can meet HALEU demand in one of two ways, depending on demand signals from industry (and government). If the HALEU demand is low but sufficient, they can invest some millions of dollars to convert some of their existing capacity to HALEU production. This requires a U.S. Nuclear Regulatory Commission (NRC) license amendment and partitioning off some of their facility to handle Category II special nuclear material. The other alternative is to expand the capacity of the existing plant by adding more centrifuges. Investment needed for this option is some hundreds of millions of dollars.

TerraPower recently contracted with Centrus to evaluate options for supplying HALEU feedstock for their uranium-metal-alloy–fueled Natrium reactor. Centrus operates the American Centrifuge Plant in Piketon, OH. A cascade of 16 AC-100M centrifuges is currently being installed at Centrus's Piketon plant and should be fully operational by early 2022. A license amendment allowing enrichment up to 20 wt% ^{235}U uranium hexafluoride has been submitted to the NRC and is currently under review.

The Fiscal Year (FY) 2019 Energy and Water Development Appropriations Act required DOE to submit a plan to Congress to develop HALEU, and in FY 2020 the DOE awarded a cost share contract with Centrus to partially fund demonstration of their AC-100M centrifuge technology to produce 19.75% enriched uranium hexafluoride gas. Once the new centrifuges are installed and the license amendment is completed, the American Centrifuge Plant will produce about 900 kgU of HALEU using 4.95% enriched uranium as the feedstock and have a production capacity of approximately 5,500 SWU each year. The demonstration facility is not sized to meet the projected HALEU requirements of the advanced reactor community. If those projections materialized, HALEU production capability would need to be sized accordingly to meet demonstration reactor fuel requirements in early-stage development.

Centrus plans to feed low-enriched uranium (LEU) at 4.95% into the HALEU facility to decrease the SWU effort needed and to take advantage of LEU supply currently available in the marketplace at costs below what it would take to justify investment in enrichment capacity that is available from the primary producers. Centrus has supply contracts with Orano and Tenex that could be used to meet these feedstock requirements. Starting with enriched feedstock material significantly enables their ability to produce HALEU. The Demo cascade could produce approximately 1 MTU per year to support the ARDP Demo reactor cores needed in the 2026–2027 time frame. Under the contract that DOE has awarded to Centrus, DOE owns the material produced by the HALEU Demo cascade until the contract ends in the first half of 2022. DOE could negotiate an extension to the contract to continue HALEU production, or Centrus could elect to take ownership of the Demo as a commercial venture if supported by offtake contracts. Regardless of ownership, the production capacity of the 16-machine HALEU cascade is small relative to the needs of the ARDP-awardees. Significant governmental and/or industry financial support is going to be required to expand HALEU production to commercial scale to enable deployment of the HALEU-fueled advanced reactors.

Centrus has been in recent discussions with both the advanced reactor development community in the U.S. and in Canada. The Ontario Power Generation recently announced it was resuming planning activities to build a grid-sized small modular reactor at its Darlington site. Three advanced reactor designs are currently under consideration for grid-scale deployment: those by X-energy, GE Hitachi Nuclear Energy, and Terrestrial Energy. X-energy is the only reactor of the three that requires HALEU. If the X-energy design is selected, it will also serve as a market signal for expansion of demand for and confidence in supply for HALEU-based fuels.

With regard to deconversion processes, Centrus has indicated its willingness to add the capabilities at their Piketon facility as well as host an advanced fuel fabrication facility provided funds are available. To secure the needed funds, a strong business case needs to be established driven by market needs. As is the case with any enrichment facility, once such a capability is established, it will be critical to sustain the capability to prevent its failure in terms of revenue generation. Some options that could be considered are

- Once the feedstock has been produced to support fabricating the first near-term deployable advanced reactor cores, the DOE could consider purchasing HALEU for supplying research reactors and medical isotope programs as opposed to continuing to downblend from the limited HEU inventory.
- Procurement of HALEU on a limited but continuous basis so as to build up a domestic stockpile as part of an expansion of the existing American Assured Fuel Supply program could also be pursued.

Downblending some of the limited supply of clean HEU has been suggested as a ready source of HALEU. BWXT Nuclear Fuel Services, Inc. (BWXT NFS), located in Erwin, TN, and BWXT Nuclear Operations Group, Inc. (BWXT NOG-L), located in Lynchburg, VA, are the only commercial NRC-licensed Category I nuclear fuel facilities in the country capable of downblending metric-ton quantities of HEU to produce HALEU feedstock. Both facilities have downblended HEU since the mid-1990s to produce over 1,000 metric tons of LEU for numerous customers and continue to do so. The BWXT NFS facility could be easily modified to create a HALEU capability. Downblended LEU and HALEU can be provided in the form of a uranium nitrate solution or an oxide powder. Capabilities to convert uranium hexafluoride, nitrates, or oxides to uranium metal via an intermediate UF_4 salt could be established. BWXT NOG-L is establishing a metal casting capability to support fabrication of HALEU fuel for use in high-performance research and test reactors.

Existing HEU inventory has many competing uses (e.g., research reactors, medical isotopes, naval reactors, and DoD users). Therefore, allocation of HEU feedstocks for downblending to HALEU in support of the advanced reactor community, which projects significant needs in comparison, is likely to be very limited and would certainly be a decision only made by DOE leadership. As a result, HEU for downblending is estimated to be insufficient to support advanced HALEU-fueled reactors.

Idaho National Laboratory (INL) is reclaiming HEU from existing spent EBR-II fuel, which is downblended to produce HALEU. This effort is similar to what was successfully demonstrated for the EBR-II SNF recycle program, which operated from 1961 to 1994 at the former Argonne National Laboratory-West site, now INL. This product is suitable for direct use in fast reactor fuels; chemical impurities and radiological contaminants inhibit its utility for thermal reactor fuels. A successful proof-of-concept demonstration to purify or "polish" this material and convert it to a high purity HALEU oxide suitable for fuel fabrication was performed at INL. INL demonstrated the capability to polish repurposed EBR-II metal HALEU product, producing purified HALEU oxide powders meeting the thermal reactor fuel fabrication specifications for recycled uranium. INL polished materials could be available pending appropriation of funds. INL HALEU stocks from EBR-II are finite—10 MT.

ROM Estimate of HALEU Needs

Based on the results from the survey of reactors and advanced nuclear fuels a rough, order-of-magnitude (ROM) estimate can be provided for the amount of uranium and UF_6 feedstock that will be needed to support the deployment of the near-term advanced reactors. This estimate includes only the feedstock needed to fabricate the first cores and does not include refueling requirements for these FOAK plants. The ROM estimate is presented in Table 14.

Table 14. ROM Estimate for HALEU to Support Near-Term Deployments

Reactor Type	U (kg)	UF_6 (MT)	Notes
Metal-Fueled Reactors			
Versatile Test Reactor (VTR)	2,200	3.3	
Natrium	17,000	22.4	
Oklo			Assumes start-up on EBR-II reprocessed uranium
TRISO-Fueled Reactors			
Project Pele	400	0.6	
Ultra Safe Nuclear Corporation MMR	2,500	3.7	
X-energy	5,000	7.4	
Kairos	200	0.3	
Fluoride Fueled Reactors			
Flibe Energy			Assumes start-up on ^{233}U
ThorCon	4,600	6.8	
Terrestrial Energy			Assumes start-up on LEU
Chloride Fueled Reactors			
None in near term			
Nitride Fueled Reactors			
None in near term			
Total for Near-Term Deployment	31,900	44.5	
A 1.2× Factor Assumed	38,280	57.9	Estimation errors and processing losses

To facilitate the deployment of advanced HALEU-fueled reactors, DOE might consider procuring 40–60 MT of HALEU hexafluoride gas and establishing deconversion capabilities. The resultant product (oxide, metal, salt, or solution) could then be sold to the advanced reactor community as needed at some agreed-to fair market price. One approach to accomplish this would be for DOE and Congress to work together to extend/modify the American Nuclear Infrastructure Act of 2020 to include the material as part of a national strategic uranium stockpile.

Deconversion of HALEU UF_6

There is currently no commercial capability to process HALEU UF_6 to a form readily usable for fuel fabrication in the U.S. Each potential fuel vendor must start with its HALEU in a commodity form to transform it into the chemical form that meets its fuel fabrication needs. it may be economically challenging, and inefficient, for each reactor developer to independently develop the processing capability necessary to convert HALEU UF_6 to its needed feed material. A central facility could be established to “deconvert” the UF_6 into common feed materials (oxide, metal, etc.) to enable and facilitate the deployment of advanced reactors.

References

42 USC. 2019. *Energy and Water, Legislative Branch, and Military Construction and Veterans Affairs Appropriations Act, 2019*. Title III–Department of Energy. Public Law No: 115-244. H. Rept. 115-697.

Accessed February 5, 2021, at https://www.congress.gov/congressional-report/115th-congress/house-report/697/1.

American Nuclear Infrastructure Act of 2020. S. 4897. 116th Congress. 2020. Accessed March 31, 2021, at https://www.congress.gov/bill/116th-congress/senate-bill/4897/text.

UN – United Nations. 1970. *Treaty on the Non-Proliferation of Nuclear Weapons (NPT)*. Accessed January 25, 2021, at https://www.un.org/disarmament/wmd/nuclear/npt/.

Appendix C

Requirements

Size and Capacity

If DOE were to decide to pursue the construction of the CARFF, it would be done following the requirements established in DOE Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*. The conceptual design phase would establish detailed requirements, analyze alternatives, and develop a conceptual design. The requirement and capabilities presented below were developed to provide an understanding of what a CARFF could look like and a rough, order-of-magnitude cost estimate. These estimates are based on familiarity and comparison with existing fuel fabrication facilities and recently produced proposals for another program:

Vendor Bay Area Descriptions	Three of these bays will accommodate at least three independent fuel fab efforts		
Chemical/Rad Area			Comments
First floor space	2,500	sq ft	50' × 50' area (includes all uranium processing)
Number of floors	3		Not all floors have to be installed
Total Area for Development	7,500	sq ft	
Overall Ceiling Height	50	ft	Allows gravity feed for chemical processing
Ventilated Volume	125,000	cu ft	
Ventilation Rate (air changes per hour)	7		
Ventilation Flow	14,583	SCFM	
Process Ventilation for Hoods, etc.	1,458	SCFM	10%
Ventilation access for 3' by 8' hoods	4		Space available for four 24 sq. ft. fume hoods; ventilation configured for ease of connect/disconnect
Ventilation access for 5' (deep) × 10' (long) × 8' (high) glove boxes	3		Space available for three 50 sq ft glove boxes; ventilation configured for ease of connect/disconnect
			only emplaced in two user bays, for 300 sq ft total
			Or all six colocated but ability to partition three and three.
Mechanical Area (Encapsulated U Only)			Comments
First floor space	20,000	sq ft	200' x 100' area (includes storage vaults, etc.)

Number of floors	1		Platforms/floors could be installed if needed
Total Area for Development	20,000	sq ft	
Overall Ceiling Height	30	ft	Allows vertical handling of fuel pins
Clean Areas			Comments
Offices / Control Room	5,000	sq ft	5 offices + 1 control room
Maintenance Shops	1,000	sq ft	20' × 50'
Lunchroom / Change rooms	9,000	sq ft	3 rooms 15' × 20' ea.
Total Clean Floorspace	15,000	ft	
Overall Ceiling Height	15	ft	

Special Nuclear Material (SNM) Type, Physical Form, and Throughput

The variety of unique fuel forms, as described in Appendix A, requires the ability to work with high-assay, low-enriched uranium (HALEU) in the form of oxides, metals, and salts. The ability to support throughput of up to 2,400 kg/month is based on an estimate of the first core for a large sodium fast reactor, which was estimated to be the largest quantity of HALEU that would be needed for the first core of the advanced reactor types considered (Appendix A).

Analytical, Measurement, and NDE Capability

Analytical capability will be required to verify acceptable ceramic, alloy, and salt microstructure and chemical and isotopic composition of fuels. Precise measurement capability will be required to verify dimensional characteristics of fuels, and nondestructive examination (NDE) will be required to quantify the level of microscopic defects in fuel cladding.

