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Assessment of Coated Particle Fuels for Space Nuclear Power and Propulsion Systems

A Report for the NESC Nuclear Power & Propulsion Technical Discipline Team

Kelsa Palomares and James Werner
Analytical Mechanics Associates, Inc., Hampton, Virginia

February 2023

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Nomenclature

ADUN	acid deficient uranyl nitrate
AGR	Advanced Gas Reactor program
Al_2O_3	alumina
ALD	atomic layer deposition
ANL	Argonne National Laboratory
CBCG	Columbia Basin Consulting Group
$C\text{-}C_f$	carbon-carbon fiber composite
cercer	ceramic ceramic fuel
cermet	ceramic metallic fuel
Cl	chlorine
CVD	chemical vapor deposition
DOD	Department of Defense
DOE	Department of Energy
F	fluorine
FB-CVD	fluidized bed CVD
FIMA	fissions per initial metal atoms
FLiBe	Lithium Fluoride-Beryllium Fluoride
FSP	fission surface power
ft	feet
g	gram
GE	General Electric
H_2	hydrogen
H_2O	water
HALEU	high assay low enriched uranium
He	helium
HEU	high enriched uranium
HeXe	helium xenon
HTGR	High Temperature Gas Reactor
HTMA	hexamethylenetetramine
HTR-PM	High Temperature Reactor-Pebble Bed Modular
HTTR	High Temperature Engineering Test Reactor
iPyC	inner pyrolytic carbon
K	kelvin
kg	kilogram
kW	kilowatt
kW_e	kilowatt electric
kW_{th}	kilowatt thermal
L	liter
LBFR	Lead Bismuth Fast Reactor
LEU	low enriched uranium
Li	lithium
m	meter
M&S	modeling and simulation
MARVEL	Microreactor Applications Research, Validation & EvaLuation
mm	millimeter

Mo	molybdenum
MPa	Megapascal
MW	Megawatt
MWd	Megawatt-day
MW_e	Megawatt electric
MW_{th}	Megawatt thermal
n	neutron
N	nitrogen
Na	sodium
NaK	sodium potassium
NASA	National Aeronautics and Space Administration
Nb	niobium
NEP	nuclear electric propulsion
NERVA	Nuclear Engine for Rocket Vehicle Application
NRC	Nuclear Regulatory Commission
NTP	nuclear thermal propulsion
OPyC	outer pyrolytic carbide
PIE	Post Irradiation Examination
PVD	physical vapor deposition
PWC	Nb-Zr-C alloy
PyC	pyrolytic carbon
Re	rhenium
RERTR	Reduced Enrichment for Research and Test Reactor program
SiC	silicon carbide
$SiC\text{-}SiC_f$	silicon carbide-silicon carbide fiber composite
SME	subject matter expert
SMR	Small Modular Reactor
SNAP	Systems for Nuclear Auxiliary Power
SNTP	Space Nuclear Thermal Propulsion
sol-gel	solution gelation
SP-100	Space reactor Prototype-100
SPAR	Space Reactor Electric Power Supply
T-111	tantalum alloy, Ta-8W-2Hf-0.02C
Ta	tantalum
TCR	Transformational Challenge Reactor
TD	theoretical density
TDT	technical discipline team
TFEVP	Thermionic Fuel Element Verification Program
TiN	titanium nitride
TREAT	Transient Reactor Test Facility
TRISO	TRIstructural-ISOtropic
TRL	technology readiness level
U	uranium
U.S.	United States
U_3O_8	triuranium octoxide
UC	uranium carbide

UC_2	uranium dicarbide
UCN	solid solution of UC-UN
UCO	uranium oxycarbide
UMo	uranium molybdenum alloy fuel
UN	uranium nitride
UO_2	uranium dioxide
U-Pu-Zr	uranium plutonium zirconium alloy fuel
U-Zr	uranium zirconium alloy fuel
$UZrH_x$	uranium zirconium hydride
W	tungsten
W	watt
YH_x	yttrium hydride
Zr	zirconium
ZrC	zirconium carbide
ZrH_x	zirconium hydride
$M	millions of U.S. dollars
$(U,Pu)O_2$	uranium-plutonium dioxide
(U,Zr)C	solid solution of UC-ZrC
(U,Zr)C-C	graphite with (U,Zr)C composite fuel
°C	degrees Celsius
μm	micrometer

1.0 Introduction

Space reactors are advantageous for in-space power and propulsion due to their capability for high power density and long operating duration. Since the 1950s, the development of these systems has been pursued within the United States (U.S.) and internationally with the goal to enable capable, robust, and sustainable exploration of our solar system. While space nuclear systems encompass radioisotope, fission, fusion, and other advanced nuclear power sources, fission reactors have been of particular interest for human exploration missions to the Moon and Mars because of their capability to provide high power levels for long periods of time, especially for exploration of regions with limited ability to leverage solar power sources. Fission provides the potential for high power density per unit mass which allows for the potential to minimize power and / or propulsion system mass compared to alternative sources. Further, this attribute can be leveraged to reduce transit times, enable more complex missions, as well as add robustness and capability to baseline missions.

There are three fundamental applications of space fission power and propulsion currently under consideration by the National Aeronautics and Space Administration (NASA): fission surface power (FSP), nuclear electric propulsion (NEP), and nuclear thermal propulsion (NTP). The system design drivers, operating characteristics, technology challenges and mission applications are broadly described in the literature [1, 2, 3, 4, 5, 6, 7, 8, 9]. There exists an extensive development history of space reactor technologies within the U.S. alone. However, through past U.S. development efforts, none of these technologies have yet been fully demonstrated or implemented in space. This results in the current need for new development of reactors and their corresponding fuel systems to meet the performance, functional, reliability, and safety requirements needed for modern space missions.

For each space reactor system, the fuel is a critical component to enable reactor reliability and performance and one of the major technical decisions that must be made for the system design. Selection of the fuel form will play a large impact on overall system performance as well as technical risk that must be addressed during the overall development program, which is expected to have a major impact on program cost and schedule. There is a wide variety of possible fuel variants that could be proposed for each system, including space reactor fuels developed through past programs, new novel fuel designs, and existing terrestrial fuels modified for space reactor applications. In this study, existing terrestrial fuel types were surveyed and assessed for use in different space reactor systems. This study aimed to identify fuel development needs to mature space reactor fuel technologies to enable future demonstration reactor operations and eventual qualification for flight operations. Through this effort, for each system (FSP, NTP, and NEP), coated particle fuel technologies adapted from existing terrestrial fuel programs were evaluated against a reference historic fuel form in the categories of performance, technical risk, and programmatic considerations (cost / schedule) to understand the benefits and disadvantages of leveraging coated particle fuel technologies for space applications.

1.1 Study Scope and Aims

This study evaluates terrestrial reactor fuel forms, with an emphasis on the coated particle fuel capability under development by interagency reactor programs, for application to space reactor systems of interest to NASA. A comprehensive review of coated particle fuel readiness and qualification status has been performed. Possible derivative fuel forms based on coated particle fuel manufacture technologies are identified for space nuclear propulsion and power applications. A subject matter expert (SME) assessment of performance range, technology development gaps, as well as programmatic cost and schedule considerations was performed for coated particle derivatives and a reference space reactor fuel form. This allowed for common space reactor fuel development challenges to be identified as well as the benefits and limitations of coated particle-based fuel designs.

1.1.1 Study Process

The study was performed in two phases (**Figure 1-1**). In the first phase, terrestrial fuel forms were surveyed, and the state of the art for coated particle fuel fabrication and existing performance databases was identified through literature review and expert interviews. Additionally, fabrication process extensibility was assessed to identify coated particle fuel derivatives based upon possible material variants or geometric modifications. The second phase of the study focused on the fuel assessment. For each system, at least one terrestrial coated particle derivative fuel form and one fuel form developed through historic space reactor programs were assessed to determine required technology development needs to support fuel qualification. Comparison of terrestrial coated particle and historic fuel derivatives allowed for relative risk to be assessed and common fuel development needs that are design independent to be identified for each system.

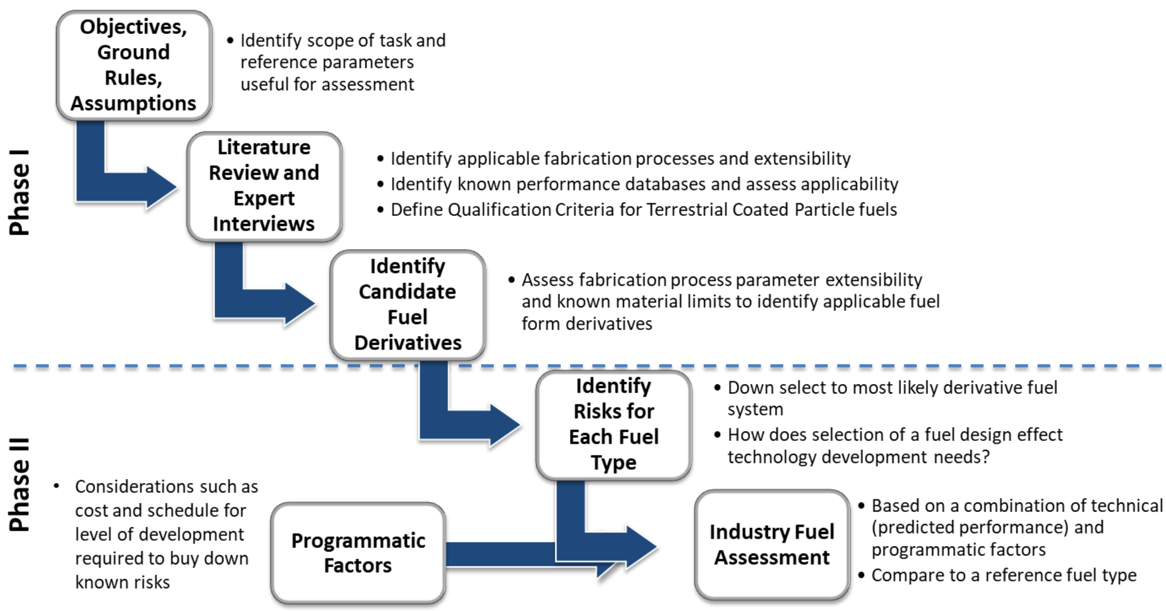


Figure 1-1 Assessment process used in this study

1.1.2 Study Constraints

To guide the assessment, a range of system performance parameters were provided by NASA technical discipline team (TDT) leadership (**Table 1.1**). These parameters are representative of the needs for space reactor systems currently under development by NASA. These parameters were used to guide decision making related to the applicable fuel forms selected for the assessment and comparison of existing performance databases to expose knowledge gaps and risks.

Table 1.1 Reference System Parameters for Current Space Reactor Applications of Interest to NASA

Application	Reactor Power	Reactor Outlet Temperature	Reactor Coolant	Operational Duration
FSP	50 kWth	1200 K	Sodium (Na) Heat Pipes	10 years
NEP	10 MWth	1200 K	Lithium (Li) or Helium Xenon (HeXe)	5 years
NTP	500 MWth	2700 K	Hydrogen (H_2)	10 hours

In addition to the reference system parameters, the following definitions and assumptions related to fuel development were imposed to ensure consistency throughout the assessment:

Terrestrial Fuel Forms – Terrestrial fuel types include all solid and molten fuel types currently in use or under development for terrestrial power reactor applications. Terrestrial fuels include coated particle fuels, metallic fuels, conventional ceramic fuels, and molten salt fuel forms. State of the art for qualified terrestrial fuel forms and advanced high temperature fuel forms currently under development identified. Coated particle fuel types were emphasized for the assessment at the request of TDT leadership.

HALEU Fuel Enrichment – All fuel types surveyed in the assessment were assumed to be limited to a high assay low enriched uranium (HALEU) enrichment (< 20% Uranium-235). For fuel forms originally developed for high enriched uranium (HEU) applications, required modifications to allow for HALEU enrichment to be used were identified.

Development Timeline - Historic space and terrestrial fuel program reference project documentation will be identified and used to assess derivative fuel form development needs, cost, and schedule.

Regulatory Guidance for Demonstration - The Department of Energy (DOE) is assumed to be the regulating authority when assessing technology development needs for space reactor fuel forms (not Nuclear Regulatory Commission, NRC, commercial qualification). This approach does not require that fuels be fully qualified ahead of a test reactor demonstration and does not require the same reliability requirements for the space reactor fuel development program as those specified for terrestrial reactors.

Assessment of Readiness and Qualification – Derivative fuel qualification and / or readiness will be assessed against:

- **Operating conditions:** Temperature, working fluid, power density, spectrum, time at temperature / operating duration, burnup
- **Manufacture specifications:** fuel specification of qualified material (includes all material compositions and subcomponent geometries)
- **Reactor configuration specific needs:** component compatibility, interelement effects, power conversion interface, reactor operations

2.0 Background and Literature Review

2.1 Background

2.1.1 Overview of Ongoing Advanced Terrestrial Reactor Development Activities

A recent survey of advanced reactor developers reveals over thirty 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.

Ongoing DOE Advanced Reactor Demonstration and Department of Defense (DOD) Pele programs are developing tailored versions of metal, oxide, and TRISO (TRIstructural-ISOtropic) fuels [10, 11]. All fuels have significant heritage from earlier fuels programs. Advanced fuel pellet and reactor structure designs will be utilized in the concepts being considered. The DOE and DOD programs are expected to require a new fuel fabrication line to support future reactor demonstration activities.

In **Table 2.1**, the advanced reactor designs are 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. In addition to specifying the fuel type corresponding to each reactor, other reactor design parameters are also included to identify possible synergies that could be leveraged for space reactor technologies. The nuclear fuel types are:

- **Uranium Oxide** - The leading advanced reactor designs would employ uranium dioxide (UO_2) fuel commonly used in conventional LEU light water reactors (LWRs) and facilities. New facilities are likely to be needed if reactor designs depend on HALEU fuel [12].
- **Uranium Carbide** – Some interest is being generated in carbide fuel development because of carbide fuels (uranium monocarbide, UC, or uranium dicarbide, UC_2) being a candidate for nuclear thermal propulsion reactor designs. There has been some effort to reestablish a graphite-matrix fuel production capability in the US to support the Transient Reactor Test Facility (TREAT) refueling and development of other test reactors [18].
- **Uranium Nitride** - Uranium nitride (UN) 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 (N) that is isotopically enriched in ^{15}N because ^{14}N has a high neutron capture cross section [20]. There are several approaches that have been explored in terms of fabricating both pelletized fuels and fuel particles.
- **TRISO Particle Fuel** - Designs using uranium oxycarbide (UCO) and UN kernels are envisioned, with UCO having a higher technology readiness level (TRL) but lower fissile density than UN. Commercial efforts are currently underway by BWX Technologies and X-energy to establish TRISO coated particle fuel fabrication lines [15, 16]. Ultra Safe Nuclear Corporation is also working on establishing a coated particle fuel production capability [17].
- **Uranium Metal** - A DOE-sponsored, pilot-scale fuel manufacturing plant to support deployment of advanced metal-fueled reactors will likely be needed. Y-12 facilities could also be used to develop advanced metal fuels. Fuels are either binary (uranium-zirconium,

U-Zr) or Ternary (uranium-plutonium-zirconium, U-Pu-Zr). New HALEU facilities customized to fabricate a specific fuel design may initially be too costly and detract from design, testing, and licensing a new advanced reactor design. Significant research and development efforts have also been made in fabrication and irradiation of uranium molybdenum alloy fuels (UMo) and Reduced Enrichment for Research and Test Reactor (RERTR) program fuels [13, 14]. While these fuels are capable of operating at high power densities, current fuels being developed are limited to low operating temperatures (< 500 °C, 773 K) and experience fuel swelling at moderate burnups. Therefore, these fuel types were not considered in this study.

- **Hydride Fuel** - Originally developed in support of the Systems for Nuclear Auxiliary Power (SNAP) and Training, Research, Isotopes, General Atomics (TRIGA) applications, hydride fuels are composed of a uranium zirconium hydride $(U,Zr)H_x$ and are a high readiness fuel form. These fuels are readily produced at the production scale and have a well-established operating database for existing TRIGA reactors. While these fuels are well understood, current fuels under production are limited to low operating temperatures (< 700 °C, 973 K) and short lifetimes (up to 1 year at peak temperature). Fuel lifetime is limited by high temperature instability of the hydride which leads to hydrogen loss and decomposition at high temperatures. Therefore, these fuel types not considered in this study.
- **Molten Fluoride Salts** - Use of a DOE-sponsored pilot-scale fuel manufacturing plant to support deployment of advanced fluoride salt reactors would be needed. The specialized radiological analytical laboratory capabilities—which are expensive to establish and require very uncommon skill sets—would be needed for a pilot-scale fuel development effort. 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 Salts** - Thermophysical properties associated with molten chloride uranium (U) and plutonium (Pu) 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 (Cl) has a lower moderating power than fluorine (F), and as a result a fast spectrum test capability will likely be needed in the future to facilitate testing [19]. A DOE-sponsored pilot-scale fuel manufacturing plant would be needed.

Key Finding: Fuel forms utilized in current advanced reactor designs will be developed to be capable of operating under similar conditions (operating temperatures, working fluids, duration) to space power reactors. Of the solid fuel options being developed, ceramic pellet (UO_2 and UN) and TRISO coated particle fuels correspond to reactor designs with the highest operating temperatures (≥ 600 °C, 873 K) and are assessed to be the best available terrestrial fuel options for high performance space reactors.

Table 2.1 Overview of Advanced Reactor Designs Currently under Development by Industry and U.S. Department of Energy Programs [21]

Reactor Names	Fuel Type	Operating Temperature (°C)	Fuel Composition	Reactor Coolant	Reactor Spectrum
ARC-100	Metal	470 (743 K)	U-10Zr Metal Alloy	Na	Fast
Bechtel, General Electric Hitachi, and TerraPower	Metal	500 (773 K)	U-20Pu-10Zr Metal Alloy	Na	Fast
Columbia Basin Consulting Group Lead Bismuth Fast Reactor	Metal	500 (773 K)	UO_2, U Metal	Lead Bismuth	Fast
General Electric Hitachi PRISM	Metal	500 (773 K)	U-Pu-Zr	Na	Fast
TerraPower Natium	Metal	500 (773 K)	U-Zr	Na	Fast
Small Modular Reactor (SMR)-160	Ceramic	315-500 (588 - 773 K)	UO_2	Water	Thermal
NuScale SMR	Ceramic	315 (588 K)	UO_2	Water	Thermal
Lead Fast Reactor Westinghouse	Ceramic	650 (923 K)	UO_2 or UN	Lead	Fast
General Atomics Energy Multiplier Module (EM^2)	Ceramic	850 (1023 K)	UC	Helium	Fast
eVinci Westinghouse	TRISO	600 (873 K)	UCO Kernel	Na Heat Pipes	Thermal
Hybrid Power Technologies	TRISO	650-850 (923 – 1023 K)	UCO Kernel	Helium	Thermal
HolosGen	TRISO	650-850 (923 – 1023 K)	UO_2 UCO Kernel	Helium	Thermal
Hybrid Power Technologies	TRISO	650 (923 K)	UCO Kernel	Fluoride Salt	Thermal
X-Energy (XE-100)	TRISO	650 (923 K)	UCO Kernel	Helium	Thermal
FLiBe Energy	F Salt	650-700 (923 – 973 K)	$2LiF_2$-BeF_2-$(^{233}U)F_4$	Fluoride Salt	Thermal
Molten Chloride Salt Fast Reactor	Cl Salt	660 (933 K)	U Pu Na K Cl	Chloride Salt	Fast
Versatile Test Reactor	Metal	350 – 500 (623 – 773 K)	U-Zr and U-Pu-Zr alloys	Sodium	Fast
Microreactor Applications Research, Validation & EvaLuation (MARVEL)	Hydride	500-550 (773 - 823 K)	$UZrH_x$	Sodium Potassium (NaK)	Thermal
Transformational Challenge Reactor (TCR)	TRISO	330 – 500 (603 – 773 K)	UN kernel TRISO in silicon carbide (SiC) matrix	Helium	Thermal

2.1.2 Terrestrial Fuel Qualification Objectives

One of the major prerequisites to the implementation of new reactor technologies is the demonstration of fuel technologies which satisfy fuel qualification requirements. Fuel qualification has been defined as "a process which provides high confidence that physical and chemical behavior of fuel is sufficiently understood so that it can be adequately modeled for both normal and accident conditions, reflecting the role of the fuel design in the overall safety of the [reactor design]. Uncertainties are understood such that any calculated fission product releases include appropriate margin to ensure conservative calculation of radiological dose consequences" [22]. Successful completion of the fuel qualification program establishes the data needed to assure decision makers that reactor operations with a given fuel type will allow safety and performance requirements to be met. Therefore, the fuel qualification process in many cases has become synonymous with fuel technology maturation, whereby the end of fuel qualification indicates a high readiness and confidence in the developed fuel form.