SNM Storage Vaults

Storage vaults will be needed for staging feedstocks before processing, and for completed fuel units before shipment. Integration of engineered features in the vault design that mitigate criticality risks will be an important consideration. The 2,400 kg HALEU capacity is based on the estimated need to store up to one month of throughput.

SNM Shipping and Receiving

There must be sufficient SNM shipping and receiving capacity to remove these logistics from the critical path for fuel fabrication. The capability necessary to support throughput of up to 2,400 kg uranium per month is estimated to be

- the ability to receive up to 1 MT of HALEU in gas, oxide, or metal form, per day
- sufficient UF_6 canister storage area for 3.5 MT of UF_6, which is equivalent to about three large transportation packages
- a 10-ton lift that can transfer payloads between the building interior and loading dock.

Cryogen/Inert Gas Storage and Supply

Inert gases will be needed for salt production and likely other chemical processing needs. Cryogens are needed for gamma spectroscopy and other analytical instrumentation. Therefore, the facility will need up to two 3000-gallon cryogen storage tanks located immediately adjacent to the building. Concrete foundation pads and systems for boil-off gas capture and distribution within the building will be needed.

Waste Streams and Off-Gas Systems

Various waste streams will be produced, from low-level solid waste resulting from routine survey and maintenance to liquid, gas, and suspended particulate streams from chemical and thermal processing. Robust waste-handling features must be included in the design of the facility, such as double HEPA filtration, off-gas treatment capability, and liquid-waste holding tanks. Specifically, the facility must be able to handle

- low-level solid wastes from routine radiochemical operations
- low-level liquid effluents from cleaning, sampling, and dissolution to support wet chemistry, polishing of optical microscopy specimens, and process waste management
- gaseous effluents resulting from thermal heat treatments, analytical chemistry dissolution, and possibly waste management
- toxic gases resulting from molten salt production, such as HF.

Safeguards and Hazard Categories

Unlimited quantities of thorium and uranium enriched to less than 20% in ^{235}U are permitted in a DOE Safeguards Category IV facility. The DOE Hazard Category would likely be 2 or 3, as determined by a Documented Safety Analysis (DSA) and supplemented with Technical Safety Requirements (TSR). Both the DSA and TSR must be reviewed and approved by the DOE owner of the facility. The facility is anticipated to be owned and operated by DOE on DOE property, and so regulated by DOE. For comparison purposes, if licensed by the NRC instead, the facility would be in NRC Category II based on handling of uranium enriched above 10% but below 20% in ^{235}U. Processing of any significant quantity of ^{233}U in addition to ^{235}U would require an NRC Category I designation, and could affect the DOE Safeguards category depending on its physical and chemical form, concentration, and other factors.

Seismic

The seismic category requirement must be determined by analysis of the largest credible earthquake that could occur given the regional geology of the facility location, and the resulting maximum surface accelerations at the facility. Such an analysis could be completed for the various preferred siting locations to provide additional input for the final choice, but should be completed before the design of the building is completed so that the structural requirements necessary to meet the required seismic category can be incorporated.

Appendix D

Perspectives of Various Commercial Fuel Vendors and Developers

As part of this assessment, several fuel vendors provided their thoughts on the future of advanced reactor fuel supply and perspective on a DOE user facility to help bridge the gap.

A U.S. fuel fabricator shared the following statement:

> As a nuclear fuel fabricator, the predominant interest is in a user's facility that could accommodate process development with enriched materials along with the delivery of demonstration and first-of-a-kind projects. This would allow new developers and fuel fabricators to prototype and demo new processes using nuclear material before proceeding with changes to the existing fabricator's facilities and reduce costs while accelerating the timeline for new processes and fuel developments.

Ultra Safe Nuclear Corporation (USNC) provided the following statement:

> Sourcing of HALEU alongside a robust infrastructure for its packaging, distribution, and conversion of feedstocks ready for processing (i.e., metal or oxide) are common needs across the advanced reactor industry that ought to be addressed by the U.S. DOE. Furthermore, support from NRIC to develop streamlined licensing pathways for receipt and handling of HALEU in industrial facilities for production of advanced fuels would be highly beneficial to the industry. Addressing these needs will benefit USNC in securing access to various TRISO-based fuel forms that it intends to deploy on its terrestrial and space nuclear energy systems.

BWXT provided the following statement:

> BWXT Nuclear Fuel Services, Inc. (BWXT NFS), located in Erwin, TN, and BWXT Nuclear Operations Group, Inc. (BWXT NOG-L), located in Lynchburg, VA, are the only commercial NRC-licensed Category I nuclear fuel facilities in the country capable of downblending metric-ton quantities of highly enriched uranium (HEU) to produce high-assay, low-enriched uranium (HALEU) feedstock. Both facilities have downblended HEU since the mid-1990s to produce over 1000 metric tons of LEU for numerous customers and continue to do so. The BWXT NFS facility could be easily modified to create HALEU. Downblended LEU and HALEU can be provided in the form of a uranium nitrate solution or an oxide powder. Capabilities to convert uranium hexafluoride, nitrates, or oxides to uranium metal via an intermediate UF_4 salt could be established.

BWXT NOG-L has reestablished an engineering-scale TRi-structural ISOtropic (TRISO) fuel fabrication line. This line has the capacity to meet the TRISO fuel supply needs to support the demonstration and initial deployments of both national security and commercial advanced reactors and microreactors. BWXT is also establishing a metal casting capability to support fabrication of HALEU fuel for research and test reactors.

The existing HEU inventory has many competing needs, and therefore allocation of HEU feedstocks for downblending to HALEU in support of these activities is very limited. As a result, there is insufficient HEU for downblending to support commercial HALEU-fueled reactors. To support deployment of advanced, HALEU-fueled reactors, BWXT has proposed the following actions be taken:

- Downblend HEU stockpiles to HALEU as a near-term "bridge" using 4.95% enriched diluent, which will extend the existing HEU resources.
- Immediately establish capabilities to produce and store both oxide and metal forms of HALEU.
- Allocate funding and commence commercial design activities for a new centrifuge-based HEU enrichment facility.
- Replenish the HEU stockpiles for future needs using the new enrichment capabilities.

An advanced fuel developer shared the following statement:

> The establishment of a single facility capable of performing research and development activities and pilot-scale production to support leads programs within the U.S. DOE complex would be of great value to all advanced nuclear fuel developers. Currently, no single DOE facility possesses our entire fuel fabrication infrastructure needs. These needs may be placed into three categories:

- supply and handling of special nuclear material
- process equipment at or near pilot-scale
- process engineering expertise

> Our fuel technology, along with many other developers, requires the use of HALEU. Access to HALEU is required for irradiation testing, leads programs, and initial reloads. The development of a single facility within the DOE complex capable of receiving and processing such quantities through leads and potentially initial reload quantities is of great interest to us and likely many other advanced nuclear fuel developers.

Process equipment suitable for performing research and development (R&D) activities on gram level quantities of material for novel fuel alloys is currently scattered among several national laboratories while the ability to process kilograms of material remains unavailable. Although the existing capabilities are helpful in performing R&D activities related to fabrication, they do not shorten the pathway to commercial availability of new fuel technologies. Furthermore, the dispersion of the existing capabilities presents challenges and inefficiencies in coordinating and executing R&D activities within the DOE complex. Facilitating work at multiple DOE facilities presents developers with challenges related to shipping, project management, and contracting, which would be solved by concentrating commercial or near commercial-scale equipment in a central facility.

In addition to providing suitable equipment, the formation of a centralized facility with wide-ranging process capabilities provides the opportunity to concentrate process engineering expertise capable of supporting the transition from laboratory-scale experimentation to leads programs. Currently, this expertise is dispersed throughout the DOE complex and difficult to leverage. Depending on the fuel form collaboration with multiple DOE laboratories to support fabrication efforts is required and gaining access to the appropriate expertise is a challenge to developers who lack an insider's perspective.

A facility capable of handling the quantities of HALEU outlined in Table 14 that combines pilot-scale process equipment with suitable expertise would be extremely valuable in our nation's efforts to commercialize advanced nuclear technologies. The analysis team welcomes the opportunity to further share their viewpoint and provide any feedback needed in support of such a facility.

Kairos Power provided the following statement:

> A user fuel fabrication facility provides a tremendous advantage to advanced reactors such as Kairos because it eliminates the costly, time-consuming step of designing and constructing a specialty fuel fabrication facility with the necessary Part 70 license. It avoids the lengthy and costly NRC engagement and review cycle, solely to demonstrate the viability of an advanced reactor technology. Reactor demonstration and reactor orders are necessary gates to facilitate the investment required for establishing a new fuel fabrication facility, especially one that must be rated for Category II operations to handle HALEU, which is the case for most advanced reactor vendors. However, fuel is necessary to power reactor operations, creating a significant barrier to commercialization. A fuel fabrication user facility eliminates the majority of the capital investment associated with reactor demonstration-scale fuel production and enables reactor operations that may subsequently result in both reactor orders as well as the capital investment required to construct commercial fuel fabrication facilities.

Appendix E

Candidate Facility Descriptions

Fuels and Materials Examination Facility

The Fuels and Materials Examination Facility (FMEF) is a U.S. Department of Energy (DOE) facility located near the Fast Flux Test Facility in the 400 Area of the Hanford Site (controlled area) in Washington State. The FMEF is about 10 miles north-northwest of the city of Richland and about five miles inside the southern perimeter of the Hanford Site (Figure 8).

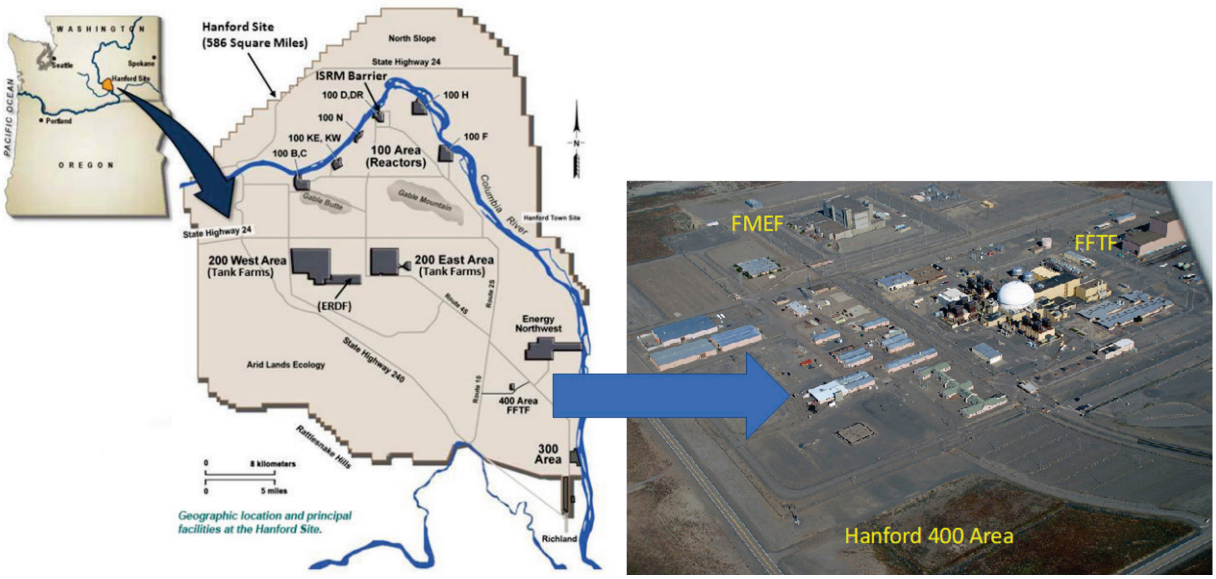

Figure 8. Location of FMEF within the Hanford Site

The FMEF floor plan is shown in Figure 9. A summary of the individual facilities within the FMEF is provided in this section.