Fuel qualification is fuel design and application specific. For example, a fuel form qualified for NEP applications is not qualified for and does not possess high readiness for use in NTP systems. Use of a fuel qualified for terrestrial applications in a space reactor does not necessarily ensure the fuel is ready for space reactor operations. The objectives of fuel qualification for advanced reactor development programs are defined in NUREG-2246, "Fuel Qualification for Advanced Reactors" [23]:

- Demonstrate process to reliably fabricate a fuel product in accordance with a specification
- Demonstrate fuel performance and ability to meet reliability needs or licensing safety-requirements through analysis and testing

Therefore, on the pathway to qualifying a fuel form, fuel technology development relies on three major activities: fabrication, testing, and modeling and simulation (M&S) [23, 24, 25, 26]. It is expected that a space reactor fuel qualification program will also span these elements.

Key Finding: Unlike terrestrial reactors, where consequences of reactor failure may cause considerable risk to the surrounding public, personnel, environment and facilities, space reactor failure during planetary or deep space operation poses the primary risk of mission failure. Therefore, ***fuel qualification for space reactors should center around ensuring reliable and predictable performance to ensure mission objectives are met***, rather than defining reliability needs primarily upon ensuring low radiological dose consequence. *Note:* space reactor fuel failure during ground testing or any planned low earth orbit operations, such as initial startup of a NTP engine, will pose some consequence to public, personnel, environment and facilities which must be addressed during the fuel development and qualification effort.

2.2 State of the Art: Coated Particle Fuel Forms

Significant international research has been performed on coated particle fuel development by the U.S., Germany, England, Japan, France, Russia, South Africa, the Republic of Korea, and China. Notably, many coated particle variants have been developed to the maturity desired for terrestrial reactor deployment with significant testing operations of coated particle-based demonstration reactors and prototype plants (**Table 2.2**) within the U.S., Germany, and England [27, 28, 29, 30, 31, 32, 33]. This historic development has been superseded in recent years with concerted efforts to develop standardized, highly reliable, and higher performing fuel forms for a variety of advanced reactor applications.

Table 2.2 Summary of terrestrial coated particle based fueled reactor demonstration and operations

Reactor	Country	Fuel Description	Operating Temperature (°C)	Power Density (W/cm^3)	Working Fluid
Dragon	England	BISO in graphite matrix in a prismatic graphite block	> 750, 1023 K	24	Helium
AVR	Germany	BISO and TRISO in graphite pebbles	< 850, 1123 K	6	Helium
Peach Bottom I	U.S.	BISO and TRISO containing graphite matrix fuel pins in graphite pins	< 850, 1123 K	8.3	Helium
Fort Saint Vrain	U.S.	TRISO containing graphite matrix fuel pins in a prismatic graphite block	< 800, 1073 K	6.3	Helium
Thorium High Temperature Reactor	Germany	TRISO in graphite pebbles	< 800, 1073 K	6	Helium
High Temperature Engineering Test Reactor (HTTR)	Japan	TRISO containing graphite matrix fuel pins in a prismatic graphite block	> 850, 1123 K	6.6	Helium
High Temperature Reactor- Pebble Bed Modular (HTR-PM)	China	6 cm diameter graphite matrix fuel spheres with 8.9% enriched TRISO	> 750, 1023 K	6.6	Helium

Current coated particle fuel development programs have primarily focused on preparing a specific fuel particle architecture, BISO (Buffer-ISOtropic or BIstructural-ISOtropic) and TRISO, for commercial advanced high temperature reactor applications [34]. Some notable recent TRISO fuel achievements include the construction and critical operations of the HTR-PM in 2021. This reactor is an advanced high temperature gas reactor (HTGR) design based on coated particles containing fuel pebbles and a gaseous working fluid [35]. Another recent achievement is the completion of irradiation testing under U.S. Advanced Gas Reactor (AGR) fuel qualification program (2002 – present). In addition to ongoing qualification programs, some research initiatives have aimed to develop coated particle fuel form variants capable of higher uranium loadings and / or burnups with variations of the TRISO fuel design as well as higher operating temperatures through the development of alternative coating materials such as zirconium carbide (ZrC) and titanium nitride (TiN) [36, 37]. The following sections summarize coated particle types investigated through past terrestrial reactor development programs (Section 2.2.1), the current AGR TRISO program (Section 2.2.2), as well as historic space reactor programs (Section 2.2.3).

2.2.1 Past Terrestrial Coated Particle Fuel Form Development Overview

Coated particle fuels have a long and successful development history dating back to the 1950s. Coated particle-based fuel forms originated during the development of high temperature fuel forms for specialty applications, such as NTP [37, 38, 27]. In historic fabrication development activities, UC_2 was identified as a fuel form candidate for high temperature reactors due to its high theoretical melting point (~2700 K) [39]. The primary focus of initial coated particle fuel development activities was for HTGR applications which utilized a graphite-based matrix fuel element with dispersed high melting temperature, ceramic uranium particles in a pebble or prismatic element geometry. For these applications, a pyrolytic carbon (PyC) coating was deposited on UC_2 kernels to protect kernels from oxidation between fabrication process steps as well as enable a more favorable interface during net-shape fuel element sintering processes. It was recognized that particle coatings had the potential to enhance fuel performance and robustness under a variety of operating conditions, especially for high temperatures. During these initial coated particle fuel development efforts (**Figure 2-1**), fuel particles typically were designed to include a high melting temperature ceramic U-compound kernel (UO_2, UCO, and UC_2 were common variants) with multiple ceramic coatings for improved fission gas retention.

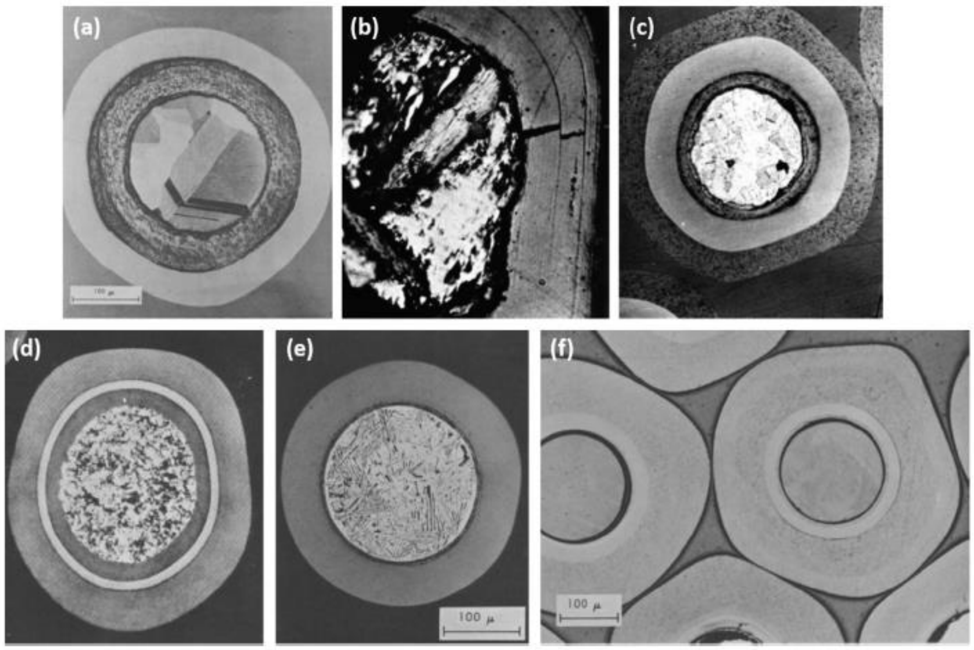


Figure 2-1 Historic coated particle fuel variants (figures and descriptions from: [29])

(a) Early example of a BISO particle. (b) Particles with "laminated" pyrocarbon layer structure demonstrating arresting of crack propagation at the lamination interfaces. (c) Particle with "Triplex" structure (porous buffer layer followed by laminar and columnar pyrocarbon layers). (d) Fertile $(Th,U)C_2$ particle used in Dragon first charge, consisting of PyC-SiC-PyC structure. (e) Carbide particle with single PyC coating layer [from] Peach Bottom first core. (f) "Duplex" $(Th,U)C_2$ particle [from] AVR first core load.

To date, most coated particle designs could be classified as either or TRISO fuel particles which are differentiated by the coating structure surrounding the fuel kernel. In BISO designs, a low and high density PyC coating is applied to the fuel kernel. The inner low density PyC layer was shown to act as a sacrificial layer between the kernel and high density outer PyC coating resulting in improved coated particle performance compared to coated particles with a single high density PyC coating. Later TRISO designs employed a more complex coating structure to further improve fission product retention. For TRISO coated particles, a low density PyC coating is first applied to the kernel, followed by a high density PyC, a SiC coating, and a final high density PyC coating as the outermost coating. For the standard TRISO coating architecture, the first coating is a low-density PyC buffer layer (50% dense) which functions to accommodate fission gas release and fission product recoils, as well as acts as a sacrificial layer to minimize crack propagation or intraparticle stresses. The second coating, the inner pyrolytic carbon (iPyC) layer, is a fully dense coating which serves as a diffusion barrier to fission products and protects kernel from corrosive interaction during SiC coating layer deposition. A dense SiC layer (~35 µm) is deposited on the iPyC to function as the primary fission gas containment layer and main structural coating. The last layer, outer pyrolytic carbide (OPyC), is a fully dense PyC coating which serves as a protective layer during the net shape fuel element fabrication process and final fission product diffusion barrier.

As shown in **Table 2.2**, BISO and TRISO coated particles were developed for reactor operating temperatures up to 850 °C (1123 K). At very high operating temperatures, standard TRISO and BISO performance is limited for terrestrial applications due to reactivity of the fuel kernel and coating layers and high mobility of some fission products at high temperatures, which ultimately results in higher fission product release from the coated particles. To enable higher operating temperatures, there has been research on higher performance TRISO coated particle designs. These designs replace the SiC coating layer of the TRISO with ZrC to allow for higher temperature operation with reduced fission product release and coating failures (**Table 2.3**).

Table 2.3 Summary of terrestrial coated-particle variants developed in support of high temperature and high burnup reactor applications [36]

Program (Country)	Peak Fuel Temperature	Kernel Compositions	Coating Architecture	Matrix Material	Form
HTTR (Japan)	1173 - 1923 K	UO_2	TRISO with ZrC	Graphite	Pellet
Deep Burn (US)	1353 - 1523 K	UCO, UO_2, UC_2	TRISO with ZrC	Graphite	Pellet

2.2.2 Advanced Gas Reactor Fuel Development Overview

The AGR program has been the primary fuel qualification program for modern U.S. TRISO fuels [34]. Under AGR, a fuel qualification program was pursued with the initial intent to develop a specific TRISO fuel form variant, a UCO TRISO particle in a cylindrical graphite matrix pellet compact, for prismatic HTGR applications. Since the onset of the AGR program, many new reactor applications have been envisioned with substantial supporting research and development efforts dedicated to demonstrating the extensibility of fabrication, modeling and simulation, and testing techniques to other coated particle fuel form variants (Table 2.4, Figure 2-2). However, for the focus of this report, the term AGR TRISO will refer to the standard fuel form variant which has received the focus of the AGR fuel qualification effort.

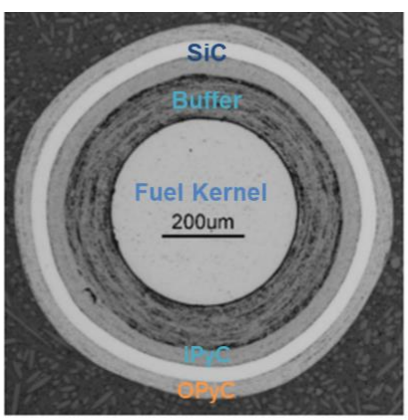
Cylindrical AGR Compacts | Pebble Fuel Form | Custom TCR Fuel Form

Figure 2-2 Example TRISO based fuel forms developed under the AGR or complimentary DOE advanced reactor / fuel development programs [40, 41, 42]

Table 2.4 Summary of TRISO Fuel Form Variations Explored through Modern U.S. Development Efforts (2010 – Present, table adapted from: [39]).

Standard AGR Fuel Form Attributes					
Kernel Compositions	**Kernel Diameter**	**Coating Architecture**	**Matrix Material**	**Form**	**Working Fluid**
UCO	425 µm	AGR TRISO	Graphite	AGR pellet compact	Helium
Other AGR TRISO-based fuel form variants include some combination of the following attributes					
Kernel Compositions	**Kernel Diameter**	**Coating Architecture**	**Matrix Material**	**Form**	**Working Fluid**
UCO UO_2 UN	425 µm 500 µm 800 µm other	AGR TRISO “Modified” TRISO	Graphite Silicon Carbide	AGR pellet compact “Standard” 6 cm pebble Modified pellet compacts (alternate size and particle volume loadings) Modified pebble (alternate size and particle volume loadings) Custom	Helium FLiBe (Lithium Fluoride-Berylium Fluoride)

The standard AGR coated particle architecture is composed of a ~425 µm low enriched uranium (LEU) UCO kernel surrounded by four coating layers [40]. The design of these layers was based on the UO_2 TRISO fuel form (Figure 2-3) demonstrated through a German development program which had excellent demonstrated performance and reliability. For the standard TRISO coating architecture, the first coating is a low-density PyC buffer layer (50% dense, 100 µm), followed by a fully dense ~40 µm thick iPyC layer, the third layer is a SiC coating (~35 µm), and the outer coating is a fully dense ~35 µm OPyC coating. Under AGR, the final net shape fuel form is a graphite matrix pellet compact (12.3 mm diameter, 25 mm length) with 25 – 40% volume fraction of coated fuel particles capable of loading into prismatic graphite blocks for HTGR applications.



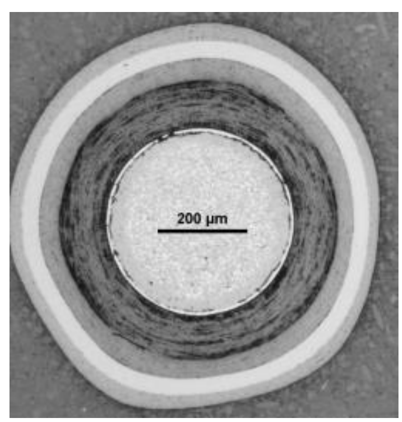


Figure 2-3 Example TRISO microstructures (left) UO_2 TRISO fuel particle with all functional coatings (right) example UCO TRISO fuel particle developed under AGR [40].

Through the AGR fuel qualification program, the AGR TRISO fuel form was developed and demonstrated under conditions relevant to HTGRs to support eventual reactor licensing. An overview of AGR fuel qualification activities is described in this section to highlight activities that are expected when qualifying a fuel for terrestrial applications. Fuel performance goals under AGR were to demonstrate a coated particle fuel form capable of operation under a peak burnup of 20% fissions per initial metal atoms (FIMA) and temperatures of 1250 °C (1523 K). Demonstrating desired reliability (measured by fission product release fraction) is a key goal for the development of this fuel form in order to demonstrate that the fuel design serves as a fission product containment mechanism. Since the start of the program in 2002, fuel development has spanned over 20 years and $367 million total investment and is planned to meet program objectives by the program's anticipated end date in 2024 [43].

Key Finding: The reference performance goals of the standard AGR fuel design guided the selection of fabrication and testing parameters for all demonstration activities. ***Therefore, modifications of the TRISO, including all non-standard variants identified in Table 2.4, would not be considered a qualified fuel form as a part of the AGR effort.*** Additionally, if it is proposed to operate AGR TRISO fuel form outside of the demonstrated operational regime through the AGR fuel qualification program (i.e., higher temperatures, burnups, fluences, etc.), these operations would also not be considered to be qualified through this program.

2.2.2.1 AGR Fuel Fabrication Process Overview

AGR fuel qualification fabrication and testing activities were supported by the DOE, academia, and reactor industry. Fabrication activities focused on the demonstration of AGR fuel particle and net-shape fuel compact fabrication techniques (including quality control methods) at the laboratory scale, up to 1 kg quantity batch sizes with an equivalent throughput rate on the order of 10 kg/year (multiple pins/year), and pilot scale (engineering scale), 1–10 kg quantity batch sizes with an equivalent throughput rate on the order of 100 kg/year (a few assemblies/year). This activity was important to demonstrate that fabrication techniques developed by the national laboratories can be reproduced at a scale relevant to future commercial applications. Fabrication activities were demonstrated using both national laboratory and industry facilities [40, 44, 34]. As shown in **Figure 2-4**, the AGR fuel fabrication process is a multi-step process which may be tailored to customize the final fuel design for its intended application [45]. In Appendix A, each process step is described, demonstrated fabrication limits are identified, and the extensibility of the process to fabricate alternate material systems is assessed.

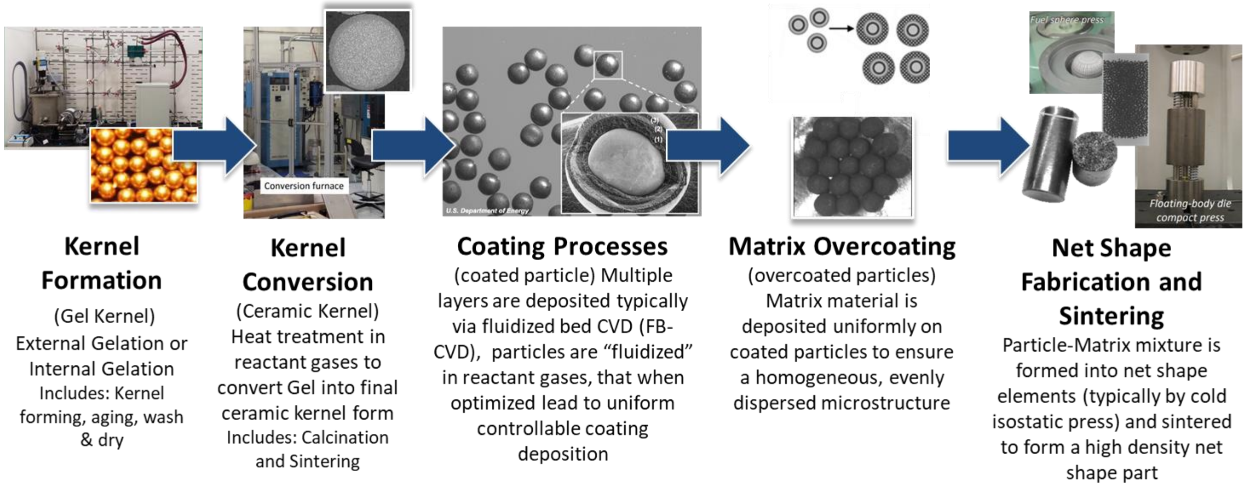


Figure 2-4 Overview of fabrication process steps in the fabrication of coated particle-based fuel forms [29, 42, 47, 48]

Key Finding: Under AGR, TRISO fuel fabrication has been demonstrated at the pilot scale and a fuel fabrication specification has been established. The fabrication processes demonstrated through AGR are extensible to other coated particle fuel variants and existing fabrication infrastructure can be used to produce alternative coated particle-based fuel forms.

Changes to particle design, such as changes to kernel size or material selection, coating thicknesses and material selection will result in a change of fabrication process parameters. ***Change in fabrication process parameters can impact the quality of the materials produced and the overall microstructure which can result in significant changes to fuel performance under operating conditions***.

2.2.2.2 AGR Fuel Performance and Testing Overview

AGR testing activities focused on demonstration of as-fabricated particles under critical operation parameters relevant to the intended reactor application. Testing pursued under this program included high temperature irradiations under relevant environments (power density, spectrum, fluence), high temperature fission product transport experiments, and high temperature post-irradiation safety testing. Irradiation testing activities were performed in 7 major campaigns (referred to as AGR-#) as shown in **Figure 2-5**. Each campaign consisted of pre-test fabrication and characterization activities, testing operations, and post-test post irradiation examination (PIE) activities. Irradiation testing goals aimed to demonstrate acceptable performance of the as-fabricated AGR fuel particles under the target conditions (AGR-1/2) and characterize fission product transport under normal and possible failure conditions (AGR-3/4). The final irradiation campaigns supported the qualification testing of engineering scale fuel compacts under relevant conditions (AGR-5/6/7). Post irradiation testing was performed on AGR-3/4 test articles to understand fission product release due to transient high temperature operations that could occur during loss of coolant or reactivity insertion accidents.