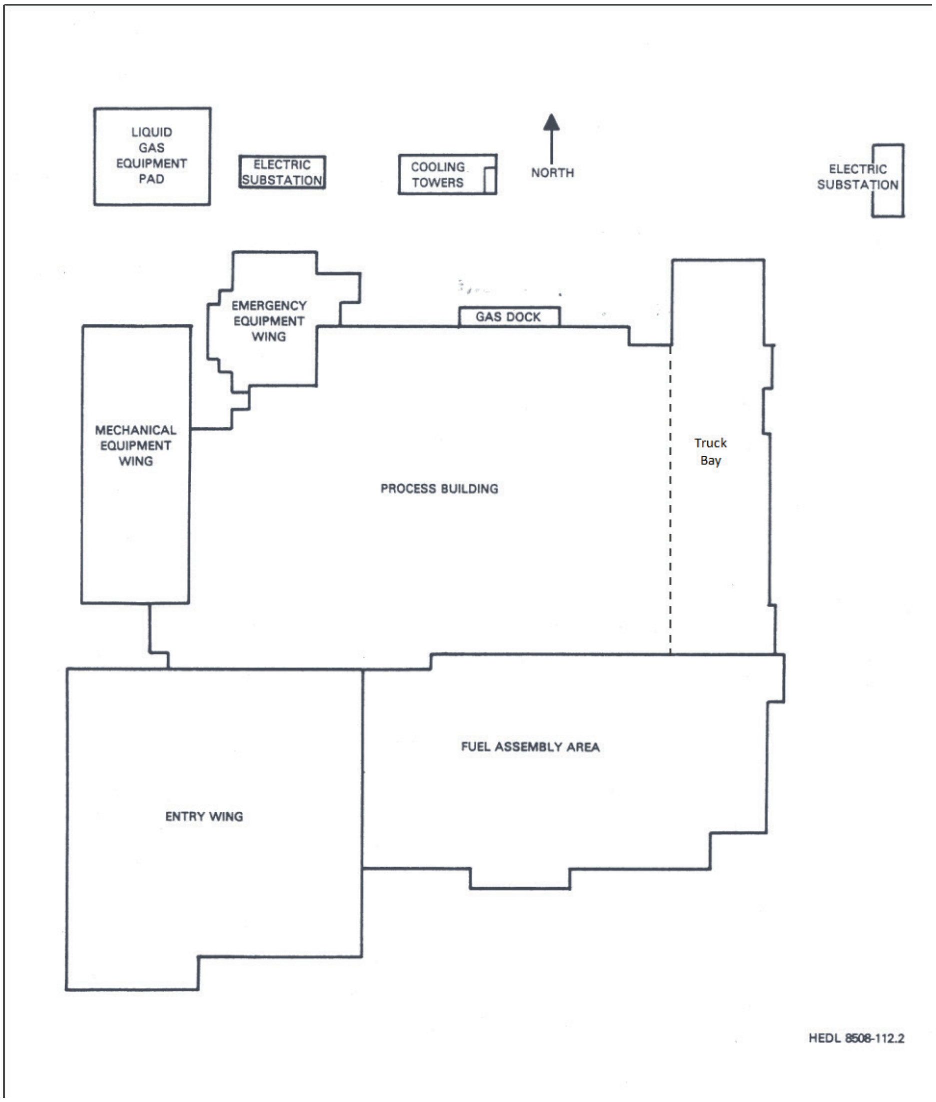

Figure 9. FMEF Floor Plan

Entry Wing

The Entry Wing contains 25,000 ft^2 of office space and administrative support areas, and employee lunch and change rooms; it also provides access to the Process Building via a security guard station and automated personnel access control portals. A partial second floor has rooms for Safeguard and Security Computers, Access Control, and Security Control.

Fuel Assembly Area

The ~19,000 ft^2 Fuel Assembly Area was designed for inspection, assembly, and storage of fast reactor fuel pins (Figure 10 and Figure 11). The Fuel Assembly Area is 104 ft by 181 ft with a height of 30 ft. It is designated Seismic Category I and is seismically disconnected from the Process and Entry Wing Buildings. It contains two subgrade pits (5.5 m deep, 9 m deep).

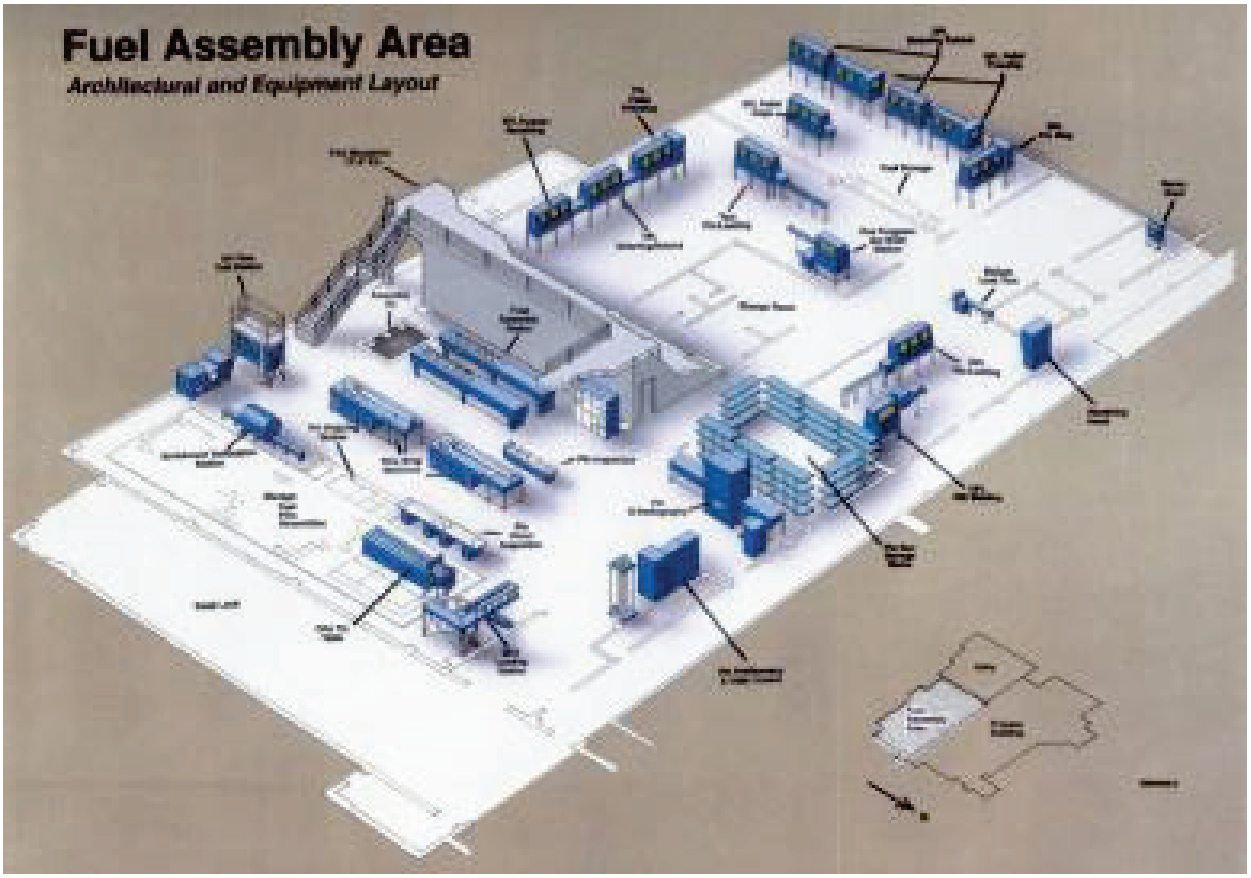

Figure 10. Original Fuel Assembly Area Architectural and Equipment Layout

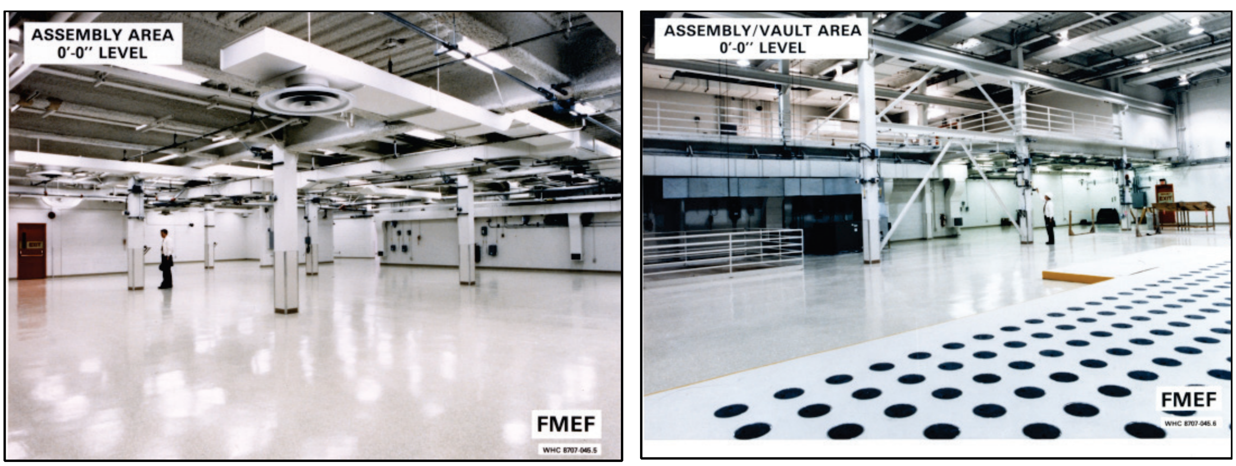

Figure 11. Fuel Assembly Area

<u>Mechanical and Emergency Equipment Wings</u>

The Mechanical Equipment Wing is an annex that adjoins the Process Building. It is 50 ft wide, 122 ft long, and 21 ft high. It provides space for nonvital services and utilities. The Emergency Equipment Wing also adjoins the Process building; it is 40 ft wide and 65 ft long. It houses two 900 kW gas turbine emergency generators and the emergency cooling water system.

Truck Bay

The truck bay is connected to the Process building and has installed, functional ventilation systems, service equipment and piping, and bridge cranes (Figure 12).

Figure 12. FMEF Truck Bay

Process Building

The heart of the FMEF is the Process Building, which is 175 ft wide by 270 ft long, has about 123,000 ft^2 of processing area. It comprises numerous compartments on six different floors (levels) surrounding a central core of three large, heavily shielded, remotely operated process cells. It extends 98 feet above ground and 35 feet below ground (Figure 13 and Figure 14).

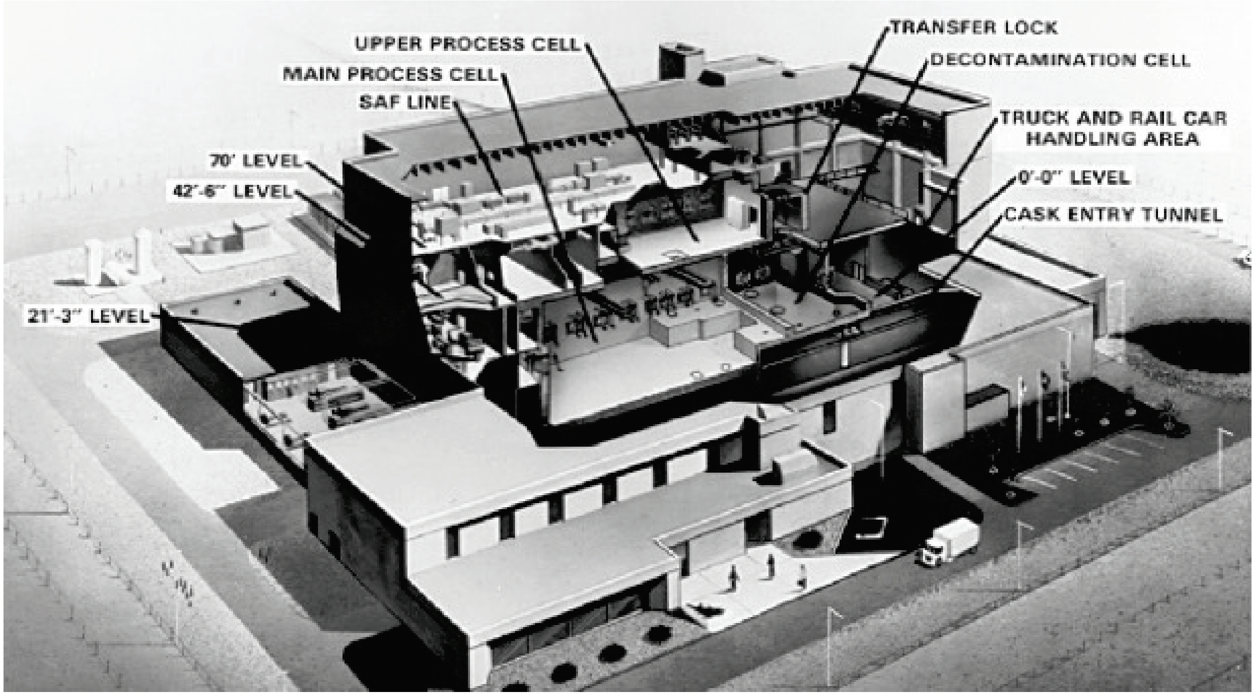

Figure 13. FMEF Process Building Cutout

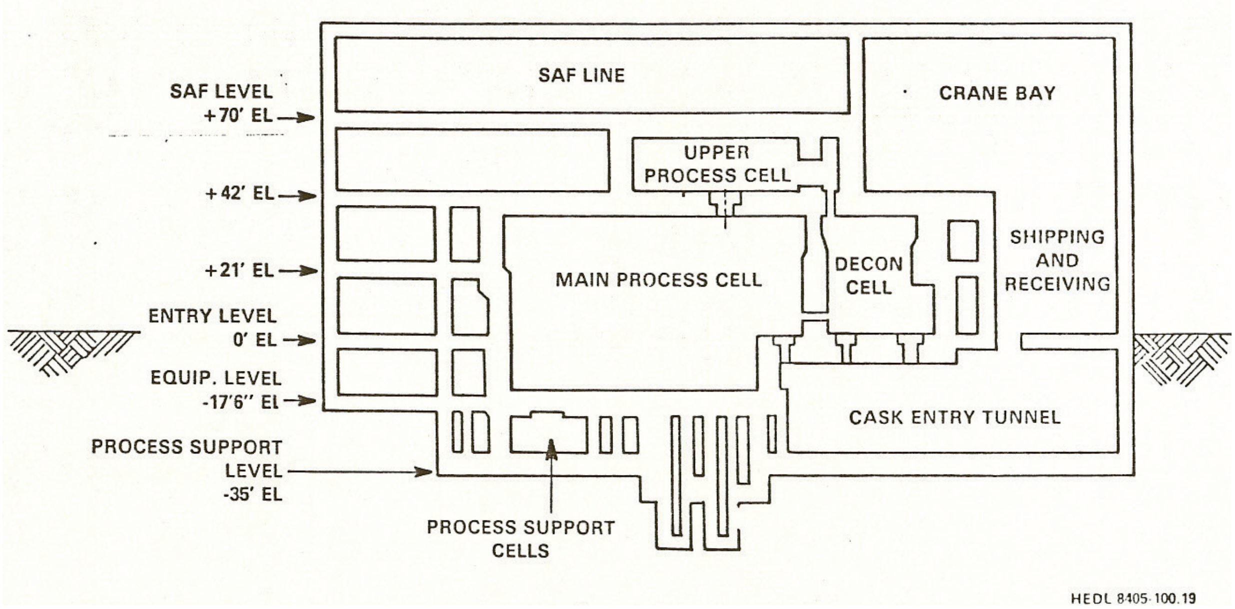

Figure 14. FMEF Process Building Longitudinal Section (Elevation View)

Process Support Level (−35 Foot Level)

The Process Support Level (Figure 15) contains numerous small and mid-sized hot cells designed to handle irradiated fuel/material samples, including destructive examination. The 14 process support cells are arranged in two parallel rows; smaller cells are 42 ft^2 while mid-sized cells are 78 ft^2. All cells are lined with stainless steel and are capable of being inerted.

Some of the hot cells have manipulators, shielded windows, and other support equipment that was installed to support the Radioisotope Thermal Generator Mission before that program was moved to another DOE site. There currently is no connection or way to transfer material between adjacent cells.

The Process Support Level houses a transfer tunnel that is used to transfer equipment and materials from the main processing cell to the decontamination cell.

The Process Support Level also houses equipment repair areas, space intended for a Training, Research, Isotopes, General Atomics (TRIGA) reactor, and a room intended for processing film from neutron radiography and metallography operations.

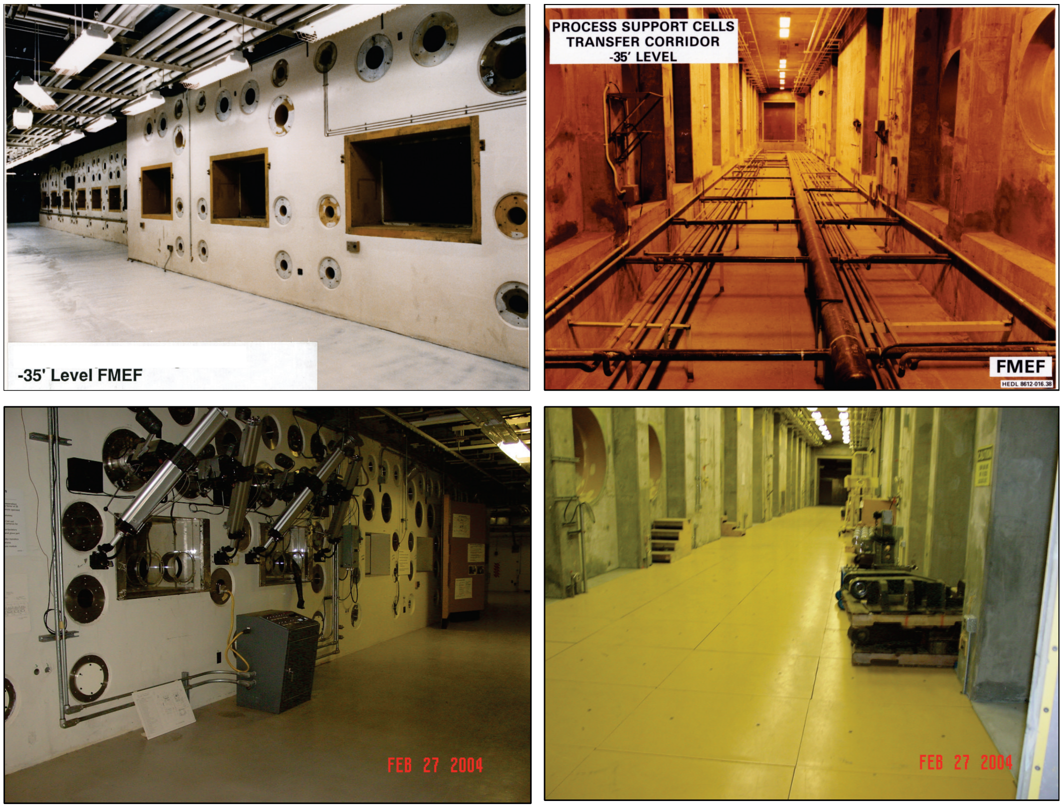

Figure 15. FMEF Process Building, −35 Foot Level

Equipment Level (−17 Foot Level)

The Equipment Level (Figure 16) consists of support utilities and service systems. It houses electrical equipment rooms, the heating, ventilating, and air-conditioning (HVAC) supply fan room, a room for filtering the main process cell, space for a TRIGA reactor, the emergency air compressor room, the uninterruptible power supply and switchgear room, the communications room, pressure control tanks for the main process cell, vacuum equipment, and analytic chemistry off-gas equipment.

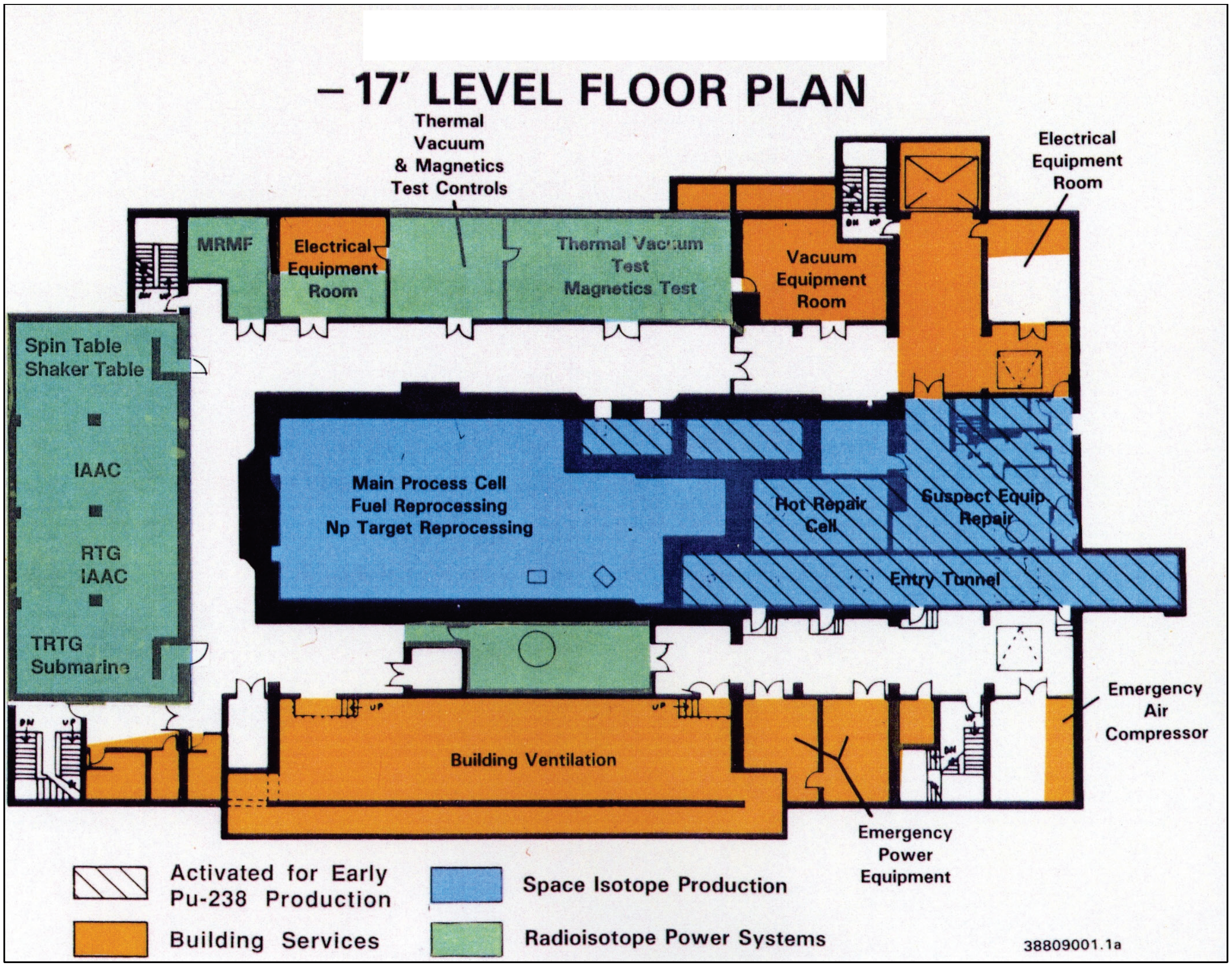

Figure 16. FMEF Process Building, −17 Foot Level Floor Plan. Note: Floor plan as laid out for the Radioisotope Thermal Generator Mission

Entry Level (0 Foot Level)

The Entry Level (Figure 17) contains general utility and service control systems, shipping and receiving operations (truck bay), the main process cell (a very large hot cell in the middle of the facility), the decontamination cell, the operations control room for facility services, the computer systems control room, and access vestibules for controlled entry.