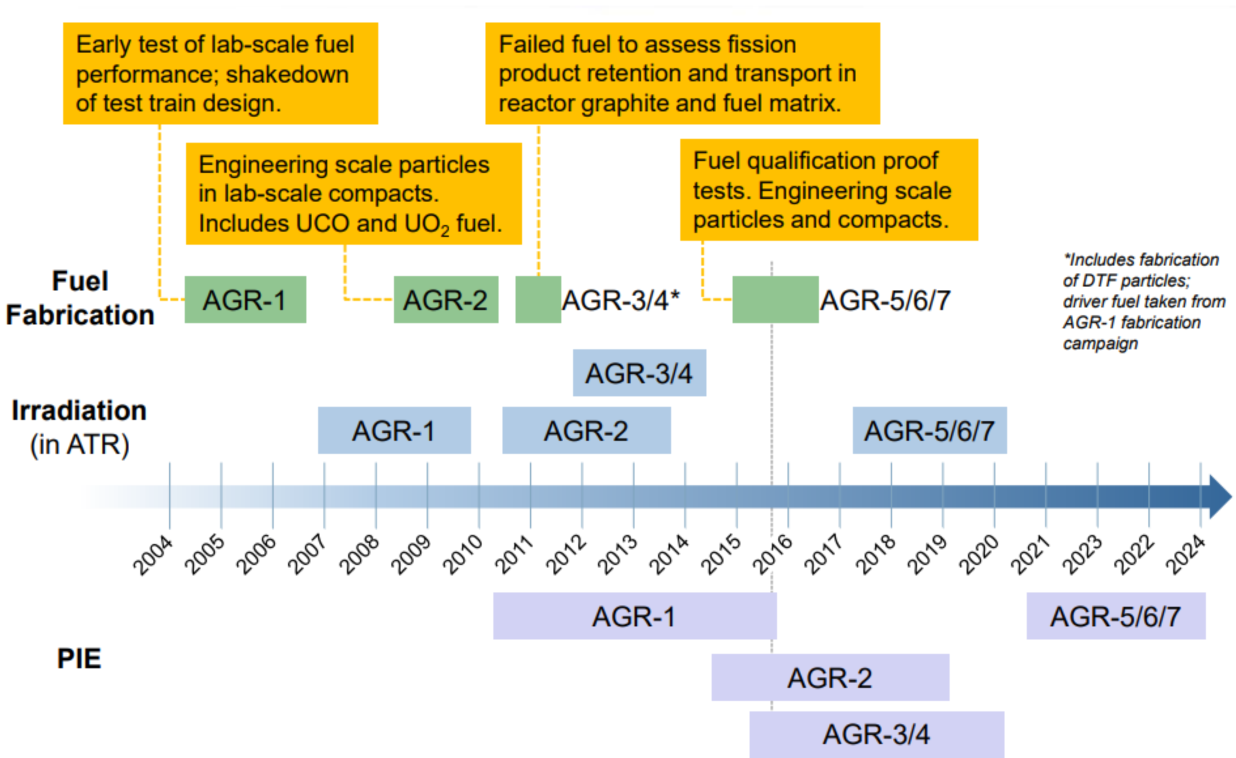


Figure 2-5 Overview of the Advanced Gas Reactor Fuel Qualification Scope and Timeline [34]

To date, all AGR irradiation testing have been completed and PIE activities of AGR5/6/7 test articles are ongoing (planned completion 2024). Over its 20-year duration, the AGR fuel qualification program will have tested 194 fuel compacts (~570,000 particles) up to peak irradiation temperatures of 1500 °C (1773 K) and peak burn up of ~15.3% FIMA (5.55×10^{25} n/m^2) [46]. Out of pile safety testing at 1600 and 1800 °C (1873 and 2073 K) for 300 hours has also been completed on AGR 1 fuel particles [47].

Key Finding: The key parameters which govern fuel performance are irradiation temperature, power density, and burnup. The AGR TRISO fuel form has been demonstrated over a range of these parameters that meets the needs for space power reactor applications. The AGR TRISO has not been demonstrated meet the high temperature performance requirements for NTP.

Fuel form reliability goals drive the required amount of fabrication and testing activities to generate the test data for verification of reliability criteria. A program must plan for enough time and funding to gain the necessary test data to meet the reliability criteria. Increased reliability requirements will increase cost and schedule for fuel development.

Throughout the AGR fuel qualification program, M&S method development (fuel performance models) has also been pursued. These models incorporate testing results for better predictive capability of fuel performance under operating conditions demonstrated during the AGR program. Post irradiation examination and testing of AGR particles is still ongoing and conclusive lessons learned are still being collected. Through these efforts, the AGR TRISO is the most mature U.S. coated particle fuel technology with well documented performance and fabrication processes [48, 49, 50, 51, 52, 53, 54].

2.2.3 Space Reactor Coated Particle Fuel Development Overview

Coated particle fuel development is not limited to terrestrial reactor programs, research and development has also been invested in coated particle fuels in space reactor development programs. U.S. NTP development programs have focused a significant portion of past fuel development on coated particle-based fuels [38, 55, 56, 57]. Coated particle fuels have also been surveyed for past NEP reactor programs, however coated particle fuel development efforts are much more limited [55, 58, 59]. Coated particle fuel development in support of historic space reactor programs is summarized in **Table 2.5**. For NTP applications, coated particle-based fuel forms can be largely grouped into three categories: graphite matrix, ceramic metallic (cermet), and particle fuels. For NEP applications, cermet and modified TRISO fuels have been considered to meet the relatively high operating temperature and long operating duration requirements, but limited investment has been pursued in the development of such fuel forms. All historic programs baselined a HEU enrichment which influenced particle design.

Table 2.5 Overview of Coated Particle Based Fuel Types Developed through Historic NTP Programs

Historic Program	Program Duration	Fuel Type	Fuel Description	Application	Notable Achievements
NERVA / Rover	1955 - 1973	Cercer	UC_2 kernel with a PyC coating in a graphite matrix	NTP	Fuels demonstrated through NTP ground test reactor operations
Argonne National Laboratory (ANL) Nuclear Rocket Program	1962 - 1968	Cermet	UO_2 with a tungsten (W) coating in a W matrix	NTP	Hot hydrogen testing and transient irradiation testing performed
General Electric (GE)-710	1963 - 1966	Cermet	UO_2 with a W coating in a W matrix, molybdenum (Mo) matrices and UN particles also evaluated	NTP / NEP	Hot hydrogen testing and in-pile irradiation of fuels (under low temperature conditions)
Space Nuclear Thermal Propulsion (SNTP)	1987 - 1994	Particle	UC_2 kernel with PyC and ZrC coatings	NTP	Hot hydrogen testing and in-pile irradiation of fuels (under reduced power density conditions)

2.2.3.1 NERVA / Rover Fuel Development Summary

The primary NERVA / Rover fuel form was composed of a structural graphite fuel matrix with dispersed coated fuel particles and ZrC protective surface coatings [38, 60]. Due to the incompatibility of the matrix and hydrogen propellant, the ZrC protective coatings were a major technology development challenge. The coated particle consisted of a 50 – 100 µm UC_2 kernel with a PyC coating (~25 µm). The UC_2 kernel was selected due to its compatibility with the graphite matrix and a PyC coating was applied to prevent UC_2 oxidation during handling of fuel particles and protection of the kernel during the fabrication process. Throughout the program, extensive fuel development and optimization was pursued [38, 60, 61]. Different variants of this fuel type were tested in nearly 20 test reactors up to 60 minutes in duration at steady state and peak fuel temperatures exceeding 2500 K. Fuels were demonstrated through NTP test reactor operations and subjected to different development tests including hot hydrogen and thermal stress testing. To support reactor testing, production scale fuel lines were established at both government and industry facilities and a quality assurance program was developed. As a result of the overall development effort, several fuel types and production scale fabrication process lines were demonstrated. In addition, complete material property, prototypic fuel performance, and reactor operations databases were established.

The phenomena governing fuel performance were identified to be structural failure and cracking, hot hydrogen corrosion, and high temperature fuel kernel migration. Significant progress was made over the program to optimize the core structural design and at the end of the program, fuel elements were capable of operating at temperatures up to 2573 K but limited to 1 hour duration due to unacceptable hot hydrogen corrosion [61]. With improved protective coatings, the upper operating temperature limit would be governed by fuel kernel migration, with the goal to retain fuel kernels within the PyC coatings in order to prevent loss of reactivity during operation. The largest remaining challenges for high performance NERVA / Rover fuel development include protective coating technology development to improve hydrogen corrosion resistance and demonstration of high temperature operations (> 2500 K) with acceptable kernel migration behavior.

2.2.3.2 Cermet Fuel Development Summary

Cermet fuels offered an alternative fuel design approach to NERVA / Rover for NTP applications. With the use of a hydrogen compatible, refractory metal matrix (tungsten, W, or molybdenum, Mo), fuel design was no longer limited by hydrogen corrosion. Typical fuel designs developed under historic cermet development programs were W-matrix cermets with dispersed ~100 - 200 µm UO_2 or UN fuel particles (~60 vol%) coated with a thin W coating (~10 µm) which were formed into extruded hexagonal elements with internal coolant channels [65, 55, 56]. Fuel elements were cladded in various refractory metal alloys, such as niobium (Nb), tantalum (Ta), W, Mo, and rhenium (Re) containing alloys, to minimize direct exposure of fuel particles to the flowing hydrogen propellant. The primary disadvantage of cermet fuel designs are the high thermal absorption cross sections of most refractory metals (especially W) and thermodynamic instability of UO_2 and UN. UO_2 reduces at high temperatures (> 1673 K), forming substoichiometric UO_{2-x}. Upon cooling, free U can form as UO_{2-x} and reverts back to UO_2 [64]. UN can completely decompose into free U and N at high temperatures without the presence of an over pressure [60].

Both the ANL nuclear thermal rocket (1962 – 1968) and GE-710 gas reactor (1963 – 1966) programs were limited in scope compared to NERVA / Rover. No ground test reactor demonstrations were performed. However, the development programs did allow for full scale, net-shape fuel element fabrication processes to be established (laboratory fabrication line), extensive hot hydrogen testing, and material property measurements. The GE-710 program also performed limited irradiation testing at temperatures up to 1727 °C (2000 K) and burnups of 1.6 atom%, which would be representative of a high-performance NEP gas reactor [55]. The ANL program performed transient irradiation testing in TREAT to test fuel robustness under conditions representative of the NTP startup (up to 16000 K/s, ~2900 K peak fuel temperature) [56].

The primary phenomena governing cermet performance were identified to be structural failure and cracking of the fuel due to thermal stresses and fission product damage (for high burnups, after > 4000 hours at ≥ 1870 K) as well as thermodynamic instability of the fuel kernel (UO_2 or UN) which lead to uranium loss and / or fuel corrosion. Significant progress was made testing fuel coupons in a hot hydrogen environment. Cermets were demonstrated up to 45 hours and 180 cycles at 2770 K, with negligible fuel loss and a hot hydrogen database was gathered for temperatures up to 3120 K. Despite this progress, without prototypic irradiation testing (irradiation under operating temperature and power density range) completed, performance limits could not be established [65]. The primary challenge for cermet fuel development is to re-establish the hot hydrogen database (NTP) and develop an irradiation database with current fuel forms over the range of operating durations and use temperatures (NTP or NEP).

Key Finding: To determine fuel design limits, testing of fuels under a combined nuclear and nonnuclear environment is recommended. ***Past programs revealed failure modes which limited fuel operation to conditions less than theoretical limits during irradiation and reactor operations testing.***

2.2.3.3 SNTP Fuel Development Summary

The final program which developed coated particle fuel forms developed for space applications is the space nuclear thermal propulsion (SNTP) program [57]. SNTP developed coated particle fuel forms for a particle bed reactor, whereby the fuel form was the particles themselves, not formed into an element with a matrix. The baseline fuel particle was composed of a 220 µm UC or UC_2 kernel with a buffer and inner PyC coating, surrounded by a final ZrC protective coating (400 µm outer diameter) [63, 66]. Over its short duration (1987-1994), the SNTP development program quickly matured the particle fuel form. Over 200,000 fuel particles were manufactured throughout the program duration and tested under hot hydrogen and in-pile high temperature irradiation conditions (non-prototypic power density, ~1 MW/L) [72]. Irradiation testing led to the discovery of fuel failure modes which limited operating temperature to much lower than that needed to meet program goals (2500 K) [63, 57].

The primary phenomena governing SNTP fuel particle failure was identified to be attack of the particle coating layers by the fuel kernel (UC_2) when operated above its melting point. Failure of the outer coating leads to loss of the fissile fuel material. To improve performance of this fuel type, technology development would be needed for a new fuel kernel type capable of higher temperature operations. During SNTP, alternative, higher performance fuels were identified based upon infiltrated kernel, mixed carbide, and interstitial dispersoid kernel variants [63]. Some fabrication studies were performed to demonstrate the feasibility of these fuel types, but no further testing has been publicly reported for alternative fuel forms.

Key Finding: From the SNTP program, the reported state of the art for UC_2 coated particles is limited to a 2500 K peak operating temperature. ***Additional technology development is required to mature NTP fuel technologies to achieve higher operating temperatures.***

2.2.3.4 Other Proposed Coated Particle Designs for Space Applications

While past NEP and FSP reactor designs have primarily baselined pellet (UO_2 or UN), metallic (UMo), or hydride ($UZrH_x$) fuel forms, there have been some studies performed to identify the benefits of coated particle fuel technologies for power reactor applications [55, 58, 59]. Major findings of past programs on the use of coated particle fuels are:

- Coated particles may offer the following advantages for power reactor applications: restrained fuel swelling compared to pellet design, prevention of fuel and fission product migration, and prevention of fuel-coolant or fuel-cladding/liner interactions.
- Space reactors have diverging operating requirements from HTGRs, the key differences that impact fuel design are higher operating temperature, higher power density (reduced reactor mass), and neutron spectrum.
- The TRISO coated particle technology is considered to be a demonstrated ("off the shelf") technology for HTGRs. A drawback of the TRISO design is the very low uranium loading which increases reactor volume and mass. TRISO designs are attractive for use in moderated reactors which are not as dependent on high fuel loading.
- With TRISO geometry to contain burnup and swelling, burnup could be pushed to higher levels to extend operating duration. Modification of the TRISO would be needed to extend operating duration to burnups of up to ~8% fissions per initial metal atom. The modified TRISO should not be considered off the shelf; development and verification would be required.
- Cermet fuel elements have the following advantages: higher effective thermal conductivity compared to pellet fuels, superior fission gas retention capability, improved mechanical stability, and minimized fission recoil damage of cladding materials.
- Due to low uranium density and high parasitic neutron absorption by the cermet metal matrix, larger core sizes may be required. This design was only recommended for fast reactor systems.

Key Finding: ***Space reactor systems have similar operating conditions, but different design drivers than terrestrial HTGR systems.***

FSP and NEP designs require a higher uranium loading fuel form to minimize required critical volume to reduce overall reactor and shield mass. Desirable modifications of existing coated particles to increase uranium loading includes: increased particle volume loading, removal of coatings, reduced coating thicknesses, and increasing kernel diameter to increase volume fraction of fuel in the particle.

NTP designs require much higher operating temperatures and a fuel form capable of high-power densities (> 5 MW/L) and hydrogen compatibility. Desirable modifications to existing coated particle fuels for NTP applications include: a high melting temperature (> 2850 K) fuel kernel, hydrogen compatible coatings, coatings with low parasitic neutron absorption, and reduced coatings / coating thicknesses to improve uranium loading or effective thermal conductivity.

2.3 Literature Review Summary and Discussion

There are a variety of existing terrestrial fuel types proposed for use in ongoing advanced reactor development activities that could be adapted for space reactor applications. These fuel types include monolithic ceramic fuel forms (UO_2, UN, UC_x), coated particle fuel forms (TRISO), metallic fuels, and other fuel forms (hydride, molten salt, etc.). Each of these fuel types are being developed for different advanced reactor applications which span different fuel operating temperatures, burnups, working fluids, and other fuel interfaces (cladding). Since fuel maturation is design and application specific, current terrestrial fuel development programs will not develop fuel forms that are fully qualified to operate at the conditions that are needed for space reactor applications.

Key Finding: For this study, UO_2, UN, and TRISO based designs were the only fuel candidates capable of meeting the reference system operating temperatures for FSP and NEP applications (1200 K, corresponds to ~1400 K maximum fuel temperature). Metallic (UMo) and hydride ($UZrH_x$) fuels would be alternative fuel candidates for lower operating temperature FSP systems (fuel temperatures of less than 1075 and 975 K respectively). Both metallic and hydride fuels have a high manufacture readiness level and existing performance database.

Coated particle fuel development has also been pursued in historic space reactor programs. This development primarily was focused on NTP applications rather than power reactor applications. For NTP systems, UO_2, UN, and UC_2 based coated particles were developed for graphite matrix, cermet, and particle fuel types. NTP fuel endurance (fuel operating duration at temperature) was limited by compatibility with the hot hydrogen environment, thermal cycling, peak operating temperature, and required power density of the fuel form. For each of the NTP fuel types developed, fuels were not capable of operating up to theoretical temperature limits when exposed to the full range of environmental conditions and designers were not confident in fuel performance projections until fuel performance was demonstrated under prototypic conditions of combined power density, temperature, and hot hydrogen environments. Historic NTP fuel performance is not proven beyond ~2700 K and requires further maturation to demonstrate extensibility to higher temperatures. Historic power reactor programs never selected coated particle-based fuels as a primary fuel form, but some programs surveyed coated particle fuels for NEP applications. From these surveys, it was determined that the most promising NTP and terrestrial coated particle fuels variants were the AGR TRISO and cermet fuel concepts. These fuels would require additional technology development for a power reactor use case and would benefit from modification to allow for reduction in corresponding reactor critical geometry.

Key Finding: Historic space reactors required different performance and enrichment (HEU) requirements which impacted coated particle fuel design. HALEU enrichment will require modification of the fuel (to increase uranium loading) and / or reactor (to increase moderation) design***. Modifications to allow for reduced enrichment will require additional technology development and HALEU variants of historic fuels should not be considered already qualified for space reactor use.***

Of the terrestrial fuel forms being developed, coated particle fuels are excellent candidates for high temperature reactor applications. The existing fuel performance database for the AGR TRISO spans the temperature range and burnups desired for power reactor applications. Some data gaps may exist based upon the specific design requirements of either the FSP and NEP reactor (peak power density, fluence / burnup, working fluid compatibility or heat transfer interface). Fuel fabrication processes and infrastructure are also well established. A potential benefit of the TRISO design for power reactors is the ability to isolate fuel irradiation effects (swelling, fission gas release, fission product interactions) within the coated particle to minimize engineering complexity of fuel structural components such as the cladding/liner and fuel plenum. A significant disadvantage of the TRISO design for FSP and NEP applications is the low uranium density (0.369 g/cm^3 assuming 35 vol% AGR TRISO packing) compared to monolithic ceramic (pellet) fuel forms (UO_2, 3.65 g/cm^3; UN, 7.16 g/cm^3). From past trade studies [58, 59], use of TRISO based fuels for HEU NEP reactors has resulted in larger core sizes and the need to modify standard

TRISO particle designs to allow for higher uranium density (increased kernel size and / or particle volume fraction). These trends are also expected for current NEP and FSP reactors and use of HALEU enriched fuel may further drive the need for improved uranium density and incorporation of a moderator to reduce critical mass. Some initial development has been performed to fabricate and test large diameter (~800 µm) UN TRISO particles which could be sufficient to meet space reactor needs [67, 68, 69].

The most probable derivative fuel forms that would be proposed for FSP applications are the AGR TRISO or a modified AGR TRISO with higher fuel particle volume loadings and / or reduced outer coating thickness and a larger fuel kernel diameter to improve uranium density. For NEP applications, specific mass of the system is a larger design driver which would require a higher uranium density fuel kernel than the AGR TRISO. Therefore, modified large diameter UN TRISO fuel particles would be the most probable coated particle derivative fuel form. Both coated particle FSP and NEP reactors would benefit from moderation to enable a mass competitive system compared to other fuel variants. These modified TRISO options are not at an equivalent readiness to the standard AGR TRISO. Modification of the AGR TRISO design to meet unique needs for FSP and NEP reactors will require additional technology development to demonstrate required modifications to the fabrication process and perform testing to demonstrate that fuel performance is still well understood.

Terrestrial coated particle fuel forms are also extensible to NTP applications. The AGR TRISO fuel form is not capable of satisfying high temperature (>2700 K) NTP operating requirements. However, existing coated particle processes can enable a wide range of kernel types and coatings which can be used either to recapture historic NTP coated particle-based fuel forms or support the development of new, novel NTP fuel forms. Required modifications for NTP applications would include high temperature coating (such as ZrC) and kernel (such as UC_2, UN, etc.) designs. Additional modifications, such as removal of coatings, larger kernel diameters and higher fuel volume loadings may also be desired to improve uranium density of the fuel form.

For NTP fuel types, significant departure from current AGR TRISO design would be necessary. The most probable derivative fuel forms that would be proposed for NTP applications would be graphite or refractory carbide matrix fuel forms with UC_x or UN based BISO or modified TRISO fuel particles with ZrC coatings. These fuels would likely be used in a moderated HALEU NTP reactor to reduce critical mass and minimize required uranium density. Fuel technology development would be needed to demonstrate fabrication processes and develop a fuel performance database. To accelerate development, design strategies and lessons learned from past NTP fuel development programs could be leveraged. Predictive fuel performance modelling could also be used to accelerate the fuel qualification and demonstration campaign. Pre-existing coated particle fuel performance codes could be adapted for fuels being developed for space applications.

Key Finding: Based upon material limits and development status, the most probable coated particle fuel options that would be proposed for space applications are:

- **FSP** – AGR TRISO or modified AGR TRISO (increased kernel diameter, reduced coating thicknesses, increased particle loading) within a graphite matrix in a moderated reactor
- **NEP** – modified TRISO with a large diameter UN kernel, increased particle loading, and modified coating layers within a graphite or SiC matrix in a moderated reactor
- **NTP** – modified BISO with a UC_x or UN based kernel or modified TRISO with a ZrC coating and UC_x or UN based kernel within a graphite or ZrC matrix in a moderated reactor

While there exists an industrial base and pre-existing infrastructure for these coated particle fuel types, modified fuels will require additional technology development and should not be considered already qualified for space reactor use.

3.0 Fuel Assessment

The goal of this assessment was to evaluate terrestrial coated particle fuel derivatives for space nuclear power and propulsion systems. For each reactor system, the coated particle derivatives identified in Section 2.3 and a historic fuel derivative were assessed (**Table 3.1**). The comparative assessment allowed for common space reactor fuel development challenges to be identified as well as the benefits and limitations of coated particle-based fuel designs. The assessment included the following categories:

- **Performance and existing performance database:** SME qualitative assessment of the ability of the design to meet or exceed reference system parameters and comparison of required fuel operating conditions to the existing performance database
- **Technology gap assessment:** identification of technology gaps based upon gaps in the existing fuel performance database and technology development needs specific to the reference reactor system
- **Cost and schedule:** projected cost and schedule investment for fuel development before a reactor demonstration (TRL 6)

The following section describes the results of the assessment. A full description of the assessment methodology is included for reference in Appendix B. Appendices C – E include the complete documentation of the rationale behind each of the assessment scores.

Table 3.1 Selected Fuel Forms Assessed for Each Space Reactor Application

Application	Historic Fuel Derivative (Reference Program)	Coated Particle Fuel Derivative
FSP	**UO_2 Pellet** (2010 Fission Surface Power Project [70])	**AGR TRISO in Graphite** UCO kernel with PyC-SiC coatings
NEP	**UN Pellet** (SP-100 [71])	**Modified TRISO in Graphite** UN kernel with PyC-SiC coating
NTP	**Graphite Matrix with UC_2 Coated Particle** (Rover / NERVA [60])	**Ceramic Ceramic (Cercer) with Modified Coated Particle** ZrC matrix with dispersed UN kernels with PyC-ZrC coating

3.1 Fuel Assessment Summary and Findings

The results of the fuel assessment are shown in Table 3.2. The following sections describe the results and major findings of the assessment for each of the space reactor systems surveyed.

Table 3.2 Fuel Assessment Results and Summary

	FSP		NEP		NTP	
	UO_2 Pellet	**AGR TRISO**	**UN Pellet**	**Modified TRISO**	**Graphite Matrix with UC_2-PyC**	**Cercer with ZrC coated particle**
Performance	Fast and thermal reactors possible with HALEU	Moderated TRISO reactors may yield competitive mass	Fast and thermal reactors possible with HALEU	Epithermal and thermal reactors possible with HALEU	Operation above 2700 K requires molten kernel operation	Operating temperatures up to 3100 K proposed (UN theoretical T_M)
Existing Performance Database	Fully established separate effects testing data	AGR irradiation database exists for relevant temperature range and burnups	Fully established separate effects testing data	Limited test data exists (particle irradiation experiments)	Fully established separate effects testing data up to 2500 K	Limited test data exists (some fuel and surrogate non-nuclear testing)
Technology Gap Assessment	4 Technology Gaps Identified	6 Technology Gaps Identified	7 Technology Gaps Identified	8 Technology Gaps Identified	9 Technology Gaps Identified	11 Technology Gaps Identified
Cost	**Low**	**Low**	**Moderate**	**Moderate**	**High**	**High**
Schedule	**Low**	**Moderate**	**Moderate**	**Moderate**	**Moderate**	**Moderate**

3.1.1 FSP Fuel Assessment Results

Performance

Due to higher uranium loadings, reactors will be smaller (lower volume and mass) with UO_2 or UN pellet fuels compared to TRISO fueled reactors. Fast and thermal reactors are possible with HALEU UO_2 fuel systems. Moderated-UO_2 reactors would yield the lowest mass. With the AGR TRISO, epithermal and thermal HALEU reactors would be possible. Modification of the AGR TRISO design for higher uranium densities (larger kernel sizes, thinner coatings, increased fuel volume loadings) and greater use of moderation in the reactors would yield the lowest mass. UO_2 was assessed to correspond to reactors capable of lower critical masses than AGR TRISO-based designs.

Key Finding: Due to low uranium density of the AGR TRISO, space reactors based on the AGR TRISO or modified TRISO fuels will require moderation to minimize critical mass for power applications. TRISO based reactor designs are also expected to be higher mass than monolithic UO_2 or UN fueled reactors.

Existing Performance Database

There exists an extensive fuel performance database for UO_2 fuel forms from its use in commercial light water reactors and development from past space reactor programs. This database fully spans the required fuel parameters for FSP. Similarly, the AGR irradiation database exists for relevant temperature range and burnups. Modification of the AGR TRISO design for higher uranium loadings would require new test data to be generated. Existing test data does exist for some AGR TRISO variants and existing fuel performance models could be used for predictive analyses and design.

Technology Gap Assessment

Based upon the fuel performance needs to meet reference FSP system parameters, the identified common technology gaps for FSP fuel development were:

- **Moderator Development -** High temperature moderators will require technology development to establish net shape fabrication processes and extend the existing performance database.
- **Production Scale Fabrication Processes and Infrastructure -** Fabrication techniques must be demonstrated to meet application specific requirements (space reactor fuel specification). Existing infrastructure can be used for initial development. for A dedicated fuel fabrication process line will be desired to ensure fabrication process control is maintained and fuel quantities can be produced at the scale needed for assembly of a demonstration reactor.
- **Integrated Reactor System Behavior –** A prototype space reactor test would allow for demonstration of fuel performance under prototypic conditions, including interactions with other components within the reactor. Addition of moderation increases the complexity of reactor control. A reactor operations database will need to be established and fuel performance demonstrated as an integrated component within the reactor system.

For UO_2 fuel form development for FSP applications, there was 1 unique technology gap (4 total) identified:

- **Refractory Cladding and Liner Materials Development -** Claddings would be either be refractory metal based (such as Nb or Ta alloys) or ceramic composites (such as carbon-carbon fiber, C-C_f, or silicon carbide-silicon carbide fiber, SiC-SiC_f). This development program would aim to establish cladding feedstocks / production processes and demonstrate cladding-liner performance with UO_2 fuel forms, such as the ability to accommodate UO_2 fission gas release and swelling at high burnups.

For the AGR TRISO, 1 unique technology gap (4 total) was identified:

- **Fuel Element – Heat Pipe Compatibility -** Chemical compatibility between the fuel element and heat pipe must be demonstrated. Graphite (AGR fuel pellet matrix) is known to be reactive with many metallic materials (including stainless steels and refractory metals) at high temperatures.

If the AGR TRISO were to be modified, 2 additional unique data gaps (6 total) were identified:

- **Modification of AGR TRISO Fabrication Processes -** Technology development will be required to optimize existing parameters to meet the needs for FSP fuel production. It is expected that existing infrastructure may be utilized to meet this need.
- **Establish Fuel Irradiation Performance Database -** Changes to fuel material properties and irradiation performance are expected due to AGR TRISO modification. Irradiation testing should be conducted to develop a database and identify impacts of fuel design modifications on fuel performance.

Key Finding: HALEU FSP reactor designs can benefit from moderation to minimize critical mass. If moderation is used, moderator development will be a key technology development challenge. If a high readiness fuel form (UO_2, UN, unmodified AGR TRISO) is selected, ***moderator development may drive cost and schedule***.

Cost and Schedule

Cost and schedule were assessed to be low for UO_2. Low cost but moderate schedule was assessed for AGR TRISO fuel development, this is due to greater reliance on moderation which is expected. Modification of the AGR TRISO fuel design would also extend program schedule.

3.1.2 NEP Fuel Assessment Results

Performance

For NEP reactor designs, the primary design driver is specific mass. Due to high uranium density and high operating temperature capability, UN was assessed as an ideal fuel candidate to reduce required critical mass. Fast and thermal reactors are possible with HALEU UN. Moderated-UN reactors would yield the lowest mass. NEP would require a modified TRISO design. The reference modified TRISO (large diameter UN kernel with PyC-SiC coating) was assessed to require moderation to minimize reactor mass but was not expected to be capable of achieving the same mass as an UN-fueled NEP reactor.

Key Finding: *FSP fuel forms are extensible to NEP applications.* FSP and NEP systems share similar fuel performance parameter requirements and require the development of an irradiation performance database under the same irradiation conditions. Use of a common fuel form between FSP and NEP would enable a common fuel production infrastructure and test data to be leveraged for both applications, which could reduce overall cost and schedule for the development of both systems.

Existing Performance Database

Due to significant development under the SP-100 program, there exists an extensive fuel performance database for UN fuel forms for NEP application. This database fully spans the required fuel parameters for NEP. There exists some test data for the modified TRISO (some particle irradiation experiments). More testing is needed to generate modified TRISO fuel performance information for NEP applications.

Technology Gap Assessment

Based upon the fuel performance needs to meet reference NEP system parameters, the identified common technology gaps for NEP fuel development were:

- **Demonstrate UN / UN TRISO Stability under High Operating Temperature Conditions -** UN is known to be unstable under high operating temperatures. The testing program should confirm acceptable stability of UN under the desired operating conditions (operating temperature and duration).
- **Development of Quality Assurance / Quality Control Techniques -** Historically, repeatability, and fabricability of UN pellet fuels has been a challenge. The development of a modified TRISO NEP fuel design will be a custom fuel for NEP applications. Therefore, the fuel development program will need to include the development of quality assurance and control techniques. Based on data generated from the testing program, the development of a fuel specification is needed for UN and modified TRISO fuel forms.
- **Moderator Development** (previously defined see Section 3.1.1)
- **Production Scale Fabrication Processes and Infrastructure** (previously defined see Section 3.1.1)
- **Integrated Reactor System Behavior** (previously defined see Section 3.1.1)

For UN fuel form development for NEP applications, there were 2 unique technology gaps (7 total) identified:

- **Refractory Cladding and Liner Materials Development -** Claddings would be either be refractory metal based or ceramic composites. This development program would aim to establish cladding feedstocks / production processes and demonstrate cladding-liner performance with UN fuel forms, including the ability of the design to exhibit chemical compatibility with UN and resist fission product attack.
- **Re-Establish NEP Fuel Irradiation Performance Database -** There exists an extensive database for UN irradiation data established under the SP-100 program, however, data gaps do exist. Testing conditions should be based upon the HALEU NEP reactor design, matching critical parameters such as the cladding interface, operating temperature, and burnup.

For the modified TRISO, 3 unique (8 total) technology gaps were identified:

1. **Modification of AGR TRISO Fabrication Processes** (previously defined see Section 3.1.1)
2. **Establish Fuel Irradiation Performance Database** (previously defined see Section 3.1.1)
3. **Working Fluid Compatibility -** Chemical compatibility between the fuel element and working fluid must be demonstrated. This may result in the need to develop protective coatings or diffusion barriers.

Cost and Schedule

Cost and schedule were assessed to be moderate for both UN and modified TRISO NEP fuel development. This assessment was driven by the amount of technology development and infrastructure development needed to address identified technology gaps while satisfying general fuel maturation needs to improve the TRL of the fuel in preparation for a test reactor demonstration. Moderation would also improve NEP reactor performance which would increase required technology development.

Key Finding: Development and demonstration of MW_e class NEP reactor designs will be a significant engineering challenge. The is significant uncertainty in scaling of existing technology candidates to a MW_e system. Demonstration of a MW_e system also increases facilities requirements to provide the right environment (will require a large vacuum chamber) as well as accommodate the necessary waste heat rejection and power distribution.

A scaled approach to NEP reactor development is recommended. This approach can allow for earlier generation of test data and reduced uncertainty in scaling as the reactor subsystem is demonstrated at incrementally greater power levels.

3.1.3 NTP Fuel Assessment Results

Performance

For NTP systems, achieving targeted I_{sp} is the primary driver for fuel form development. Therefore, fuel candidates must be capable of operating at extremely high temperatures in a hydrogen environment. The reference performance parameters of this study are beyond what has been demonstrated through past U.S. NTP programs. For the Rover / NERVA derivative fuel form, operation above 2700 K would require the fuel kernel (UC_2) to exceed its melting point. Operating durations of 10 hours would be possible with technology development of channel coatings to prevent hot hydrogen attack. HALEU designs based on the Rover / NERVA fuel form would also benefit from modification of the fuel design to improve uranium density (higher fuel volume loading) and a moderated reactor design to minimize reactor mass. The reference cercer system had significant uncertainty in its performance potential. While the fuel form design leverages high melting temperature and hydrogen compatible materials, cercer fuel performance limits are not understood due to lack of a pre-existing performance database. Operation up to the theoretical melting temperature of UN could be possible if the ZrC matrix and coated particle coatings are capable of providing the conditions to prevent UN dissociation or containing UN dissociation products. Cercer based reactor types would also benefit from moderation to minimize reactor mass.

Existing Performance Database

There is a well-established existing fuel performance database for the Rover / NERVA derivative fuel form. This database includes a fully established separate effects testing (irradiation, hydrogen corrosion, and high temperature studies) database up to 2500 K as well as prototypic performance data from NTP test reactor experiments. Testing to higher irradiation temperatures ($\geq$ 2850 K) would be necessary to demonstrate the fuel is capable of meeting reference system parameters. A fuel performance database is not established for cercer fuels, some fuel and surrogate test data exists for laboratory fuel samples under hot hydrogen testing.

Key Finding: ***To reach reference system parameters of this study, NTP fuel performance parameters would exceed that which has been demonstrated through past U.S. development programs.*** Additional technology development is needed to expand the existing fuel performance database for NTP fuels.

Technology Gap Assessment

Based upon the fuel performance needs to meet reference NTP system parameters, the identified common technology gaps for NTP fuel development were:

- **Fuel Performance Demonstration under Prototypic Conditions –** One of the biggest technical risks for a NTP reactor-engine demonstration is NTP fuel performance under prototypic conditions (combined effects). The existing database will need to be confirmed and expanded for Rover / NERVA derivative fuels. Cercer fuels will need to develop the fuel performance database.
- **Development of Quality Assurance / Quality Control Techniques –** The NTP fuel development program will need to include the development of quality assurance and control techniques (including a fuel specification) based on generated test data.
- **Moderator and Insulator Development –** in addition to moderator development (previously defined see Section 3.1.1) NTP reactors will also require insulator development to thermally isolate the high operating temperature fuel element from other core components.
- **Production Scale Fabrication Processes and Infrastructure** (previously defined see Section 3.1.1)
- **Integrated Reactor System Behavior** (previously defined see Section 3.1.1)

For the Rover / NERVA derivative fuel form development for NTP applications, there were 4 unique technology gaps (9 total) identified:

- **Fuel Channel Coating Development –** Hydrogen corrosion limited historic Rover / NERVA fuels to lower performance than this study's reference system performance parameters. Improved hydrogen compatible channel coatings or liners will need to be developed.
- **Modification of Rover / NERVA Fabrication Processes -** Technology development will be required to "recover" equivalent fuel fabrication processes and modify processes to improve fuel uranium density. It is expected that existing infrastructure may be utilized to meet this need.
- **Demonstrate Molten Kernel Operation** – To meet the fuel performance parameters of this study, demonstration that the fuel form can reliably operate above the kernel melting point is needed.
- **Demonstrate Transient Performance under NTP Start Up Conditions** – NTP engines require a fast reactor start up (~100 K/s) which can cause thermal shock and fatigue over

multiple cycles. The fuel and protective coatings must be demonstrated to be capable of withstanding NTP transient conditions for multiple cycles.

For the cercer fuel form, 6 unique (11 total) technology gaps were identified:

1. **Development of Coated Particle Fabrication Processes** – Technology development will be required to modify existing coated particle fuel processes for NTP fuel production. It is expected that existing infrastructure may be utilized to meet this need.
2. **Establish Low Hafnium Content ZrC Feedstocks** – Existing ZrC feedstocks are not optimized for nuclear applications and can contain impurities which negatively impact reactor criticality. Specialty feedstocks will need to be developed at a sufficient scale for NTP technology development.
3. **Hot Hydrogen Compatibility -** Chemical compatibility between the fuel element and working fluid must be demonstrated. This may result in the need to develop protective coatings or diffusion barriers.
4. **Develop Net Shape Fuel Element Fabrication and Assembly Processes -** ZrC-matrix fuels are low readiness and fuel fabrication processes are not yet established. Net shape fuel element fabrication processes and methods to assemble / bond full scale element require development.
5. **Fuel Irradiation Performance -** Cercer fuel response under NTP irradiation conditions is unknown. Separate and combined effects testing of ZrC cercer fuel forms under prototypic power densities, irradiation temperatures, transients, and burnups should be used to develop the fuel performance database.
6. **Cercer Fuel Performance Model -** Predictive fuel performance models do not currently exist for cercer fuels. New models will require validation based on results of fabrication and performance (separate effects and combined effects testing) demonstration activities.

Cost and Schedule

Cost was assessed to be high, and schedule was assessed to be moderate for the development of both fuel types. While NTP fuel forms corresponded to more technology gaps and lower readiness fuel forms than FSP and NEP systems, NTP reactor operating times are short (<10 hours) which significantly accelerates testing for development. However, since NTP reactors require operating conditions much different than that for power reactors, existing infrastructure to support testing is limited and cannot provide the full range of prototypic conditions to meet the bounding parameters of the design. Therefore, significant facilities investment (high cost) would be needed to demonstrate NTP fuel forms and reactors.

Key Finding: ***Due to the unique operating conditions of NTP fuel forms, significant investment in specialty facilities would be needed to demonstrate fuel performance under prototypic conditions.*** Fuel development could occur quickly due to the short operating times for NTP reactors (<10 hours) and reduced duration required for development testing.

3.1.4 Future Space Reactor Fuel Production and Qualification Needs

For each fuel type, fuel qualification activities and supporting infrastructure was assessed based on the readiness of the fuel form and identified technology gaps. It was found that fuel qualification can be structured into three phases which span initial fuel technology development to reactor operations:

- **Phase I** would include all initial fuel technology development including screening of fuel form types and fabrication technologies. Based on test data, fuel design and fabrication optimization can begin. Existing laboratory scale fabrication and testing equipment capable of testing fuel under separate effects conditions would be needed during this phase.
- **Phase II** includes all activities until the completion of component level development. During phase II, fabrication processes are demonstrated to produce and assemble full scale fuel assemblies (reactor unit cell) or bundles. Demonstration tests are performed on these fuel components and integrated fuel assemblies (includes non-fuel components such as moderator) to test fuel under near-prototypic conditions (combined effects conditions) which matches or bounds critical parameters which impact fuel performance. For UO_2, UN, and TRISO based fuels, existing production scale equipment could be used to support fabrication activities for this phase. For NTP fuels, a first of a kind "pilot" scale fuel production facility will be needed to fabricate and assemble full scale components. This pilot line could be a government or industry facility. New engineering scale (capable of full-scale component production) equipment will be needed for non-fuel reactor components (such as moderators and insulators).
- **Phase III** corresponds to demonstration of fuel forms under true prototypic conditions via prototypic reactor operations. All fuels will require the development of a fabrication process line which will allow for fuel element production at the quality and quantity needed for the demonstration test reactor operations (Phase III). Power reactors may be tested at existing facilities, modification of facilities may be needed to support MW_e scale NEP reactor operations. NTP reactors will require a new or modified facility for demonstration testing.

Please refer to the full assessment in Appendix F for detailed information on the expected fuel qualification steps for each of the fuel types considered in this study.

4.0 Conclusions

Fuel selection will play a large impact on overall space reactor performance as well as technical risk that must be addressed during development, which is expected to have a major impact on program cost and schedule. There is no "off the shelf" qualified space reactor fuel form and infrastructure remaining from past space reactor fuel development programs is limited. Use of terrestrial fuels has been identified as an opportunity to reduce technical risk for space reactor fuel development through the use of established fuel fabrication processes and performance databases. There is also the opportunity for reduced fuel development cost and schedule by leveraging pre-existing fabrication and testing infrastructure.

Ongoing advanced reactor development activities are maturing terrestrial fuel forms capable of operating under similar conditions (operating temperatures, working fluids, operating duration) to space power reactors (NEP and FSP). Of the fuel options being developed, ceramic pellet (UO_2 and UN) and TRISO coated particle fuels correspond to reactor designs with the highest operating temperatures (≥ 600 °C, 873 K) and are assessed to be the best available terrestrial fuel options for high performance space reactors. Of the many possible variants of coated particle fuels, the AGR TRISO is the most mature coated particle variant available in the U.S. and is projected to finish fuel qualification activities in 2024 after 22 years and a projected $367 million total investment.