The main processing cell is heavily shielded (up to 5 feet thick) and was designed to provide a large, inert-atmosphere, alpha-emitter–tight enclosure in which automated and semi-automated irradiated fuel could be handled. The base of the cell is below grade, on the Equipment (−17 ft) level. The interior of the cell is 100 ft long, 40 feet wide, and 53 feet tall. It is lined with zinc-coated carbon steel. There are 24 work stations on the Entry Level and four work stations on the upper main processing cell level (12-foot level). Each work station has penetrations for a viewing window, two manipulators, and additional penetrations for utility/instruments/control. Hot cell windows and manipulators were not installed.

The decontamination cell is also a heavily shielded hot cell and has eight window work stations. It was designed for the decontamination of fuel pins, irradiated capsules, and materials for transfer to other locations in the FMEF, decontamination of in-cell equipment, and packaging of waste.

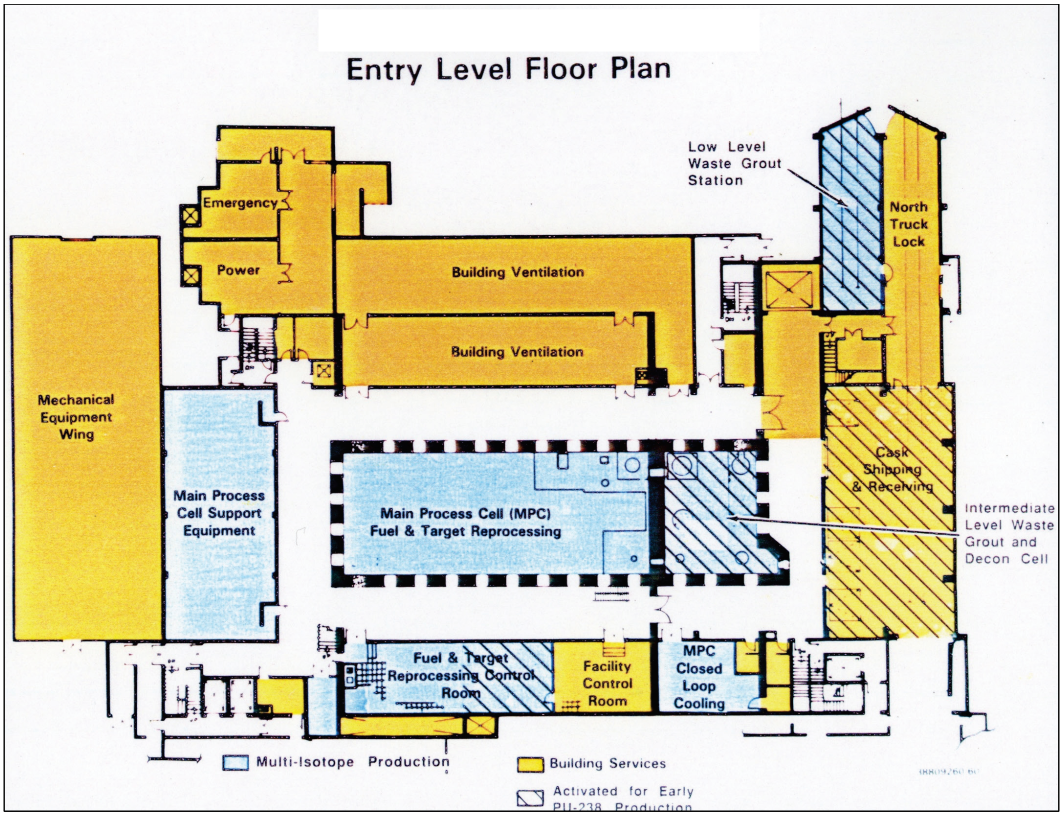

Figure 17. FMEF Process Building, 0 Foot Level Floor Plan. Note: Floor plan as laid out for the Radioisotope Thermal Generator Mission

Chemistry Level (21 Foot Level)

The Chemistry Level (Figure 18) provides analytic chemistry laboratories, glove boxes for large-quantity special nuclear material (SNM) handling, and open-faced hoods for small quantity SNM measurements.

The Chemistry Level also houses the Special Nuclear Material Storage vault. (Figure 19) Installation of the SNM vault is complete, including a handling robot and stacker/retriever system in the controlled storage area. This equipment is still in place. The spent nuclear fuel vault has a storage capacity of 4,000 kg Pu in plutonium oxide or 10,000 kg Pu in compressed pellets.

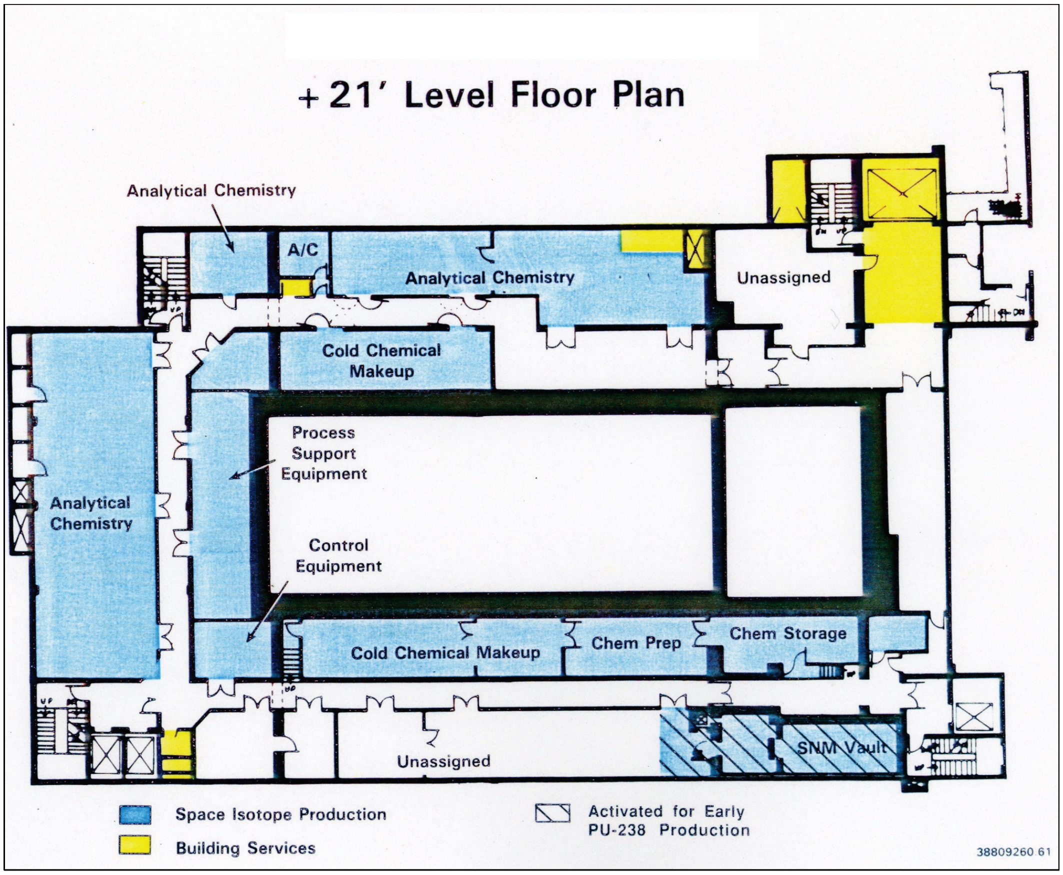

Figure 18. FMEF Process Building, 21 Foot Level Floor Plan. Note: Floor plan as laid out for the Radioisotope Thermal Generator Mission

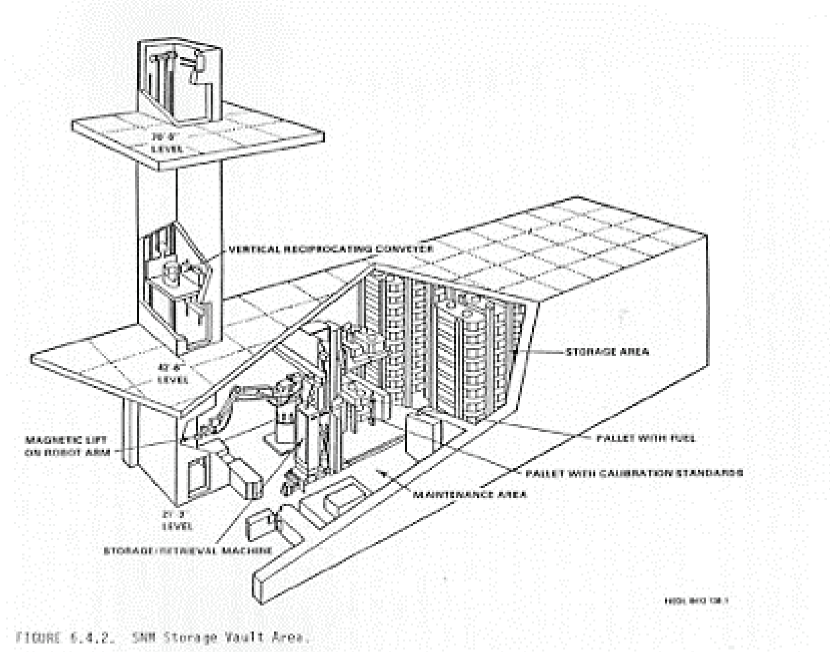

Figure 19. FMEF Process Building, Special Nuclear Material Storage Vault

Fuel Fabrication Level (42 Foot Level)

The Fuel Fabrication Level (Figure 20 and Figure 21) was designed to support the fabrication of fast reactor fuel. It houses the upper process cell, an alpha-emitter–tight hot cell designed for post-irradiation fuel examination, spiked fuel fabrication, or fuel recovery operations. The upper process cell has 14 workstations with penetrations for windows, manipulator, and shield plugs. It has a room designed for receiving and processing SNM. It also has rooms that were designed as a fully integrated test pin fabrication line using shielded, alpha-emitter–tight glove boxes.

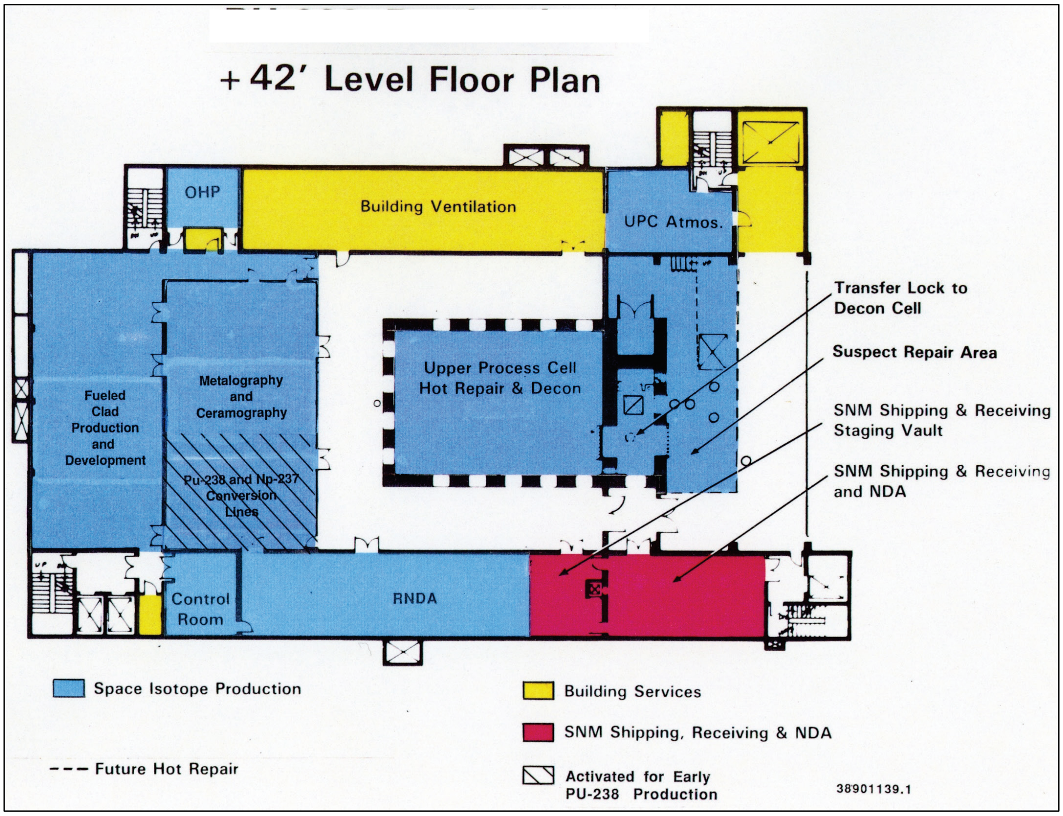

Figure 20. FMEF Process Building, 42 Foot Level Floor Plan. Note: Floor plan as laid out for the Radioisotope Thermal Generator Mission.

Figure 21. FMEF Process Building, 42 Foot Level Hot Cells and Laboratory Space

<u>Secure Automated Fabrication Level (70 Foot Level)</u>

This level contains the Secure Automated Fabrication (SAF) Line, which was constructed to manufacture mixed oxide fuel pellets for fast reactors at a rate of 8 kg/h (~7500 pellets/h). The SAF line is separated into three processing areas (powder, pellets, pins) and was designed to run remotely. All process equipment is contained in shielded glove-box–type structures, which provide the capability to process fuel materials with higher radiation exposures. The powder and pellet area equipment completed preoperational testing and was ready for hot start-up before the supporting fast reactor program was terminated. All process equipment for the SAF line is still installed. (Figure 22 and Figure 23)

If the installed equipment were removed, the 70' level and its mezzanine would present a large multiple purpose area/capability.

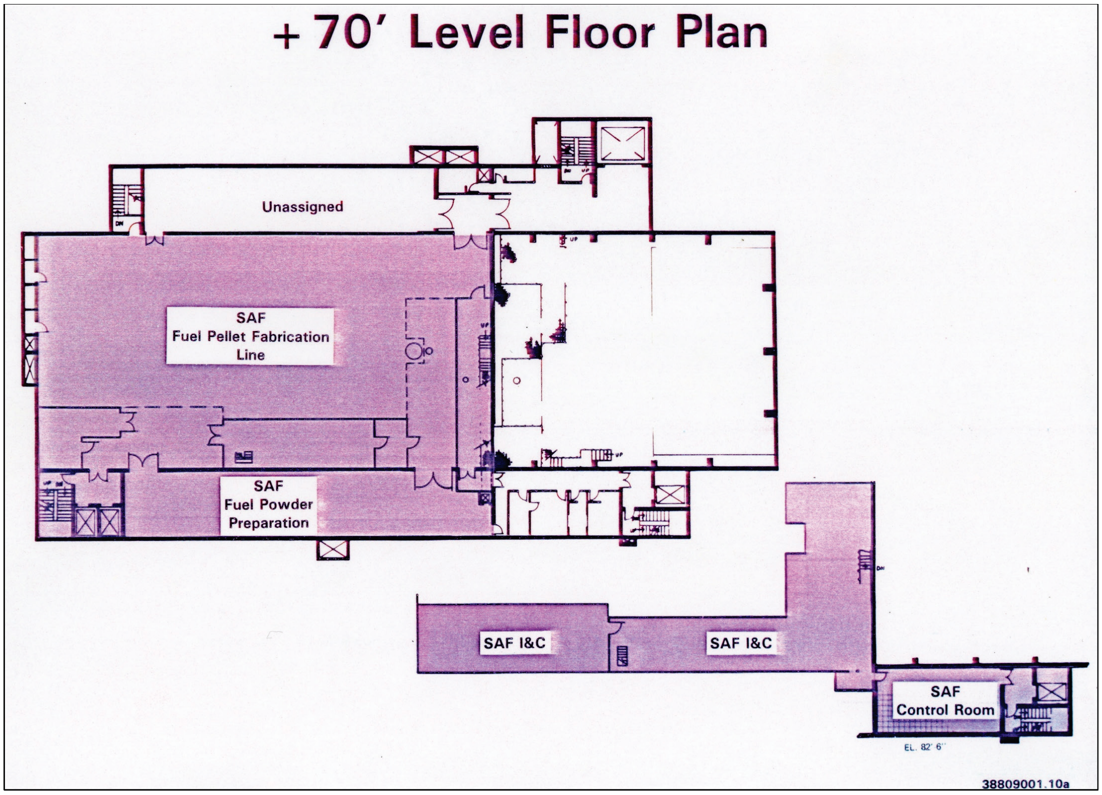

Figure 22. FMEF Process Building, 70 Foot Level Floor Plan

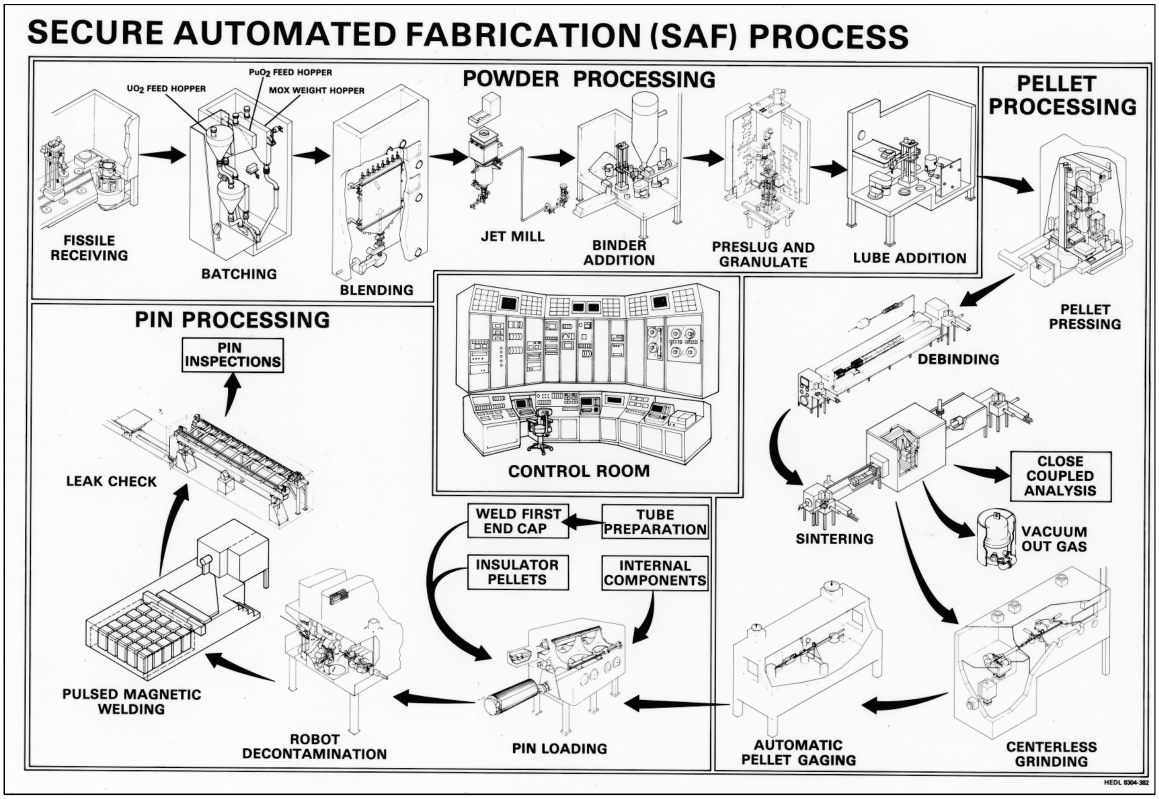

Figure 23. Secure Automated Fabrication (SAF) Process

Radioactive Liquid Waste Treatment Facility (MFC-798) Floor Plans

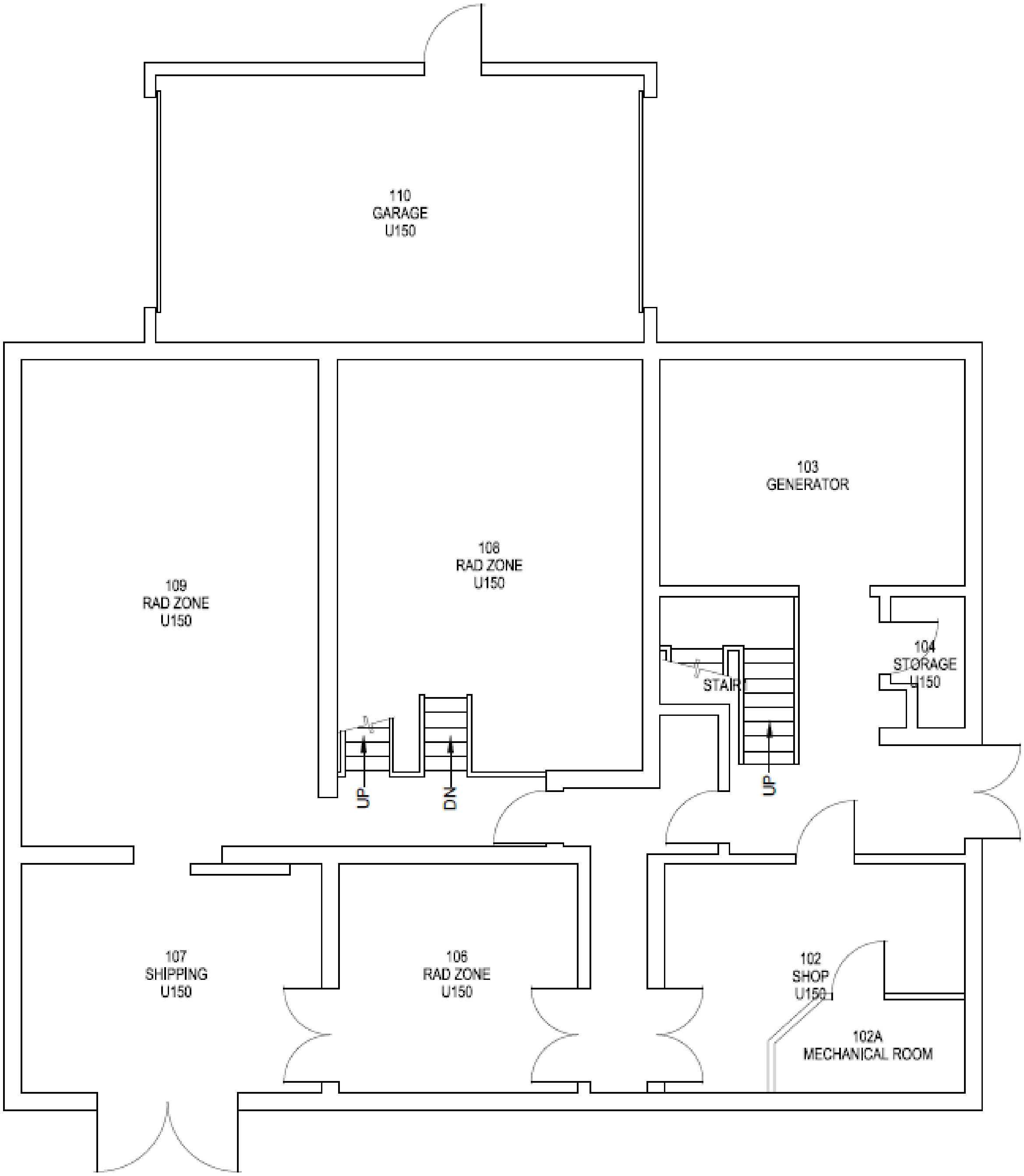