The objectives of fuel qualification are to demonstrate: 1) a process to reliably fabricate a fuel product in accordance with a specification, and 2) fuel performance and ability of the to meet reliability needs or licensing safety-requirements through analysis and testing. To meet these objectives, fuel qualification programs are designed to be specific to a particular fuel design and application. Use of a fuel qualified for terrestrial applications in a space reactor does not necessarily ensure the fuel is ready for space reactor operations. For the existing AGR TRISO, fuel performance has been demonstrated over a range that meets the needs for space power reactor applications. While the AGR TRISO performance database spans the operating parameters expected for space power reactors, this fuel type is not optimized for space reactor applications. Further, it was found that modification of fabrication processes would result in changes to fuel microstructure which can significantly impact performance. These modifications would not be considered qualified under the current qualification program.

For space applications, reactor performance benefits from fuel forms which are capable of minimizing reactor critical mass and maximizing operating temperature. These design drivers would strongly impact fuel design. The most likely coated particle variants to be proposed are:

- **FSP:** AGR TRISO, modified AGR TRISO
- **NEP:** modified TRISO with a large diameter UN kernel
- **NTP:** Rover / NERVA derivative **(**coated UC_x in a graphite matrix) or cercer fuel (modified TRISO with ZrC coating and UC_x or UN kernel in a ZrC matrix)

For each system, coated particle variants (identified through the state-of-the-art survey) and a reference historic derivative space reactor fuel were assessed for the categories of performance, existing performance database, technology gaps, cost, and schedule. Comparison of terrestrial coated particle and historic fuel derivatives allowed for relative risk and common fuel development needs to be identified. For each system, historic fuel derivatives corresponded to a reduced number of technology gaps and a more established fuel performance database. Modified coated particles were assessed to require greater technology development to optimize fabrication processes and develop an existing performance database.

For power reactor systems (FSP and NEP), historic fuel derivatives were assessed to be capable of enabling higher performance (reduced mass) systems. Like coated particle fuels, historic power reactor fuel derivatives, UO_2 and UN, are also being developed for advanced reactor applications. Therefore, all power reactor fuel options of this study were assessed to be capable of leveraging existing fabrication and testing infrastructure and expanded terrestrial reactor performance databases. For these fuels, to meet high performance KPPs, technology development would be needed to establish a cladding-liner material system which allows for fuel performance over extended operating durations (5 - 10 years). For HALEU reactors, incorporation of a moderator would allow for smaller core sizes and would be a major technology development area for the program. Key findings of the use for coated particle fuel for FSP and NEP applications include:

- FSP reactors would benefit from modification of the AGR TRISO to improve uranium density. However, this modification would require technology development for fabrication process optimization and extension of the existing fuel performance database, which was assessed to increase development timeline from low to moderate.
- Due to the high readiness of fuels assessed for FSP and ability to leverage existing fabrication and testing infrastructure, FSP fuel development was assessed to correspond to the lowest cost development program.
- NEP reactors require higher performance fuel forms and demonstration of the ability of the fuel and moderator to withstand required operating temperatures under higher power densities than FSP designs. Development and demonstration of the fuel and moderator to satisfy higher performance requirements was assessed to correspond to increased cost and schedule for reactor development.
- The modifications to optimize the AGR TRISO for NEP applications would be a greater divergence than required for FSP and does not allow for direct use of the AGR performance database. Existing fabrication equipment could still be used to support modified TRISO technology development.
- Coated particle fuels were not assessed to correspond to any performance benefits or reduced technology development compared to reference historic fuel concepts for power applications.

NTP reactors cannot directly leverage terrestrial fuel forms, coated particle variants would need significant modification for NTP reactors. Existing terrestrial coated fuel performance databases are not extensible to NTP applications, but fabrication process infrastructure could be modified for the production of specialty NTP fuel forms. There is an extensive history of coated particle fuels for NTP applications, selection of a historic derivative fuel form allows for existing performance databases to be used in the design. However, performance targets of this study exceed that demonstrated through any prior program and would require technology development to demonstrate fuel performance under more demanding operating conditions. Leveraging a custom coated particle variant could allow for a design which is not susceptible to the known material breakpoints and failure modes of historic fuel options. However, novel coated particle fuel forms will require extensive additional testing to develop a performance database for the new fuel form. Further, past programs have revealed that theoretical material operating temperature limits are reduced under prototypic NTP conditions, therefore, there would be risk in achievable fuel limits until prototypic environments testing was achieved. Due to the unique operating conditions of the NTP reactor, NTP reactors will require a new or modified facility for testing to demonstrate fuel performance under prototypic conditions (match irradiation temperature, power density, and hot hydrogen environment). Specialty testing facilities are expected to be a driver for overall NTP fuel development cost and schedule.

To enable high performance space reactor systems, reactor technology development will be needed. Reduced performance targets would allow for a wider trade space of technology options (including alternative candidates with high readiness level and existing performance databases). To meet high performance KPPs, critical HALEU reactor technologies that must be developed are the fuel and moderator. Space reactors can leverage terrestrial fuel technologies. Power reactors can leverage existing infrastructure, established performance databases and the high fuel readiness of coated particle and ceramic pellet fuel types from ongoing advanced reactor development programs with some technology development to meet high performance KPPs. NTP can benefit the most from existing coated particle fuel infrastructure as this can be used to fabricate derivatives of historic fuels or new custom fuels. Since NTP fuels would require significant modification of existing coated particle fuel types, more investment in technology development and fabrication infrastructure modifications would be anticipated for NTP fuel development.

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Appendix A: Terrestrial Coated Particle Fuel Fabrication Process Overview

As shown in Figure A-1, coated particle fuel fabrication is a multi-step process which may be tailored to customize the final fuel design for its intended application [45]. The process shown below is based upon the overall process required for AGR fuel form production, however most of these steps would be expected to be required for the production of alternative coated particle-based fuel forms. In the following sections, each process step is overviewed, demonstrated fabrication limits are identified, and the extensibility of the process to fabricate alternate material systems is assessed.

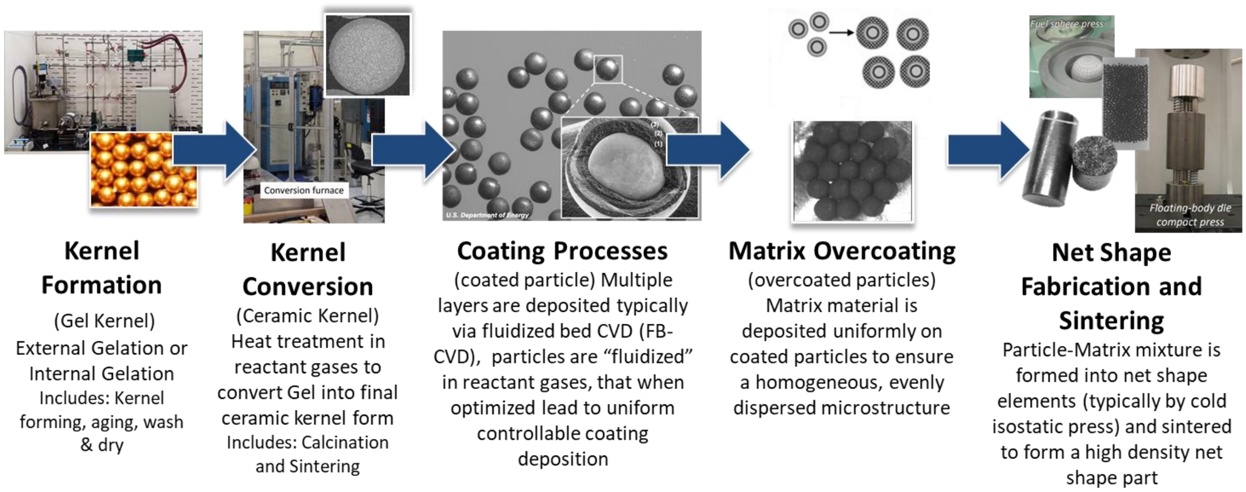

Figure A-1 Overview of fabrication process steps in the fabrication of coated particle-based fuel forms [29, 42, 47, 48]

Kernel Formation

The first step in the fabrication process is to produce a kernel precursor that can be converted into the ceramic fuel kernel. The two most common methods are solution gelation (sol-gel) processes: internal gelation and external gelation. The methods described in this section have only been demonstrated for ceramic fuel particle applications and are not anticipated to allow for conversion to a metallic fuel particle based on subject matter expert interviews. Both methods start by converting a uranium containing precursor (typically U_3O_8) to an acid deficient uranyl nitrate (ADUN) via reaction with nitric acid. This solution is heat treated and diluted before reaction with hexamethylenetetramine (HTMA) and urea to form a broth mixture.

Differences between the methods occur in the broth to gel conversion process. Kernels are formed through in the next step, typically by passing the broth solution through a vibrating nozzle to form droplets which spherodize as they drop through ammonia (gaseous or aqueous solution) which reacts with the kernels to form the gel for external gelation methods or drop into a solution (such as silicone oil) for aging (internal gelation process). For the later process, heating of the droplets after their formation allows for homogeneous reaction of the solution to form the gel. Following the internal or external gelation process, gel kernels are washed (removes unwanted residual precursors) and dried in preparation for the next fabrication step. The gel kernels are a hydroxide-based precursor of the correct shape that is converted to a ceramic in the next step.

This process has been demonstrated for the production of precursor gels for UO_2, UC_2, UCO, and UN kernels. For all ceramics other than UO_2, carbon additions are typically added to the broth to enhance the conversion process and allow for a more homogeneous final kernel microstructure. This process is well understood for UO_2 and UCO kernel precursor gels. Use of alternative metal oxide precursors can allow for the production of mixed oxide, carbide, or nitride kernels, examples: $(U,Pu)O_2$ and (U,Zr)C. While original gel droplets that are formed are oversized and shrink during drying and conversion processes, final kernel diameters of 150 – 800 μm are typical from the process described in this section. Fabrication of smaller diameter kernels would require modification of the droplet forming technique, techniques such as microfluidics have been proposed to allow for the fabrication of smaller diameter kernels [72]. Internal gelation processes have been demonstrated under AGR to yield more spherical kernels than external gelation methods which can be beneficial for the deposition of uniform coatings [37].

Kernel Conversion

Following the formation of precursor gel kernels, kernels are heat treated in a process gas (calcinated) to convert them to a porous, oxide ceramic kernel. For oxide kernels, these kernels undergo a sintering process to fully densify the kernels to near theoretical density (TD). For all other kernels, porous oxide kernels are sintered with a process gas to convert the kernels to the desired final chemistry. This process is well understood for UO_2 and UCO kernels and can result in near full theoretical density kernel formation. Alternative chemistries, UC_2 and UN have also been demonstrated. UC_2 kernels are typically proposed to be fabricated using the same process gas and sintering chemistry as required for UCO (solid solution of UO_2-UC_2) kernels but by allowing the full conversion process to occur. UN kernel production is typically proposed to be performed as an extra step once UCO or UC_2 kernels undergo initial conversion. These kernels are then subjected to a nitrogen containing process gas and heated to convert to a UCN (solid solution of UC-UN) final product which is nearly fully UN [68, 67]. The required reaction with process gas for UCN kernel production typically competes with densification during the conversion process, this results in a lower density kernel (high 80% to low 90% TD) following the reaction step. It has been proposed to use a post-conversion heat treatment process, such as hot isostatic pressing, to allow for near TD kernel densities [73].

Coating Processes

Once kernels have been fabricated, they are used as feedstocks for coating processes. The standard TRISO coating process steps are described in this section and extensibility of coating methods are identified. The standard TRISO coating has 4 coating process steps to produce the buffer, iPyC, SiC, and OPyC layers. Each of these steps may be adjusted to allow for changes in the final coating composition, geometry (coating thickness), or microstructure (density). Conventional TRISO coatings are produced through chemical vapor deposition (CVD) processes. CVD methods utilize reaction of gaseous precursors at high temperature to deposit coatings on a material. This method has the advantage of rapid coating deposition which is relatively scalable from small (g) to large (kg) batch sizes.

Using a fluidized bed CVD (FB-CVD) process, TRISO kernels are first transferred to a chemical reactor where they are heated, fluidized, and reacted with the precursor gases. For the initial buffer coating an acetylene reactant gas and argon carrier gas is used to deposit a porous PyC layer. The high density iPyC layer is deposited through reaction of propylene and acetylene gases with an argon carrier gas. Methyl trichlorosilane and hydrogen are reacted to form the SiC layer. The final high density OPyC layer is formed again through the reaction of propylene and acetylene gases with an argon carrier gas. Thickness of the final coating typically scales with reaction duration (if gas flow rates and temperatures remain constant).

Process parameters, such as reaction temperature, gas flow rate, and mixture ratios may be varied to tailor the microstructure of the final coating. If an alternative material is desired, the CVD process may be tailored to the application to allow for nearly any material to be deposited based on the selection of precursor gases and process temperature. However, kernels may exhibit chemical incompatibility with precursor gases resulting in chemical reaction and attack of the microstructure which may introduce impurities, degrade microstructural features, or cause a change in starting composition (loss of uranium or change in kernel stoichiometry). In these cases, a protective coating, such as high density PyC, may be added to prevent direct exposure of the kernel. It should also be noted that kernels may also be sensitive to process temperatures where repeated exposure to high temperatures may cause an evolution in kernel stoichiometry, phase distribution, and other microstructural features such as grain size. Alternative coatings may be produced in existing laboratory and industry facilities through modification to allow for safe handling of reactant gases (including mass flow controllers, precursor gas storage, as well as post-deposition gas waste treatment, storage, and disposal) and possible furnace upgrades to ensure required deposition temperatures. Alternative coatings that have been demonstrated in place of the SiC layer include: ZrC, TiN, and alumina (Al_2O_3) [36]. Refractory metal coatings have also been demonstrated using CVD processes directly on UO_2 kernels [74].

Alternative proposed methods for coated particle production include atomic layer deposition (ALD) and physical vapor deposition (PVD). ALD methods are a thin film coating technique that, like CVD, uses two precursor gases to deposit a coating on the desired substrate. As opposed to the CVD method described earlier, ALD is distinguished as saturating, the resulting coating is built up layer by layer allowing for near atomic level control over the final coating microstructure. Limitations of the ALD process include slower deposition times and thinner coatings. ALD scalability to the production scale is possible and used for specialty energy and thermal applications. Unlike CVD or ALD, PVD methods are a thin film coating technique that rely on the sputtering of a precursor solid of liquid phase material to directly deposit onto the desired substrate through vapor transport. PVD coatings may be either ceramic or metallic and are typically on the order of several µm or less. Like ALD, scalability to the production scale is possible and in use for specialty commercial applications. Both of these techniques have not been applied to commercial TRISO coating activities and likely would not be able to meet TRISO coating specifications due to limitations in achievable coating thicknesses. Each requires additional development for coated particle applications.

Net Shape Fabrication Processes

The final steps in the fabrication of coated particle-based fuel forms are to fabricate the net shape fuel form. Net shape fabrication processes may include coated particle matrix overcoating, net shape fuel sintering, net shape fuel assembly, and / or net shape fuel element coating. For typical terrestrial applications, the first three of these process steps are routinely performed with TRISO particles in a graphite matrix for 6 cm fuel spheres and ~1.23 cm diameter, 2.54 cm length fuel pellets.

For traditional terrestrial applications, matrix overcoating is performed on as-fabricated coated particles (TRISO) by depositing an even layer of fine matrix powders on to the coated particle surface with the use of a binder. The masses of TRISO and matrix powder feedstocks are weighed and tracked throughout the process to ensure the desired volume loading of fuel is achieved. This step may be skipped but typically results in a less uniform final element density if excluded. Overcoated powders are provided as a feedstock for net shape sintering.

Net shape sintering processes typically require cold pressing of the overcoated particle feedstocks into the correct net shape, followed by sintering at high temperature which allows for full densification of the material. Following sintering, the fuel element may be further prepared through finishing activities to remove unwanted material and provide the desired surface finish. This process is well established for fuel spheres and pellets. As-fabricated spheres may be provided directly for loading in the reactor or undergo required coating processes (also typically performed by CVD methods). Pellets may be provided for assembly into graphite modules for prismatic reactor designs.

Alternative net shape processes and methods have been proposed through other recent DOE programs, such as additive manufacturing [44]. However, these methods are considered to be at a low manufacture readiness level and require additional development and refinement to understand process parameter effects on as-fabricated fuel performance and properties.

Extensibility of Coated Particle Fuel Fabrication Processes

Based on the literature review and subject matter expert interviews performed for this study, the extensibility of coated particle fuel fabrication processes was evaluated, and different variants identified. **Table A.1** summarizes these variants and categorizes each variant with respect to the current knowledge base for fabrication of each coating, kernel, or fuel form option. High readiness variants are options that are readily produced with current infrastructure or have been previously produced on the production scale. Other demonstrated variants are identified which include options that have been demonstrated on the laboratory scale in either modern or historic fuel development programs. The last category includes all other options which have been previously proposed based on known extensibility of existing fabrication infrastructure.

Table A.1 Summary of Coated Particle Fuel Form Variations Identified Through this Study

Kernel Compositions	Kernel Diameter	Coating Options	Applicable Fuel Systems	Forms
Any Ceramic U-kernel	**Variable**	**Many, Ceramic or Metallic** limited by possible U-kernel attack of precursor gas and may require modification of pre-existing equipment	**Composite or Particle Fuels**	AGR pellet compact and modified pellet compacts (alternate size and particle volume loadings)
Highest Readiness: UO_2, UC_2, UCO **Others Demonstrated:** UN, UC, UCN **Others Proposed:** solid solution carbides and nitrides (U,Zr)C, (U,Zr)CN, etc.	**Highest Readiness:** 150 – 800+ μm **Possible:** < 150 μm (requires microfluidics)	**Highest Readiness:** BISO (buffer only), TRISO (buffer, iPyC, SiC, OPyC) **Others Demonstrated:** "TRIZO" (buffer, iPyC, ZrC), metallic (W), other PyC multilayer coatings, other ceramic (Al_2O_3) **Others Proposed:** Alternative refractory ceramics (oxides, nitrides, carbides) and metallic coatings (Mo, other)	**Highest Readiness:** Graphite matrix with dispersed BISO or TRISO particles (cercer) **Others Demonstrated:** W- and Mo-matrix cermet, SiC and ZrC matrix cercer, other cercer variants, SNTP particle fuels **Others Proposed:** Alternative metallic (Re, Nb, Ta, etc.) and ceramic (nitrides, carbides, oxides, borides, and including solid solutions) matrices	"Standard" 6 cm pebble and modified pebble (alternate size and particle volume loadings) Prismatic channeled fuel elements Particle fuels (~1 mm or less in diameter) Custom

Appendix B: Reference Reactor Material Performance Information

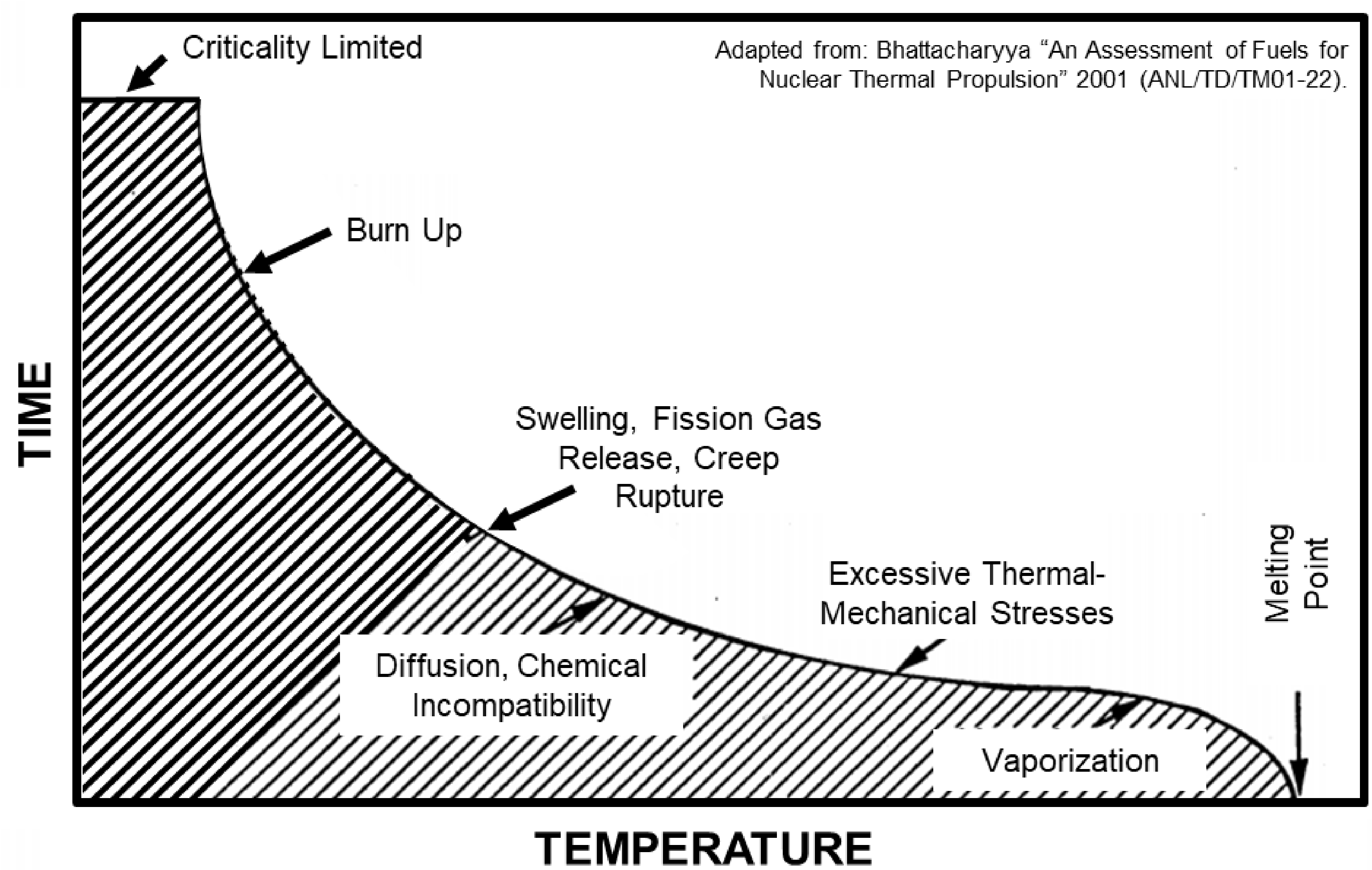

Figure B-1 Relationship between space reactor operating conditions (temperature and operating duration) and known failure modes of space reactor fuel systems (adapted from [64]).