Figure 24. Radioactive Liquid Waste Treatment Facility (RLWTF) First Floor

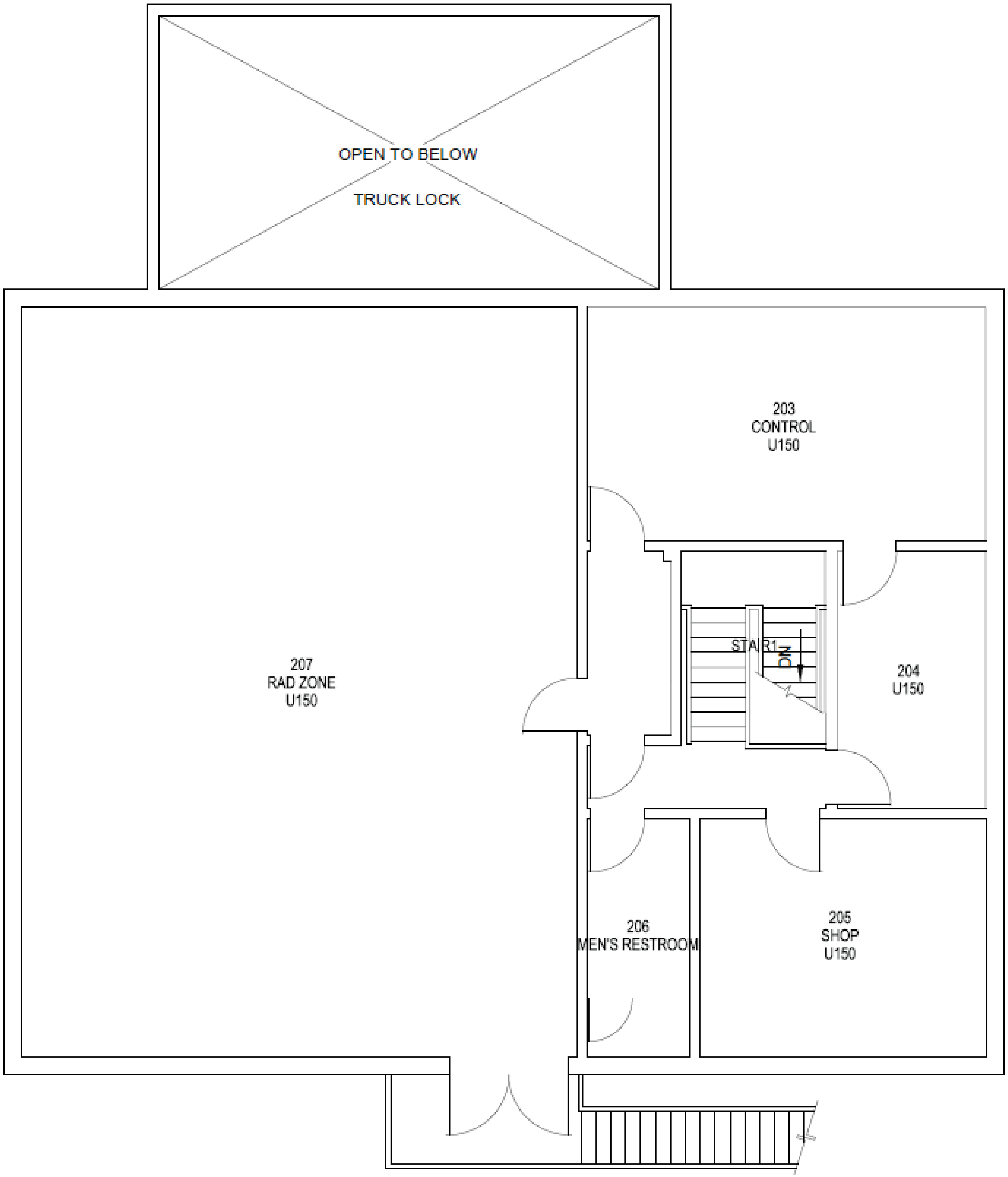

Figure 25. RLWTF Second Floor

Fuel Processing Restoration (FPR) Facility (CPP-691) Floor Plans

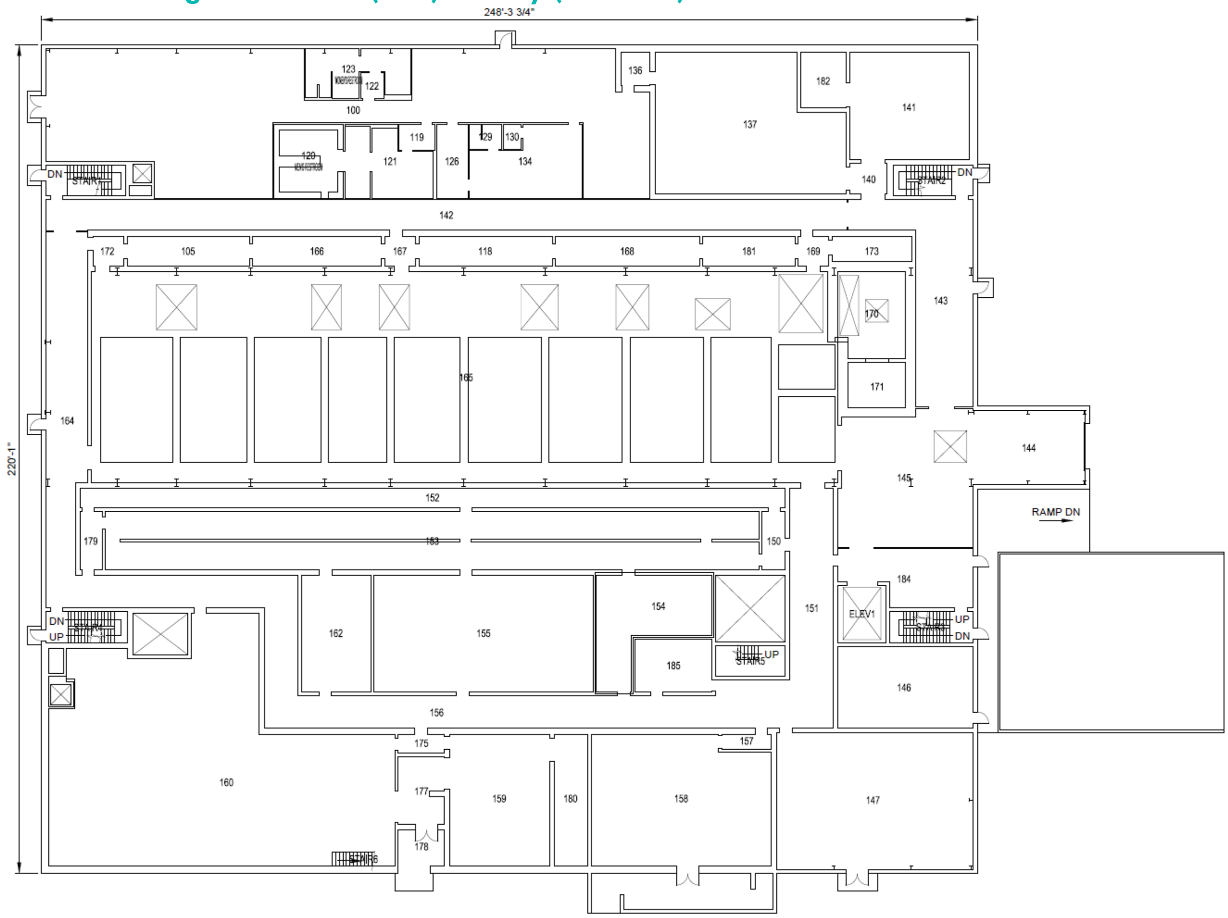

Figure 26. FPR First Floor

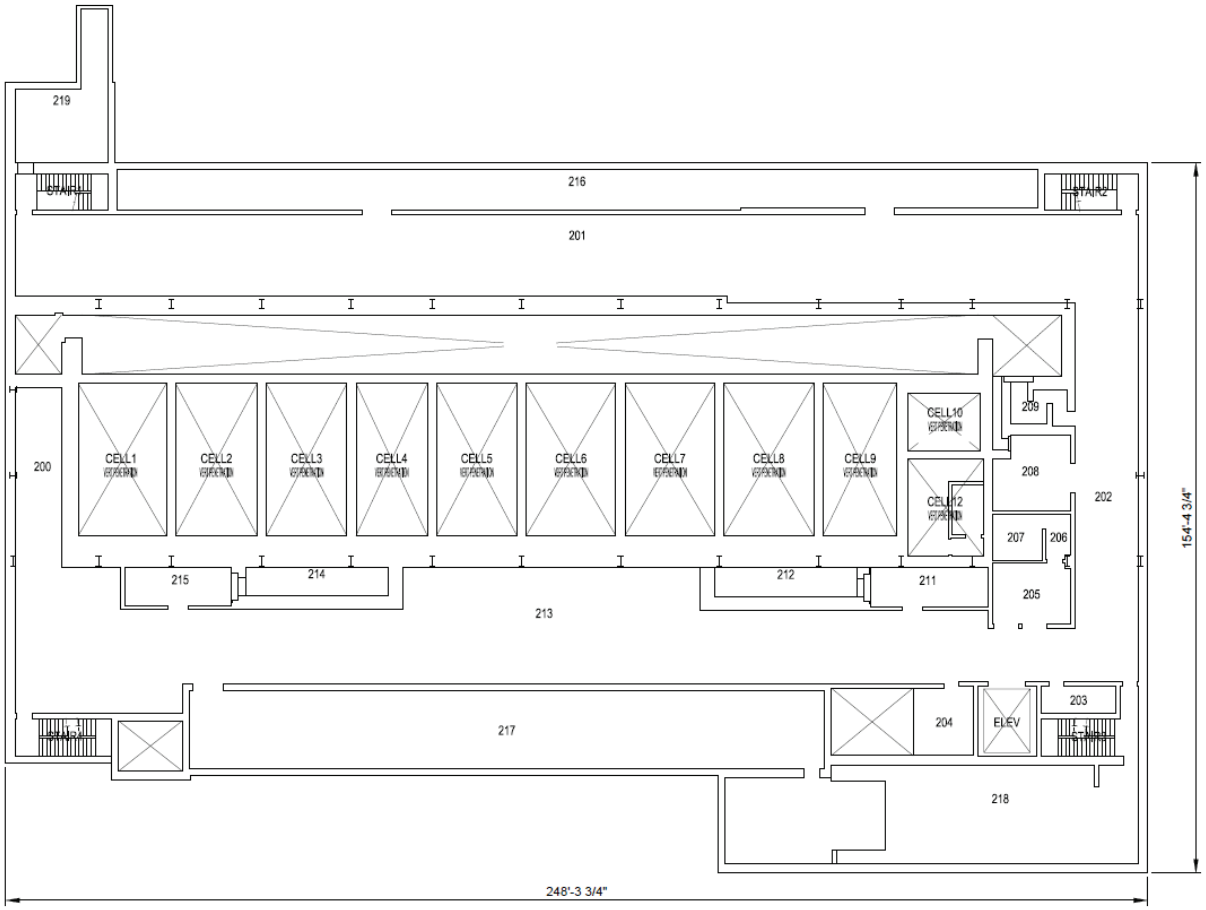

Figure 27. FPR Second Basement Level

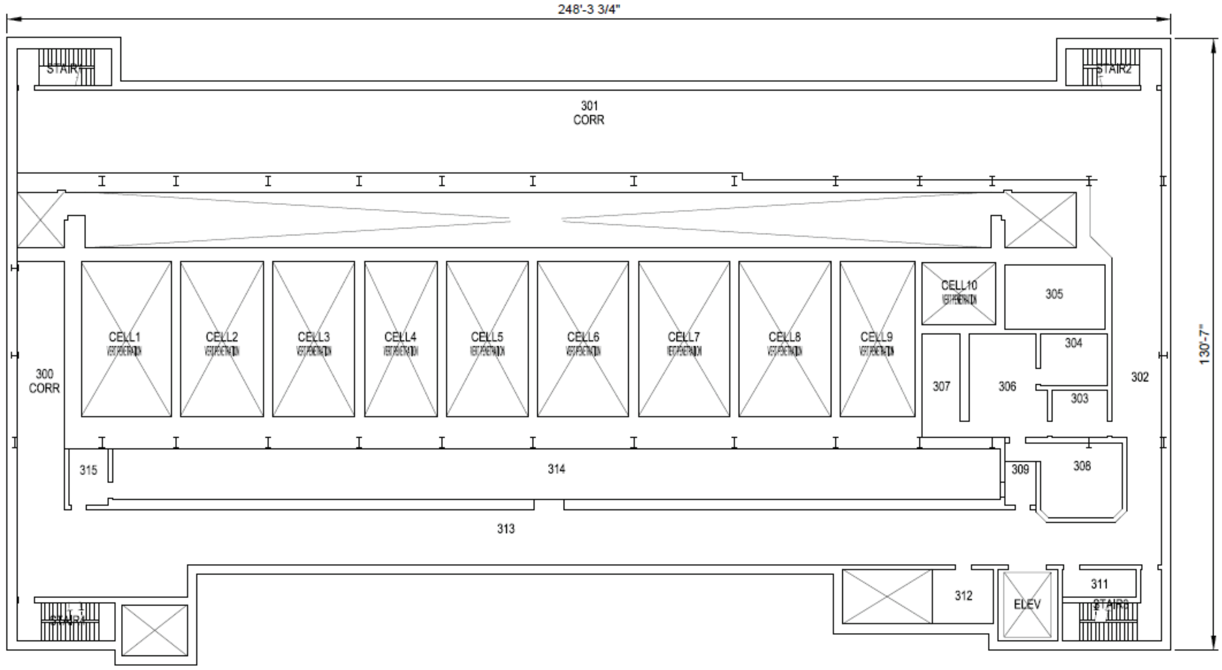

Figure 28. FPR Third Basement Level

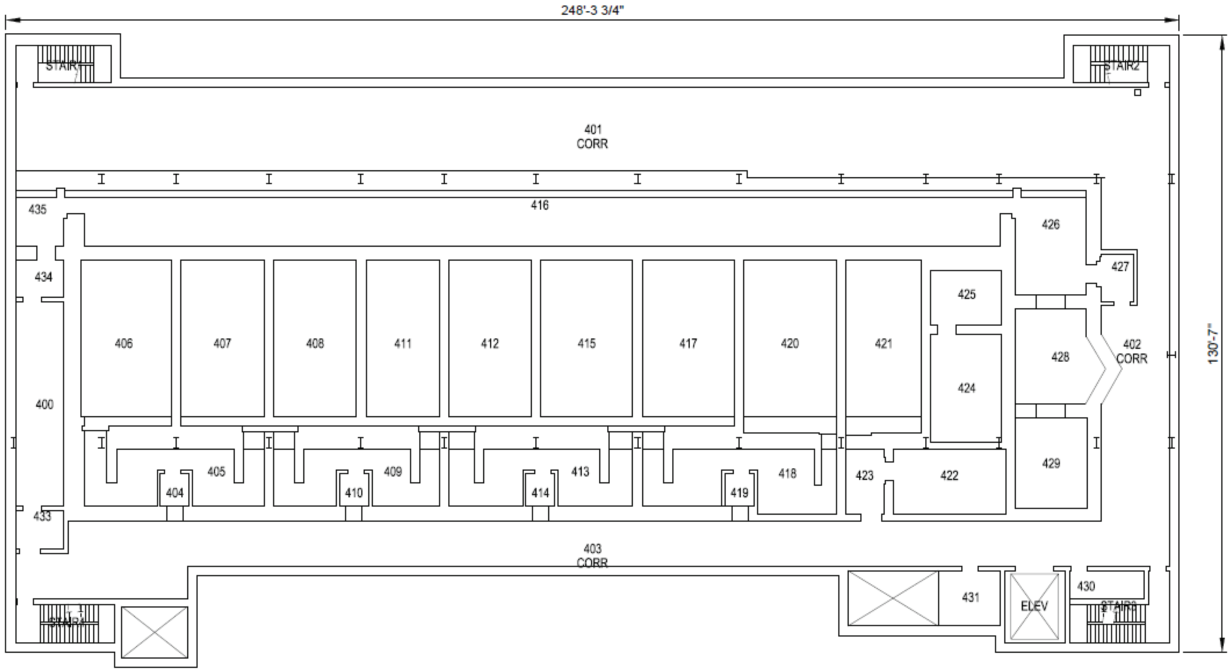

Figure 29. FPR Fourth Basement Level

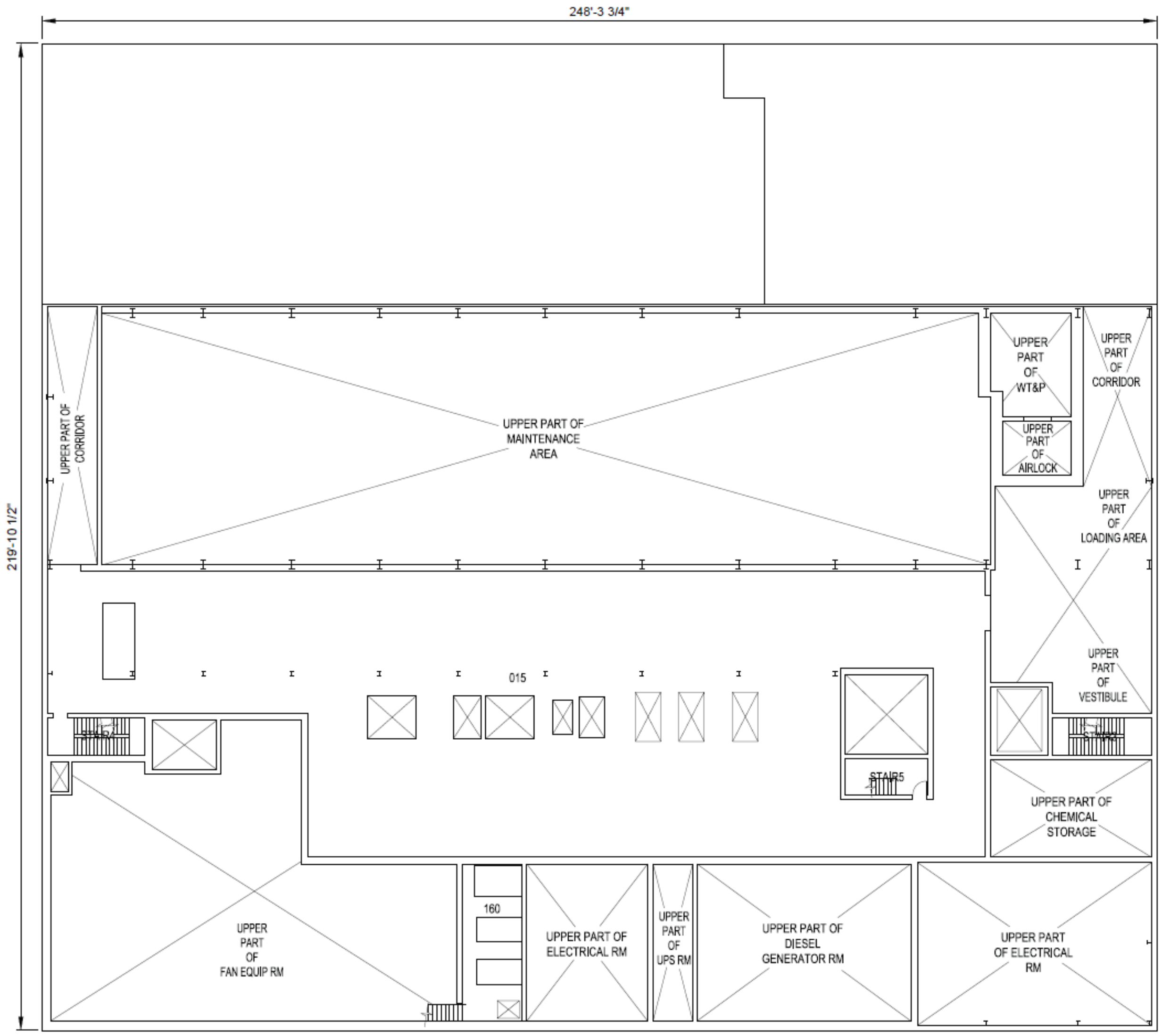

Figure 30. FPR Mezzanine Level

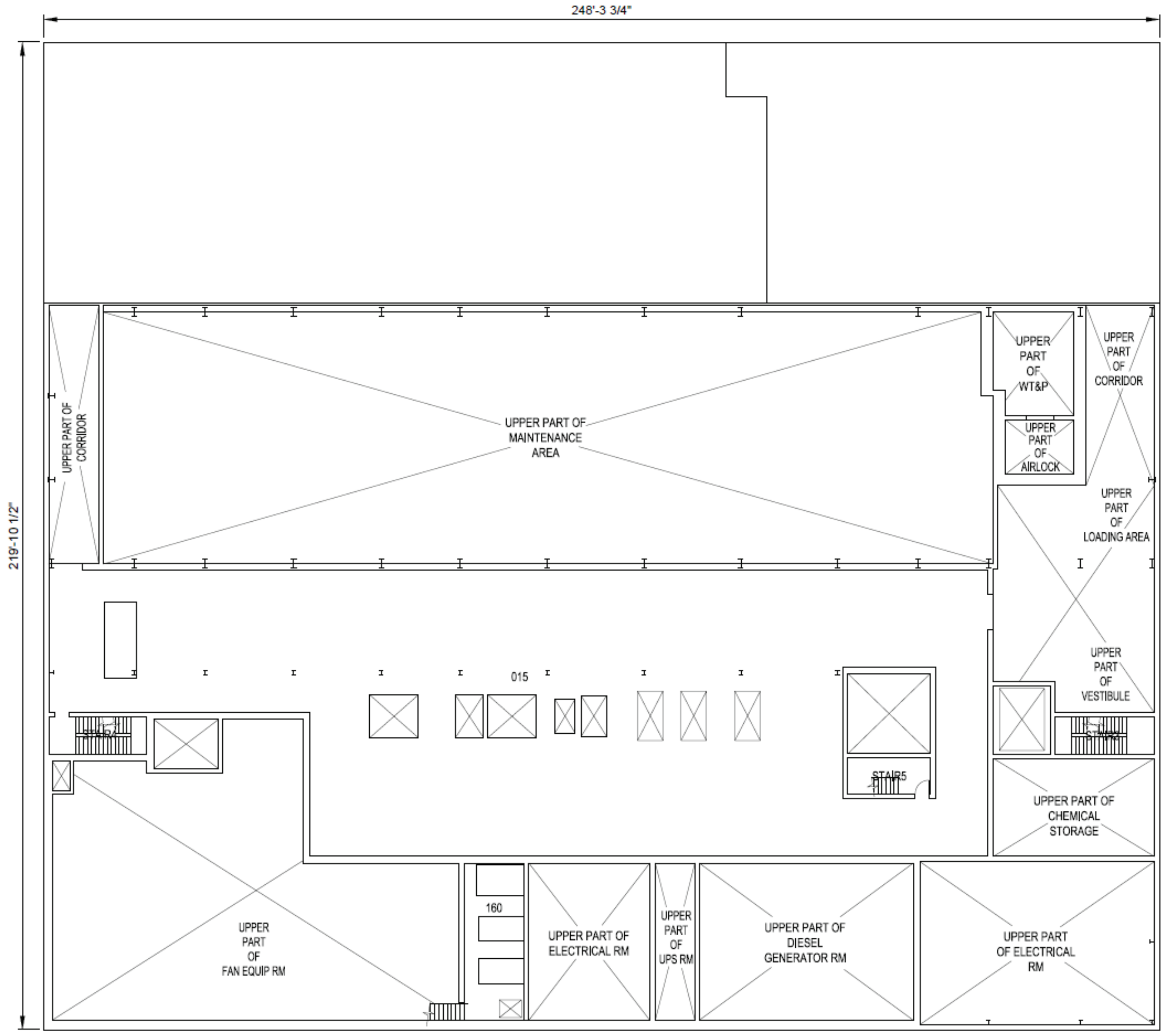

Figure 31. FPR Upper Level (Second Floor)