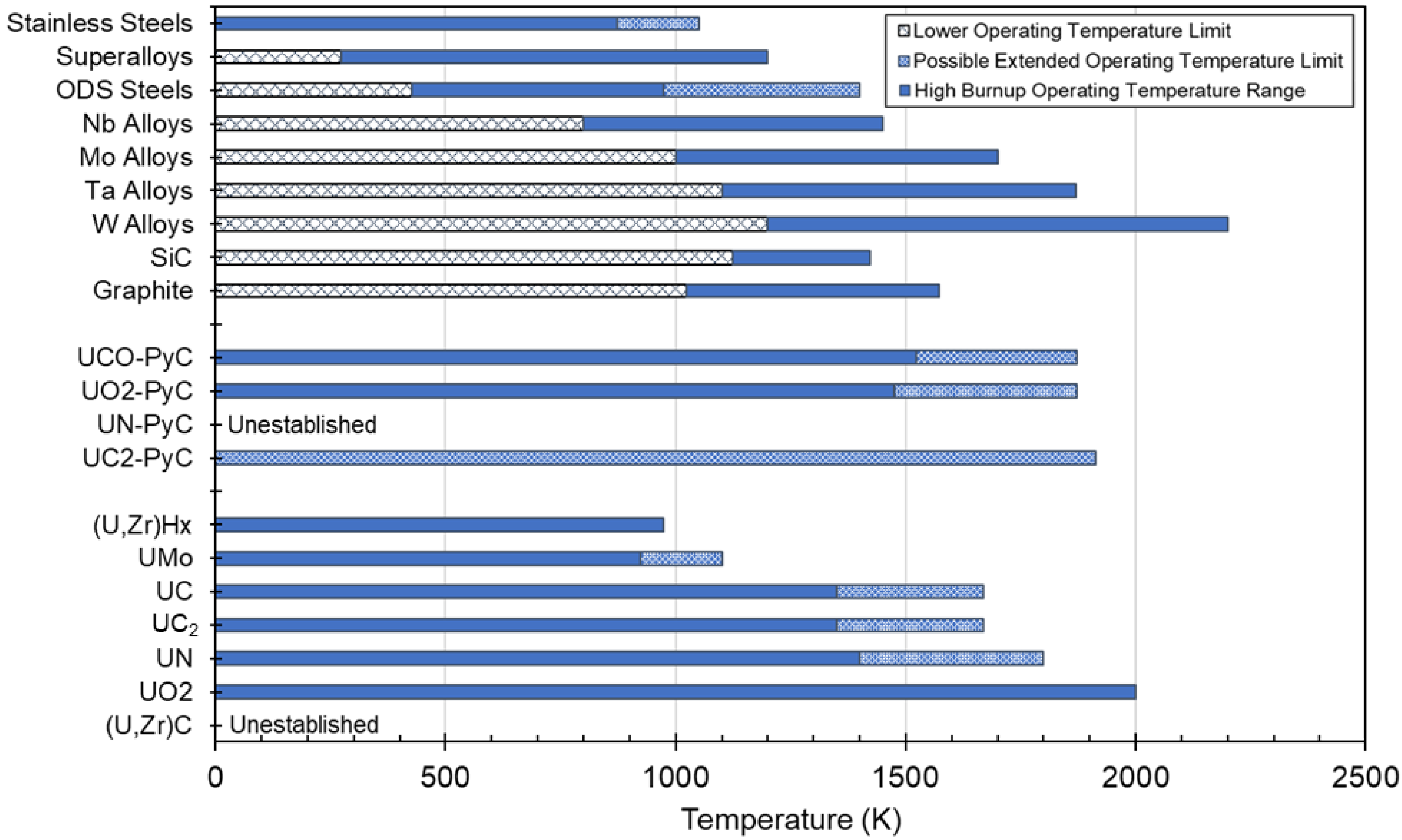

Figure B-2 Predicted operating temperature range for power reactor candidate fuel materials (Adapted from: [75, 76, 77, 78, 79])

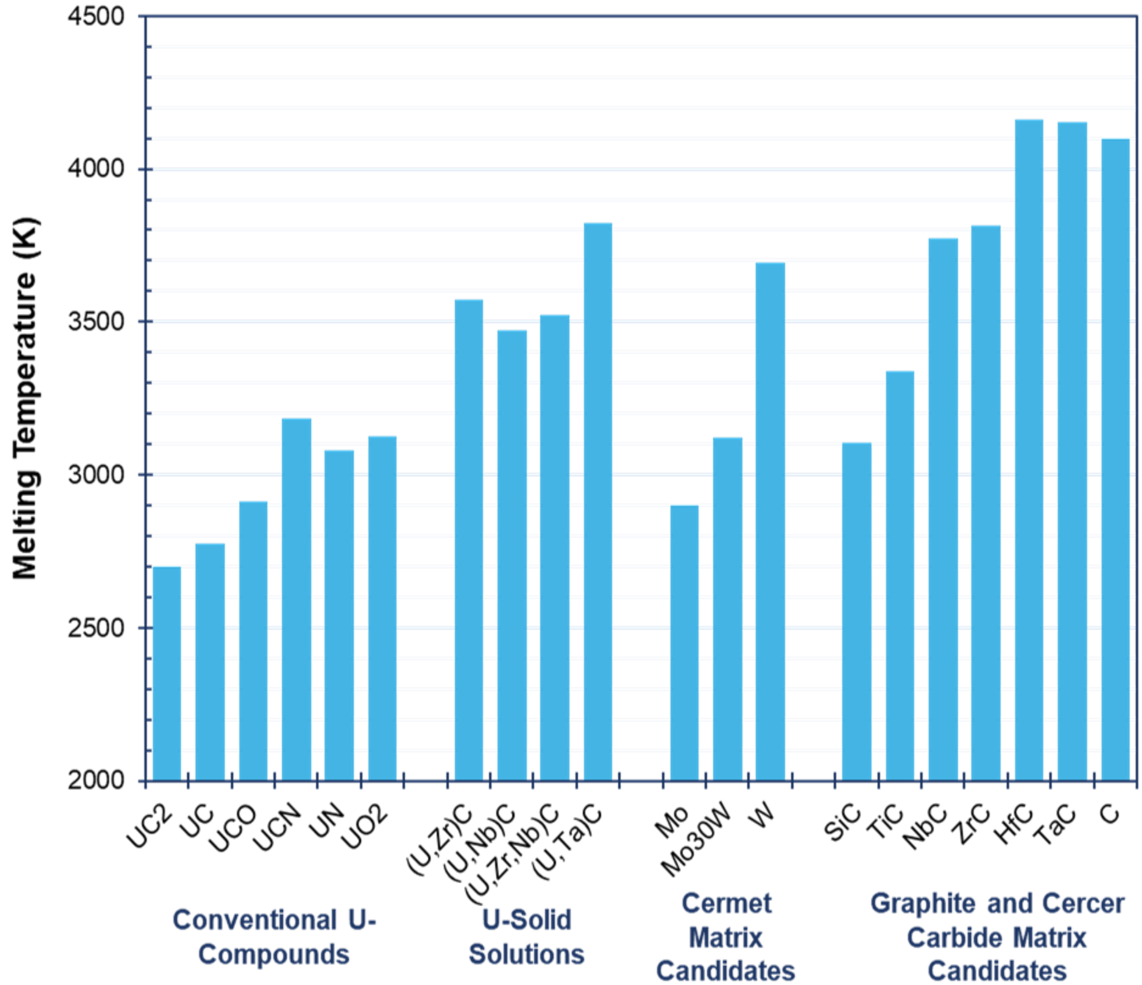

Figure B-3 Melting Temperature of NTP Fuel Material Candidates (originally from [80])

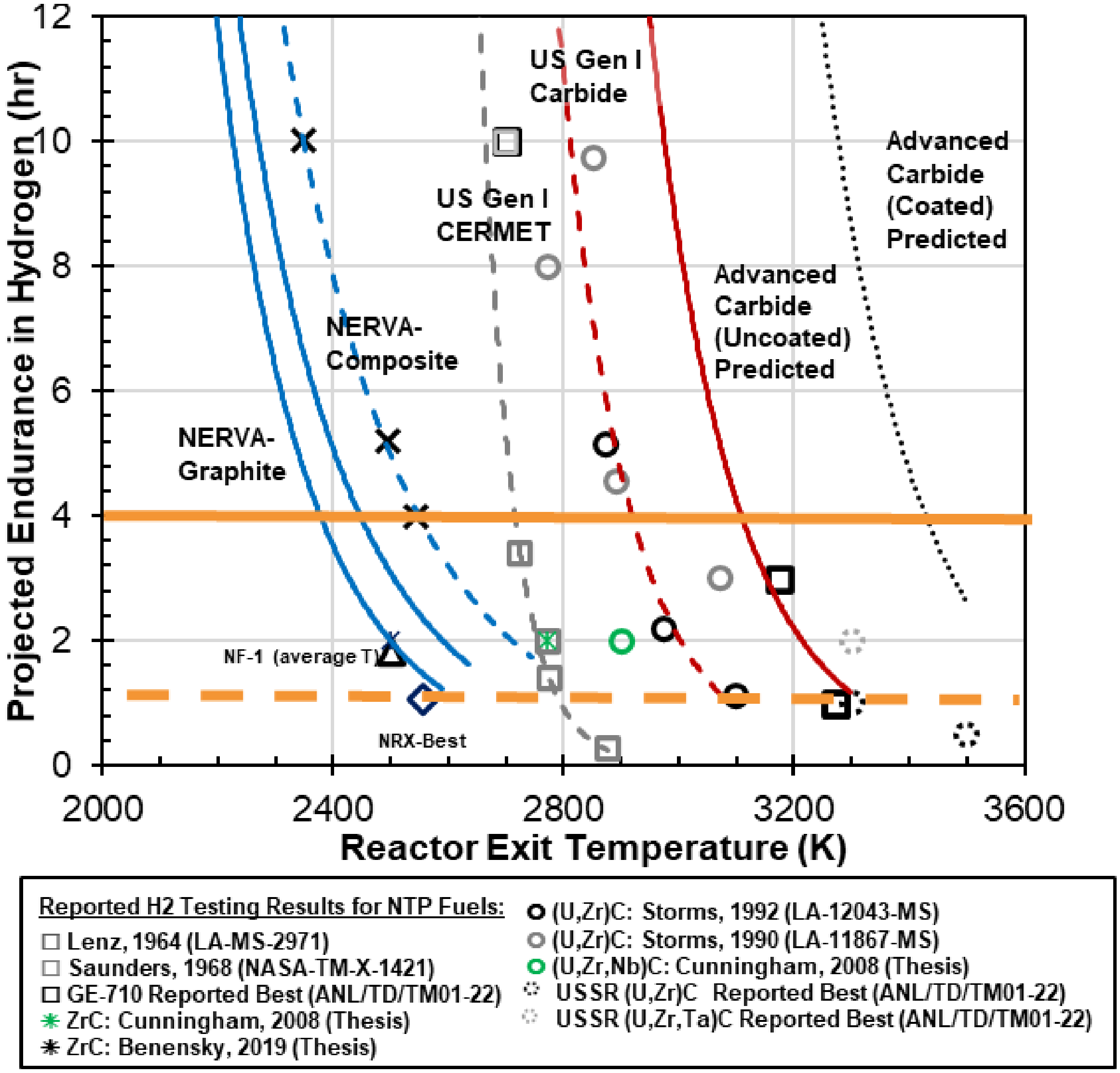

Figure B-4 Predicted endurance of NTP fuels based upon historical test data (originally from: [80])

Appendix C: Assessment Methodology

The goals of this assessment were to identify key technology development needs and related risk for terrestrial derivative fuel forms. For each space reactor system included in this study, a coated particle-based fuel form, derivative from existing AGR TRISO fabrication methods, was identified for evaluation. For each system, the corresponding derivative fuel form was required to have the potential to meet the reference system performance parameters for the respective system. To identify the relative level of risk and required technology development, a reference historic fuel derivative was included in the assessment for comparison. Fuel forms from prior power and thermal propulsion reactor development programs were identified and one reference fuel type (capable of satisfying reference performance parameters selected) was selected for each system. Selected fuel technologies were assessed with respect to the following categories:

- **Performance:** performance capability, existing performance database
- **Risk:** identification of technology gaps
- **Programmatic:** anticipated cost and schedule of required fuel development before a reactor demonstration (TRL 6)
- **Facilities and Qualification:** identification of facilities needs to establish a production capability and identification of the testing program needed to achieve fuel qualification.

The following sections describe the technical approach for each assessment category.

Performance Assessment Considerations

The performance assessment completed for this study is broken into two parts: evaluation of the existing performance database for each fuel form and projection of expected performance of the fuel form based on existing data. System performance parameters were translated into fuel performance parameters (**Table C.1**) and the existing fuel performance database was compared to these parameters to expose gaps which should be addressed through the fuel qualification program. The fuel performance parameters evaluated for this study included: power density, peak fuel operating temperature, and operating duration. Power density describes the thermal power per unit fuel volume and is dependent upon reactor thermal power and reactor mass (volume). For space reactors, designers typically aim to minimize reactor mass to minimize launch and spacecraft mass, which results in higher power densities than traditional terrestrial reactor designs. However, for low power reactors (< ~50 kW_e) where mass is criticality limited, power density will be lower and limited by the minimum critical volume of the reactor at a given power level. Peak fuel operating temperature is related to reactor exit temperature. Since the primary function of the fuel is to transfer heat to the coolant, the fuel will always operate at a higher temperature than the reactor outlet temperature. The exact operating temperature is dependent upon reactor power density, fuel geometry, and fuel thermal properties and is typically in the range of 150 – 200 K greater than the reactor exit temperature. Additional considerations for fuel design include working fluid compatibility and operating duration. The fuel must be chemically compatible with the working fluid or protective coatings must exist to enable chemical compatibility. Reactor operating duration will need to satisfy system lifetime requirements. Reactor operating duration most directly impacts burnup of the fuel form and the neutron fluence reactor materials will be subjected to.

Table C.1 Desired Fuel Performance Parameters for Space Reactor Applications

Application	Power Density (W/cm^3)	Peak Fuel Operating Temperature (K)	Reactor Working Fluid Compatibility	Operating Duration (Fluence, n/m^2)
FSP	≤ 50	1400+	Na Heat Pipes (Mo)	10 years (2.5×10^{25} n/m^2)
NEP	≥ 100	1400+	Li or HeXe	5 years (2.5×10^{25} n/m^2)
NTP	≥ 5,000	2850+	H	10 hours (3.6×10^{23} n/m^2)

The performance assessment findings of this study are limited to the reference system parameters provided by NASA which correspond to high performance systems for a lunar surface power mission or crewed Mars in-space transportation missions. While changes to the parameters impact whether or not the existing fuel performance database spans the entire corresponding range needed for the design, there are some material breakpoints which limit fuel materials that can be considered for the application. These breakpoints are most sensitive to temperature and reactor operating duration. Fuel and cladding material will be temperature limited by melting point, fuel swelling, chemical compatibility, and creep rupture behavior for a prescribed reactor operating duration in power reactors and similarly will be limited by melting point, chemical compatibility, high temperature vaporization, and fatigue for nuclear thermal propulsion reactors. The temperature and operating duration limits of materials assessed in this study are high and representative of high-performance systems, there are other fuel and cladding material candidates which are capable of operating at reduced operating conditions (Appendix B, **Figure B-2**) but not included in the assessment.

When identifying the existing fuel performance database, fuel performance under both relevant nuclear and non-nuclear environments was assessed. The following aspects were considered when comparing the existing performance database to desired space reactor performance parameters:

- ***Non-Nuclear Environment (temperature and compatibility)*** – What temperature range has this fuel been documented to be exposed to? Were these exposures performed under representative operating environments (such as working fluid or cladding interfaces) and lifetimes (including transients, number of thermal cycles)?
- ***Irradiation Environment (power density and fluence)*** – What range of irradiation performance has been demonstrated for this fuel type? Has the fuel been tested under representative power densities and total irradiation durations (fluence)?
- ***Combined Effects and Reactor Operations*** – Has any testing been performed on this fuel system under combined effects testing relevant to the space reactor system of interest? Have any reactor operations been demonstrated with this fuel type under combined effects conditions desired for current applications?

Technology Gap Assessment Description

For each fuel system, critical technology gaps (risks) were identified related to fuel manufacturability, fuel performance and reliability, and unique integrated reactor system development needs.

Cost and Schedule Assessment Description

Fuel development cost and schedule were assessed based upon qualitative ranges relevant to NASA space reactor planning activities. Fuel development cost and schedules were constrained to that projected to be required to support a reactor subsystem technology demonstration (TRL 6) and only consider fuel development, therefore this assessment does not include costs associated with assembly and testing of the entire reactor subsystem for TRL 6 .

The schedule ranges used in this study are:

- ***Low*** – There is high confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029.
- ***Moderate*** – There is moderate confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029. There is high confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2035.
- ***High*** – There is low confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2029. There is moderate confidence that the proposed technology is capable of being matured to enable a NASA integrated system demonstration of the proposed reference system parameters by 2035.

The cost ranges used in this study are:

- ***Low*** – Current infrastructure exists to enable production of test articles and testing under representative conditions. Required feedstocks are commercially or readily available. Limited investment may be needed for facilities modification on the order of $25M or less throughout the length of the development program.
- ***Moderate*** – Current infrastructure exists which may be capable of modification to enable production of test articles and testing under representative conditions. Required feedstocks are commercially or readily available. Some new facility infrastructure investment may be needed but is not anticipated to exceed $100M throughout the length of the development program.
- ***High*** – Infrastructure does not exist which can be modified to enable production and testing of test articles under representative conditions. Required feedstocks are not yet available. Significant investment in facility infrastructure investment may be needed and is likely to exceed $100M throughout the length of the development program.

Facilities and Qualification Assessment Description

The last element of the assessment included identifying specific development tasks and supporting facilities to enable the fuel qualification program. NASA study leads provided input on specific questions to be addressed in this assessment:

- For the historical fuels, what is needed to reestablish a production capability?
- For the coated particle fuels, what is needed to modify the current production capability?
- For both, what testing is needed to qualify the fuel for the NASA application?

The results of the facilities and qualification assessment are included in Appendix G.

Appendix D: Fission Surface Power Fuel Assessment

FSP systems are expected to play a significant role in the exploration and colonization of space. FSP systems include a nuclear reactor, electric power generation, heat rejection systems and conditioning units. This allows the system to provide high power levels (> 10 kW_e) for long operating durations wherever there may be such a need in space. Current designs are being developed for lunar surface applications that are extensible to Mars surface applications. To reduce heat rejection requirements and thereby minimize system mass and volume required for launch, FSP systems aim for high thermal efficiencies which is achieved with a high reactor operating temperature and dynamic power conversion. Thus, some synergism can be exploited with advanced reactor projects that are developing high temperature reactors at greater power levels (such as Very High Temperature Reactor, Enhanced Accident Tolerant Fuel, and High Temperature Micro Reactor programs). However, while mass and volume are of great importance for FSP, these parameters are not as significant than what is needed for an NEP system. Instead, the ability of the fuel and other critical system components to survive long operating durations (10 years) becomes a more important design driver. As a result of this, the choice of nuclear fuels and the reactor coolant systems and the power conversion systems differ in many important ways from the development needs for an NEP system. The system parameters for an FSP system used for this study are as follows:

- Reactor power - 50 kW_{th} (typical electric power level of ~10 kW_e)
- Reactor outlet temperature - 1200 K,
- Reactor coolant / heat transport - Na heat pipes,
- Operating duration - 10 years

In FSP systems, the fuel is the source of thermal power for the system and the reactor is coupled with a power conversion unit to generate electricity. A high temperature fuel form is desirable for higher efficiency space applications and the fuel design must be capable of operating for up to 10 years without replacement. Consideration in this study was also given to mass and volume of the reactor and shielding requirements as all these factors will affect the viability of the launch and deployment of candidate reactors. Minimum critical dimensions are of particular interest since the shielding for a FSP may be much greater than for an NEP (for protection of the crew performing operations on the surface) and typically scales proportionally to reactor volume. Minimizing reactor mass and volume requires a fuel form which can minimize the critical core volume while sustaining criticality for up to 10 years. Thus, FSP fuels must be demonstrated to be capable of reliable operation for high burnups and operating temperatures. Desirable fuel attributes for FSP are:

- **High uranium fuel density.** A high uranium density (Uranium-235) will allow for smaller reactor designs. Fuels that have a low uranium density (such as particle fuels) will typically require more fuel elements, more moderator elements and / or more reflector material to sustain criticality through the reactor operating duration and minimize reactor critical volume.
- **High operating temperature capability.** To decrease specific mass, high conversion efficiency is desired for the power generation system. This increases the attractiveness of a reactor capable of heating working fluids to higher operating temperatures compared to traditional terrestrial applications.

- **Irradiation tolerance.** The fuel does not exhibit adverse fuel cladding interactions over the operating duration. Failure caused by swelling or corrosion of the fuel pin would lead to fission product release from the fuel element and loss of the uranium from the reactor core.
- **Good thermal conductivity.** A fuel that has high thermal conductivity will keep the peak thermal temperatures in the fuel low. Thermal conductivity may evolve over fuel operating duration due to irradiation damage incurred during fuel operation. If the thermal conductivity degrades, then the fuel will be required to operate at higher temperatures which affects the core neutronics (reactivity and power profiles) to maintain performance. Higher operating fuel temperatures increases the possibility of fuel-cladding interactions and rupture.
- **Structural stability.** The fuel will need to survive a variety of loads, vibrations, and shock from launch and in-space operations. Any bending, deformation or fracturing of the fuel or fuel element during launch or operations will affect the core neutronics as well as thermal characteristics or the reactor.
- **Existing fuel property, performance, and reactor operations database.** If fuel properties and performance under relevant conditions is well characterized, there is increased confidence in predictive modeling data and reduced technical risk in the fuel qualification program for a given design. Existing reactor operations data reduces risk for system level demonstrations and can bolster related safety analyses required for ground demonstration test facilities.
- **Fabrication process readiness and availability.** Leveraging existing fabrication processes can reduce the technology development efforts pursued in support of fuel qualification. Availability of fabrication process equipment allows for immediate prototyping of required test articles to be used in demonstration / testing activities.
- **Test facility availability.** Availability of in pile and out of pile test capabilities for separate effects testing and integrated fuel / moderator testing. Do test and PIE facilities exist for fuel, cladding and moderator for prototypic conditions?

Three different fuel types relevant to FSP applications were surveyed in this assessment: UO_2 pellet, UN pellet, and AGR TRISO particle-based fuel forms. An overview of metallic and hydride fuel forms is also included in the fuel overview section, but these fuel forms were excluded from the assessment due to their inability to operate at the required temperatures needed to meet the reference system parameters. It is noted that other fuel types may also be options for FSP reactors with lower performance conditions (see Section “Technology Gap Assessment, Metallic and Hydride Fuels for Fission Surface Power Applications” for more information).

UO_2 and UN are both high readiness fuel candidates with heritage from U.S. space power reactor development activities (NEP applications). UO_2 and UN fuel possess sufficient technology readiness level but will require confirmatory testing to assure chemical and dimensional stability. The AGR TRISO is another moderate readiness candidate, with proven irradiation performance under temperatures and burnups relevant to FSP through the AGR fuel qualification program. This fuel form has not yet been developed for space power reactor applications, but it has been evaluated as a candidate space power reactor fuel in historic programs. HALEU UO_2 and UN pellet fuels could likely be used in both fast and moderated reactor systems. Moderated systems may be the lowest critical mass. However, coated ceramic particles whether using UO_2 or UN fuel as the fuel kernel are not optimal for FSP use where reactors are criticality limited because of its low uranium density, which will make the reactor volume and mass large. The AGR TRISO was assessed to require additional moderation to minimize reactor mass for FSP applications and may require modifications to the particle to increase kernel diameter or particle volume loading in order to increase uranium density within the fuel. Other options which deviate from the established AGR manufacture specification and its existing performance database, modified AGR TRISO fuels, will require technology development to establish the corresponding performance database for the fuel and optimize corresponding manufacture techniques.

With respect to performance, it is expected that FSP reactors will be smaller (lower volume and mass) with UN or UO_2 pellet fuels compared to coated particle-based fuel forms. Introduction of moderation was assessed to allow for the minimum FSP reactor mass regardless of fuel type. However, moderator candidates are at a lower readiness than each of the fuel forms surveyed and would likely be a schedule driver for FSP reactor development. Therefore, moderated reactors would require a longer development schedule regardless of spectrum or fuel type but, overall fuel development cost could be manageable. This is because there is the potential to leverage existing fabrication and testing equipment to mature fuels to the level needed to support a TRL 6 system demonstration.

Breakpoints were identified for FSP fuel development schedule projections based on material selection. At operating temperatures exceeding 1200 K, refractory alloys are needed to ensure material survivability under long duration high temperature irradiation, due to their high temperature irradiation tolerance and creep resistance. Refractory alloy fabrication infrastructure will need to be established to support the development program. If operating temperature requirements could be reduced (< 1100 K), it is anticipated that UO_2 cores could use stainless steel or superalloy claddings. This would allow for reduced development timelines (shorter schedule) since infrastructure, database, and methods exist. If the operating temperature cannot be reduced, UN and UO_2 fuel development activities will require a refractory metal alloy development program and longer schedules would be required for fuel development. The TRISO reactor design is well suited for high temperature applications (originally developed for this temperature range) and would not benefit from a refractory metal and fuel pin liner development program.

FSP Fuel Form Overview

UO_2 for Fission Surface Power Applications

UO_2 fuel is by far the most developed and understood fuel form. It has a moderate fuel density, but low thermal conductivity properties which results in higher peak fuel temperatures compared to UN operating under the same conditions. The limiting factors associated with UO_2 fuels for space applications are fuel swelling at high temperatures, high temperature vaporization, chemical compatibility with cladding, and fission product release at high burnups which can lead to pressurization of the fuel pin (gaseous fission products) or fission product-cladding chemical interaction (solid fission products). UO_2 fuel can be used in either a fast or moderated reactor system. Technology development activities can be done with existing equipment and facilities. For working fluid operating temperatures of 1200 K or greater, a refractory material will be needed for the cladding. Barrier coatings (or liners) may be required to prevent chemical incompatibility with the cladding (UO_2 is incompatible with Nb, Ta), fission product cladding-interactions, and / or working fluid interactions. A dedicated HALEU UO_2 production line will be necessary for reactor production activities. Full scale production of HALEU net-shape pellets to desired specifications will need to be developed.

UO_2 Performance Assessment

UO_2 has an extensive fuel performance database that has been developed through different research and development as well as commercial programs [82, 83]. This database is primarily based upon fuel performance data from commercial light water reactor operations. UO_2 and mixed oxide fuels have also been proposed and studied for liquid metal reactors (LMRs) and gas cooled fast reactor applications [84]. Therefore, a wide range of testing has been performed on UO_2 fuel forms with different claddings, working fluids, and reactor operating conditions (spectrum, power density, fuel temperature). UO_2 has been a candidate fuel type for several historic space power reactor programs: Space reactor Prototype-100 (SP-100) / Space Reactor Electric Power Supply (SPAR) [85], TOPAZ / NEPSTP [8, 86], Thermionic Fuel Element Verification Program (TFEVP) [87], Project Prometheus / Jupiter Icy Moons Orbiter (JIMO) [58], and Nuclear Systems / Affordable FSP Project [70]. Through both the SP-100 and TFEVP, UO_2 fuel was tested at high irradiation temperatures and with representative cladding interfaces desired for power reactor applications [87, 88]. A summary of the existing performance database is compiled in **Table D.1** [82, 84, 88, 87].

Table D.1 Comparison of the Existing Fuel Performance Database for UO_2 Fuel Forms to FSP Application Fuel Performance Parameters (*PWC - Nb-Zr-C alloy, **EBR – Experimental Breeder Reactor)

	Peak Fuel Temperature (K)	Working Fluid	Interfaces	Power Density (W/cm^3)	Operating Duration (or Burnup)	Reactor Operations
Study Reference	1400	-	Refractory Cladding	≤ 50	10 years	-
Existing Performance Database						
LWRs	Varies > 1473	H_2O	Zirconium (Zr)-alloy Cladding	55 - 90	years	Yes
LMRs	Varies >973	Na	Steel Cladding (most common)	3.5 - 133	years	Yes
SP-100	1000 - 2200	Li	Nb-1Zr Cladding (PWC* clad was new baseline, W and Re liners)	not reported	months (≤ 6% FIMA)	No (EBR** II irradiation experiments only)
TFEVP	1700 - 1950	-	W, Nb	not reported (2 - 6 W/cm^2)	≤13,500 hr (0.07 - 1.4% FIMA)	TOPAZ Reactor Experiments performed within the US

Through historic development activities, operating duration limiting phenomena identified for UO_2 fuel forms for power reactor applications include fuel swelling, fission gas release and fission-product cladding interactions, and acceptable high temperature strength / creep behavior of the selected cladding for the fuel system. UO_2 operating temperatures up to 2000 K for 5 years was proposed through the TFEVP [81], therefore the system performance parameters of this study are anticipated to be achievable with the selection of the correct cladding option. UO_2 swelling under high temperature irradiation is relatively low compared to UC and UN [85, 86] For all monolithic fuel types, swelling should be limited (< 20% proposed during Systems for Nuclear Auxiliary

Power (SNAP)-50, [87] to prevent significant changes in geometry that can impact reactor power, temperature, and stress profiles which can impact thermodynamics of the core (thereby impacting reactor performance) and reduce design margins during operation.

Due to the high uranium loading of the fuel form, it is expected that this fuel type would correspond to smaller reactors and / or require less moderation. For long operating durations and high burnup, optimization (minimization) of the reactor volume will be primarily driven by accommodating fission gas release. UO_2 swells and releases more fission gas at higher temperatures, requiring either a longer fuel plenum, thicker fuel pins, or release of the fission gas from the plenum to space. A longer fuel pin directly increases the mass of the shield, and a thicker fuel pin impacts the core size and mass. System trades will need to be performed to establish optimum fuel pin designs and performance.

UO_2 Technology Gap Assessment

The following technology gaps were identified for UO_2 fuel development for FSP applications. Overall, UO_2 fuel performance is well understood for FSP operating conditions. Therefore, UO_2 fuel forms had the least amount of technology gaps identified.

1. Refractory Cladding and Liner Materials Development

At operating temperatures above 1100 K, stainless steels and superalloys do not exhibit the desired mechanical properties for use as structural materials within the reactor core. Therefore, development of FSP reactors under the system parameters selected for this study would require a refractory materials development program for claddings and associated liner materials for the desired temperature range of the core. These claddings could either be refractory metal based (such as Nb or Ta alloys) or ceramic-ceramic composites (such as $C\text{-}C_f$ or $SiC\text{-}SiC_f$). This development program would aim to establish cladding feedstocks and alloy production processes, demonstrate cladding fabrication to meet FSP geometry and purity specifications, confirm cladding properties relevant to the design and response to high temperature irradiation, and develop assembly and joining processes to allow for sealing of pellets into claddings and assembly of the cladded fuel element into the reactor. Barrier coatings or cladding liner development may also be required to prevent undesirable reactions driven by chemical incompatibility between the cladding and fuel or fission products. The cladding-liner system could also be engineered to prevent or minimize fission product migration out of the fuel assembly. The current history or the state of the art for high temperature cladding and liners is not addressed in this report as it is focused on the basic fuel types. Additional research and literature investigations are needed to understand the current materials properties and production capabilities that are available to support FSP and NEP systems for HALEU fuel systems.

2. Demonstrate Production Scale Fabrication Processes and Infrastructure

UO_2 fabrication techniques are well understood but must be demonstrated to meet application specific requirements. UO_2 pellet production will be required to be demonstrated to meet the fuel specification established for the FSP reactor. This will include fabrication of overall fuel geometry and corresponding tolerances, as well as impurity content, stoichiometry, and enrichment. Established fabrication processes will need to be demonstrated to scale to the production rates needed for FSP reactor assembly and testing. Confirmatory testing of as produced fuel forms is recommended to demonstrate as-fabricated fuels exhibit the acceptable performance extrapolated from the existing fuel performance database. Existing infrastructure may be leveraged for research and development activities, but a dedicated fabrication process line will likely be desired by industry to ensure full quality and process control is maintained during the fabrication of fuel for the demonstration and flight reactors.

3. Integrated Reactor System Behavior

The separate effects database for UO_2 fuel forms is well established. The primary performance database gap for UO_2 fuel forms will be demonstrating acceptable fuel performance under prototypic conditions, including interactions with other components within the reactor. A reactor operations database will need to be established and fuel performance demonstrated as an integrated component within the reactor system.

4. Moderator Development and Integrated Fuel / Moderator Performance Demonstration (Thermal Reactors Only)

FSP HALEU fast reactor designs for power levels (7-10 kW_e, 40-60 kW_{th}) have been shown to result in a significant mass penalty (> 100% increase) compared to HALEU thermal reactors [92]. Introducing moderation into the FSP reactor is anticipated to result in the smallest HALEU reactor critical mass and volume. Moderators are relatively low TRL for U.S. space power reactor systems due to the low heritage from past national space programs. Major challenges for moderator development include the development of net shape moderator fabrication and assembly techniques, demonstration of moderator stability under all design operating modes, and demonstration of controllable reactor operations with a moderator. The ability of a component to efficiently moderate neutrons is dependent upon the moderator material composition (high density, low atomic weight elements are the most efficient moderators) as well as moderator component geometry / placement (moderator spacing and position impacts the probability neutrons will interact with the moderator to slow down and probability that thermal neutrons are capable of being absorbed in the fuel, not elsewhere in the reactor). Therefore, it is important to show during the development effort that the moderator composition is stable and the moderator is capable of retaining its structural integrity so that the reactivity of the moderator (or moderator contribution to the neutron balance) is maintained.

Metallic hydride moderators (such as zirconium hydride, ZrH_x, and yttrium hydride, YH_x) present unique operating challenges to ensure the hydrogen is not lost, or no significant hydrogen migration within the component occurs which will impact the thermalization of neutrons and power profile over the length of the element. The moderator design must also prevent catastrophic cracking resulting in a neutron streaming path which can lead to loss of criticality. Planned combined effects fuel testing should include the moderator components as a part of the assembly to capture any fuel-moderator interactions under relevant conditions. If undesirable interactions are observed, they can be mitigated before an integrated reactor system test is conducted. Additional research and literature investigations are needed to understand the current materials properties, performance, maximum operating duration, and production capabilities that are available to support FSP and NEP systems.

UN for Fission Surface Power Applications

UN pellet fuel is also a viable candidate with a significant performance database developed for space reactor applications. It has high fuel density and high thermal conductivity properties. The limiting factors associated with UN fuel performance are high temperature UN dissociation (limits maximum temperature-operating duration capability), chemical compatibility with cladding, fission product release at high burnups (lower solid fission product retention compared to UO_2), and stability / fatigue behavior under multiple thermal cycles. UN fuel can also be used in either a fast or moderated reactor core and would likely provide the smallest critical mass and volume.

Technology development activities can be done with existing equipment and facilities. Additional fuel development testing will be needed (especially with respect to temperature-operating duration, due to its high temperature dissociation characteristics) to properly characterize this fuel for FSP applications. A dedicated HALEU UN production line would likely be needed for reactor production activities as this currently does not exist within industry.

UN Performance Assessment

UN fuels have not been commercially deployed in the U.S. like UO_2 fuel forms, however a large performance database does exist for UN fuel types from liquid metal and fast reactor development programs [93, 94]. Fuel performance data corresponding to these programs primarily consist of fast spectrum irradiations (temperatures ≤ 1023 K) with power densities (> 100 W/cm^3) and burnups (~100 MWd/kg) in the range desired for FSP applications. UN also has one of the most extensive fuel performance databases for space power reactor applications. Development and testing on UN fuel forms was pursued through the historic SNAP-50 [95], the NASA Lewis Compact Reactor Program [96, 97], and SP-100 [88, 98, 99]. UN was also surveyed as a candidate fuel in the JIMO program [58]. These historic programs allowed for a large collection of high temperature and irradiation test data to assess UN chemical compatibility with possible claddings, UN performance under irradiation environments, and cladding-working fluid compatibility (primarily focused on compatibility with Li). **Table D.2** presents a summary of the existing UN performance database [93, 94, 95].

Table D.2 Comparison of the Existing Fuel Performance Database for UN Fuel Forms to FSP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	Working Fluid	Interfaces	Power Density (W/cm^3)	Operating Duration (or Burnup)	Reactor Operations
Study Reference	1400	-	Refractory Cladding	≤ 50	10 years	-
Existing Performance Database						
LMR	< 1023	Na and Pb	Steel Cladding	3.5 – 133	years	No
SNAP-50	> 1263	Li (He Gap)	Nb-1Zr alloy	-	1150 – 13000 hours	No
SP-100	1100 – 2100	Li	Nb-1Zr PWC-11 (W or Re liner)	-	7 years (4.5% FIMA)	No
NASA Lewis Compact Reactor	1103 – 1263	Li	T-111	-	- (Up to ~1% FIMA)	No

Following the completion of UN pellet testing in support of the SP-100 program, UN operating duration of at least 7 years at operating temperatures of 1500 K were predicted with peak operating temperature potential of up to 1800 K [85]. The SP-100 fuel form was to be qualified for 2 years of operation at 1500 K at the end of the program.

Depending on the reactor operating conditions required for the FSP reactor design, UN may be able to meet the desired FSP performance parameters of this study. Due to the high uranium loading of the fuel form, FSP reactor types that would correspond to smaller reactors and / or require less moderation. While UN has been demonstrated to be sensitive to similar limiting performance phenomena identified for UO_2 for space reactor applications, it does exhibit different response to irradiation which impacts UN performance [86, 85]. Key phenomena to consider for UN fuel performance is UN dissociation behavior at high temperature and swelling phenomena. At high operating temperatures and low-pressure environments (such as what is expected for a heat pipe space power reactor), UN can dissociate leading to the formation of free N_2 gas and molten uranium (~1405 K melting temperature). Compared to UO_2, UN is more sensitive to swelling under high temperature irradiation [86].

See Appendix E, Section "NEP Fuel Overview, UN for NEP Applications" for technology gaps identified for UN fuels for power reactor applications.

AGR TRISO for Fission Surface Power Applications

The AGR TRISO is also a candidate fuel with existing test data and fuel models from the AGR program that can be applied for the design of FSP systems. It has a low fuel density and moderate fuel thermal conductivity properties. The limiting factors associated with TRISO fuels are concerned with limited fuel densities that can be achieved and the maximum time / temperature capability at the anticipated FSP operating temperature. A core based on this fuel type would likely have the largest core mass and volume of the three due to low uranium loading. Technology development activities can be done with existing equipment and facilities. TRISO particles can maintain structural integrity at extremely high temperatures, reaching as high as approximately 1,600 °C (1873 K). Additional fuel development testing will be needed for any modifications to the AGR TRISO to properly characterize this fuel for FSP applications.

AGR TRISO Performance Assessment

The existing TRISO coated particle fuel performance database has been established primarily in support of HTGR applications (He working fluid) [37]. Fuel performance data corresponding to these programs primarily consist of epithermal to thermal spectrum irradiations, peak temperatures exceeding 1500 K, with low power densities (< 100 W/cm^3) and burnups (up to 20% FIMA) in the range desired for FSP applications. Some testing has been performed at power densities, temperatures, and burnups exceeding that expected to be needed for FSP applications. TRISO particle fuels have been proposed for use in historic space reactor programs due to their high temperature and burnup capability as well as their demonstrated ability to constrain fuel swelling effects largely locally to the coated particle and fission product retention. However, no experimental studies have been performed using TRISO-based fuel forms in any of the historic space reactor development programs. A summary of the existing performance database for TRISO fuel forms is compiled in **Table D.3** [37].

Table D.3 Comparison of the Existing Fuel Performance Database for the AGR TRISO Fuel Form to FSP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	Working Fluid	Interfaces	Power Density (W/cm^3)	Burnup (or Fluence)	Reactor Operations
Study Reference	1400	-	Graphite Matrix, Na Heat Pipe with Steel Structure	≤ 50	10 years operating duration (2.5×10^{25} n/m^2)	-
Existing Performance Database						
German AVR Program (UO_2 TRISO)	1623	He	Graphite Matrix Pebble	40	10% FIMA (6×10^{25} n/m^2)	Yes
Japan HTTR Program (UO_2 TRISO)	1768	He	Graphite Matrix Compact	40	6% FIMA	Yes
US Peach Bottom (UC_2 BISO)	~1913 +/- 50	He	Graphite Matrix Compact	80	9.39% FIMA (4.2×10^{25} n/m^2)	Yes
US Fort Saint Vrain (UC_2 TRSIO)	1573	He	Graphite Matrix Compact	60	16% FIMA (4×10^{25} n/m^2)	Yes
US AGR Program (UCO TRISO)	1678	He / Neon	Graphite Matrix Compact	150	20 at% FIMA (5.6×10^{25} n/m^2)	No

Although the existing TRISO fuel form performance database is constrained to terrestrial applications, the required operating conditions for HTGRs share similar operating requirements for space power reactors. The AGR TRISO fuel form will be qualified for up to 1678 K operating temperatures and 20 at% FIMA burnups, well exceeding that needed to satisfy the FSP and NEP system performance parameters of this study. Lifetime limiting phenomena for TRISO fuel forms have been identified through ongoing research activities for advanced reactor applications [100, 101]. Although limiting phenomena identified for standard TRISO applications are primarily focused on preventing fission gas release, these phenomena may also impact fuel operating temperature and operating duration for space reactor applications. These phenomena include:

- Kernel migration and kernel-coating interactions (high temperatures)
- Pressure vessel failure due to internal gas pressure (high burnup)
- Coating cracking and volume change due to irradiation effects (high temperature and burnup)
- Fission product-coating interactions (high temperatures and burnup)
- Silicon carbide coating decomposition at high operating temperatures (high temperatures)

Current TRISO fuel forms are well optimized for the operating temperatures and burnups of interest to this study and should not exhibit life limiting phenomena that would impact fuel performance under space power reactor conditions. Due to the low uranium loading of the fuel form, FSP reactor types that would correspond to this fuel type would be larger on average and / or require more moderation.

AGR TRISO Technology Gap Assessment

1. Modification of Existing AGR TRISO Fuel Fabrication Processes for Higher Uranium Densities

To increase uranium densities for FSP applications, it is recommended that the AGR TRISO be modified to larger kernel diameters and increased fuel volume loadings within the pellets. It is expected that existing infrastructure may be utilized to meet this need, but technology development will be required to optimize existing parameters to meet the needs for FSP fuel production.

2. Establish Fuel Irradiation Performance Database for FSP Operating Environments

FSP applications will require higher power densities than the established AGR TRISO fuel performance database. Further, modification of the AGR TRISO fuel form will result in changes to the fuel microstructure which may impact fuel performance. Changes to fuel material properties and irradiation performance are expected due to AGR TRISO modification. Fuel development of this fuel type for FSP should include confirmatory irradiation testing to gather data to show that the existing AGR fuel performance database is valid for FSP applications or identify any impacts of changes to fuel design and operating conditions on fuel performance.

3. Fuel Element – Heat Pipe Compatibility

Chemical compatibility between the fuel element and heat pipe must be demonstrated for the FSP fuel form based on the AGR TRISO. Graphite (AGR fuel pellet matrix) is known to be reactive with many metallic materials (including stainless steels and refractory metals) at high temperatures. Protective coatings or diffusion barriers may be required to be developed to enable compatibility between the fuel and heat pipe. Separate effects testing should include acceptable demonstration of fuel element and heat pipe compatibility.

4. Moderator Development and Integrated Fuel / Moderator Performance Demonstration

This concept requires moderation similar to that needed for the UO_2 option. Please refer to UO_2 Technology Gap 4 for a full description.

5. Demonstrate Production Scale Fabrication Processes and Infrastructure

While all fuel types will require that a production-scale HALEU fuel line be established, the AGR TRISO is anticipated to have additional technology development required in this area. This assessment is driven by the need to establish specialty fabrication processes and feedstocks for moderator as well as possible protective coatings between fuel and heat pipe components. Existing infrastructure may be leveraged for research and development activities, but a dedicated fabrication process line will likely be desired by industry to ensure full quality and process control is maintained during the fabrication of fuel for the demonstration and flight reactors.

6. Integrated Reactor System Behavior

This is a universal risk for all reactor fuel systems. A reactor operations database will need to be established and fuel performance demonstrated as an integrated component within the reactor system.

Metallic and Hydride Fuels for Fission Surface Power Applications
Metallic UMo fuels have relatively high readiness to meet FSP needs and are estimated to be produced at 10-100 kg per year [102]. UMo alloy fuel has the highest uranium loading out of each of the fuel candidates identified in this section which would allow it to achieve the lowest critical mass for fast or moderated HALEU cores. UMo fuels are a suitable option if the reactor temperature (< 800 °C, < 1073 K) and burnup are sufficiently low. The limiting factors for metallic fuel performance are low relative melting temperature and high fuel swelling under high temperature, high burnup conditions. UMo has been successfully demonstrated under FSP reactor conditions at lower operating temperatures (up to 840 °C) [76]. Government and industry infrastructure exists for fabrication of UMo fuels for technology development activities.

Uranium zirconium hydride ($UZrH_x$) is also a high readiness fuel that can be procured from TRIGA suppliers but requires technology development to meet FSP temperature and operating duration requirements. Like UMo fuels, if FSP design temperatures were lower, $UZrH_x$ fuels could offer the advantage of high manufacture readiness, existing fuel performance databases, and an existing reactor operations database. The limiting factors for hydride fuel performance are high temperature hydrogen loss from the fuel and swelling under high temperature conditions. $UZrH_x$ fuels previously developed in support of SNAP-10A were developed for a peak operating temperature of 975 K (700 °C) for at least one year [103].

Due to the inability of these fuel forms to enable the desired FSP system parameters for this study, these fuel forms were not included as a part of the assessment.

Cost and Schedule Assessment

FSP fuel candidates were each assessed to correspond to a low-cost development program due to existing fabrication and testing infrastructure. Anticipated schedule for fuel development was anticipated to be low for UO_2 and AGR TRISO fuel forms. However, refractory metal cladding development (pellet fuels) and moderator development (coated particle fuels, optional pellet fuels) would be schedule driving and likely result in a moderate schedule for overall system readiness ahead of a TRL 6 reactor demonstration test. Due to less recent experience base for UN pellet fuel forms, a moderate schedule is anticipated for UN pellet fuel development. There is the opportunity to accelerate schedule for FSP development if refractory metal cladding and moderator development can be avoided, which could reduce overall schedule too low for UO_2 pellet fuels. Laboratory scale infrastructure exists for the fabrication and testing of subscale fuel sample prototypes under separate effects conditions desired for Phase I and II testing.

UO_2 Assessment

UO_2 fuel can be readily produced and obtained from commercial or Government facilities. HALEU UO_2 fuel may be produced at quantities acceptable enough to meet development needs for phase I and II testing. If refractory materials are needed for the cladding (> 1100 K), additional cladding development to establish the fabrication processes capable of meeting FSP requirements (geometries, purity level, alloy type, etc.) will need to be established and demonstrated.

Cost: Low

Schedule: Low (T > 1100 K), Moderate (T < 1100 K)

UN Assessment

UN fuel can be readily obtained from Government facilities. HALEU UN fuel may be produced at quantities acceptable enough to meet development needs for phase I and II testing. Some additional technology development is needed to recapture the technology demonstrated under the SP-100 program. This would include fabrication demonstration of fuel pins and fuel-cladding assembly processes, as well as demonstration testing (nuclear and non-nuclear) to demonstrate acceptable UN stability (negligible dissociation) under required operating conditions. Therefore, a moderate fuel development schedule is anticipated for UN pellet fuel types.

Cost: Low

Schedule: Moderate

PYC- SiC TRISO Assessment

TRISO fuel can be readily obtained from commercial and Government facilities. HALEU coated particle production lines are currently in the process of being established and HALEU coated particles may be able to be fabricated at low quantities using existing government facilities which should be sufficient to meet the needs of Phase I and II testing. Some technology development will be needed to modify the fuel form to enable higher uranium densities (increase kernel diameter and fuel volume loadings). This was not anticipated to significantly impact the fuel development schedule compared to UO_2 (low). However, reactors of this type will require moderation to minimize reactor mass. A moderate schedule is expected for moderator development.

Cost: Low

Schedule: Moderate (moderator development required)

Appendix E: Nuclear Electric Propulsion Fuel Assessment

NASA is currently studying NEP systems as an option for human exploration of Mars and the outer solar system. Recent NASA studies for 2-year-round trip Human Mars architectures evaluated hybrid-chemical / NEP systems with a chemical stage for high-gravity maneuvers near Earth and Mars and a 2 MWe NEP stage for interplanetary thrusting [104]. The NEP stage uses a nuclear reactor to generate electricity to power high I_{SP} thrusters (> 2,000 s) for in-space propulsion. The high I_{SP} of NEP systems enables the spacecraft to carry less propellent, allowing more mass for payload. NEP is also an attractive option for outer planet science missions in the power range from about 10 kW_e [105] up to 200 kW_e [58]. NEP systems are similar to FSP systems in that they include a nuclear reactor, power conversion, heat rejection, and power management & distribution. The mass (or more precisely, the ratio of mass to power or specific mass) of the total NEP power system is a major driving factor due to the direct influence on achievable mission performance. Low specific mass NEP power systems tend to require high reactor temperatures and high output power levels. As a result, the nuclear fuel, reactor coolant, and power conversion technology is likely to be different from the choices made for an FSP system. The system parameters for an NEP system used for this study are as follows:

- Reactor power - 10 MW_{th}
- Reactor outlet temperature - 1200 K,
- Reactor coolant / heat transport – pumped lithium (Li) or helium xenon (HeXe),
- Operating duration - 5 years

In NEP systems, the reactor provides thermal power to a power conversion subsystem that supplies electric power to the electric propulsion thrusters. Increasing reactor exit temperature is desirable to increase the thermodynamic efficiency of the power conversion cycle which generally reduces the radiator area (generally lower heat rejection subsystem mass) and decreases the reactor thermal power (generally lower reactor subsystem mass) to achieve the lowest system specific mass. Like FSP systems, this goal often drives the NEP fuel form to be at a higher operating temperature than typical terrestrial designs. However, some synergisms can be exploited with advanced reactor and fuel development projects, such as Very High Temperature Reactor [106], Enhanced Accident Tolerant Fuel [107], and High Temperature Micro Reactor [108], which may be leveraged to help share development costs. While a high temperature fuel form is desirable for NEP applications, operating temperature capability must be balanced with desirable material and nuclear properties to minimize reactor mass as well as enable long operating life (high burnup, creep resistance). A desirable attribute of NEP fuel systems is high uranium loading to allow for reactor critical mass to be minimized and provide flexibility in reactor spectrum choices. Compatibility with the working fluid (liquid metal or gaseous) must also be considered in the fuel design and it is desired that the fuel be at a high technology readiness. The specific attributes desirable for NEP fuels are:

- **A high uranium fuel density.** A high uranium density (specifically U-235) will allow for smaller reactor designs. Fuels that have a low uranium density (such as particle fuels) will typically require more fuel elements, more moderator elements and / or more reflector material to sustain criticality through the reactor operating duration and minimize reactor critical volume.
- **High operating temperature capability.** To decrease specific mass, high conversion efficiency is desired for the power generation system. This increases the attractiveness of

a reactor capable of heating working fluids to higher operating temperatures compared to traditional terrestrial applications.

- **Irradiation tolerance.** The fuel does not exhibit adverse fuel cladding interactions over the operating duration. Failure caused by swelling or corrosion of the fuel pin would lead to fission product release from the fuel element and loss of the uranium from the reactor core.
- **Good thermal conductivity.** A fuel that has high thermal conductivity will keep the peak thermal temperatures in the fuel low. Thermal conductivity may evolve over time due to irradiation damage incurred during fuel operation. If the thermal conductivity degrades, then the fuel will be required to operate at higher temperatures which affects the core neutronics (reactivity and power profiles) to maintain performance. Higher operating fuel temperatures increases the possibility of fuel clad interactions and rupture.
- **Structural stability.** The fuel will need to survive a variety of loads, vibrations, and shock from launch and in-space operations. Any bending, deformation or fracturing of the fuel or fuel element during launch or operations will affect the core neutronics as well as thermal characteristics or the reactor.
- **Existing fuel property, performance, and reactor operations database**. If fuel properties and performance under relevant conditions is well characterized, there is increased confidence in predictive modeling data and reduced technical risk in the fuel qualification program for a given design. Existing reactor operations data reduces risk for system level demonstrations and can bolster related safety analyses required for ground demonstration test facilities.
- **Fabrication process readiness and availability.** Leveraging existing fabrication processes can reduce the technology development efforts pursued in support of fuel qualification. Availability of fabrication process equipment allows for immediate prototyping of required test articles to be used in demonstration / testing activities.
- **Test facility availability.** Availability of in pile and out of pile test capabilities for separate effects testing and integrated fuel / moderator testing. Do test facilities and PIE capabilities exist for fuel, cladding and moderator for prototypic conditions?

Three different fuel types surveyed in this assessment are relevant to NEP applications: UO_2 pellet, UN pellet, and modified TRISO particle-based fuel forms. Anticipated modifications for TRISO fuel forms for NEP applications include increasing the kernel diameter and switching to a higher volume loading uranium compound (such as UN) to increase the particle loading. NEP particle coatings may also be removed, or their thickness reduced and fuel volume loading within the matrix (SiC or graphite) to improve fuel volume loading further. Historical technical interchange meetings with industry identified that UO_2 and UN are the most suitable chemical fuel forms for NEP [109, 110]. Both these chemical forms are well known to U.S. developers and possess sufficient knowledgebase which can be verified (confirmatory testing) for NEP application. Between them, however, UO_2 possesses less desirable physical and mechanical properties (e.g., density and thermal conductivity) but has the highest quality irradiation knowledgebase and is widely used. On the other hand, UN - due to its superior thermophysical properties - is being developed for use in light water and advanced reactors with special cladding as part of DOE's Accident Tolerant Fuels (ATF) Program [111]. HALEU UO_2 and UN pellet fuels could likely be used in both fast and moderated reactor systems. Moderated systems may be the lowest critical mass. UN coated particles are the chemical form of choice for the SNP Nuclear Thermal

Propulsion program and DOE's Transformational Challenge Reactor program [112, 113]. There is potential for coated particle fuels to both retain fission products and fuel swelling primarily local to the coated particle, which may result in a more robust fuel form and testable reactor design. However, the maturity of this fuel form is low compared to reference pellet fuel types and the AGR coated particle. A reactor of this type would require additional moderation to minimize mass for an NEP system.

In general, it was assessed that each fuel form is capable of performing under the operating durations and temperatures that would correspond to the reference NEP system parameters. It is expected that NEP reactors will be smaller (lower volume and mass) with UO_2 and UN pellet fuels when compared to coated particle-based fuel forms due to higher uranium loading. Comparable reactor sizes may be possible with modified coated particle fuels, but they would require greater moderation and longer fuel development schedule due to lower technology readiness. Cost and schedule were assessed to be moderate for both UN and coated particle fuel forms. Schedule may be accelerated with the use of a UO_2 fuel form due to the large existing performance database for UO_2 fuel forms. For NEP systems, alpha is the primary driver and minimizing reactor mass / volume is of high interest.

NEP Fuel Form Overview

UO_2 for NEP Applications

A summary of UO_2 performance considerations for space power applications is included in Appendix D. The findings reported in this section also apply to NEP applications. UO_2 fuel can be used in either a fast or moderated NEP reactor system. The fast reactor variant may be larger and require more fuel due to criticality constraints but would not require any moderator development.

UO_2 Performance Assessment

The existing UO_2 performance database is compared to NEP fuel performance parameters in **Table E.1**. Compared to FSP systems, NEP fuel operating durations will be shorter. Therefore, creep will be less limiting in the selection of structural claddings and fuel exposed to less extreme burnup conditions. Additional considerations for NEP applications include cladding and working fluid compatibility. NEP reactors will likely utilize a refractory metal cladding and candidate material compatibility with Li and He-based working fluids are well established [79, 114, 77, 115, 75]. In summary, most material candidates are expected to exhibit acceptable compatibility with HeXe and Li. However, materials may be sensitive to impurity content inherent to the working fluid which will further reduce limiting operating temperatures than if considering solely creep rupture.

Table E.1 Comparison of the Existing Fuel Performance Database for UO_2 Fuel Forms to NEP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	Working Fluid	Interfaces	Power Density (W/cm^3)	Operating Duration (or Burnup)	Reactor Operations
Study Reference	1400	Li or He-Xe	Refractory Cladding	≥ 100	5 years	-
Existing Performance Database						
LWRs	Varies > 1473	H_2O	Zr-alloy Cladding	55 - 90	years	Yes
LMRs	Varies >973	Na	Steel Cladding (most common)	3.5 - 133	years	Yes
SP-100	1000 - 2200	Li	Nb-1Zr Cladding (PWC clad was new baseline, W and Re liners)	not reported	months (≤ 6% FIMA)	No (EBR II irradiation experiments only)
TFEVP	1700 - 1950	-	W, Nb	not reported (2 - 6 W/cm^2)	≤13,500 hours (0.07 - 1.4% FIMA)	TOPAZ Reactor Experiments performed within the US

UO_2 Technology Gap Assessment

Technology development activities can be done with existing equipment and facilities. Barrier coatings may be required to prevent chemical incompatibility (UO_2 is incompatible with Nb, Ta), fission product interactions, and / or working fluid interactions. Molybdenum and Niobium based cladding material may suitable, but development and testing activities would be required. A dedicated HALEU UO_2 production line will likely be necessary for reactor production activities. An NEP test facility for long term testing may be averted if reactor component designs are within known limits or requires limited extrapolation from existing databases. SiC-SiC_f type cladding with a liner may also prove to be a viable cladding material, but development and testing will be needed. Full scale production of HALEU net-shape pellets to desired specifications will need to be developed. Development and fabrication of cladding material (possibly refractory metal or SiC-SiC_f) to meet operational requirements is needed. It is anticipated that this fuel form with the high temperature cladding will follow the general fuel development cycle to achieve TRL 6 starting from lab scale equipment, to engineering production scale equipment, and ultimately to full scale production equipment.

UN for NEP Applications

A summary of UN performance considerations for space power applications is included in Appendix C. The findings reported in this section also apply to NEP applications. UN fuel can also be used in either a fast or moderated NEP reactor system.

UN Performance Assessment

The existing UN performance database is compared to NEP fuel performance parameters in **Table E.2**. Compared to FSP systems, reduced reactor operating durations for NEP systems reduces uncertainty in high temperature, high burnup fuel operating behavior which allows for higher confidence that UN can satisfy NEP system performance parameters.

Table E.2 Comparison of the Existing Fuel Performance Database for UN Fuel Forms to NEP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	Working Fluid	Interfaces	Power Density (W/cm^3)	Operating Duration (or Burnup)	Reactor Operations
Study Reference	1400	Li or He-Xe	Refractory Cladding	≥ 100	5 years	-
Existing Performance Database						
LMR	< 1023	Na and Pb	Steel Cladding	35 – 133	years	No
SNAP-50	> 1263	Li (He Gap)	Nb-1Zr alloy	-	1150 – 13000 hours	No
SP-100	1100 – 2100	Li	Nb-1Zr PWC-11 (W or Re liner)	-	7 years (4.5% FIMA)	No
NASA Lewis Compact Reactor	1103 – 1263	Li	T-111	(2.8×10^{14} n/cm^2 s)	- (Up to ~1% FIMA)	No

In the case of UN, swelling would be higher and much more sensitive to the operating temperature and appears to be consistent with modeling / correlation predictions [93, 116]. At the anticipated early generation NEP operating conditions, a bounding estimate of 6% is suggested for fuel swelling along with minimum (<1%) fuel gas release.

UN Technology Gap Assessment

1. Verify UN Stability Under High Temperature-Long Lifetime Operating Conditions

UN performance is known to be sensitive to operating environment (operating pressure), cladding compatibility, the presence of light element impurities, stoichiometry, phase purity (presence of other U_xN_y phases), and presence of metallic FPs under extended exposure to high operating temperatures (> 1400 K) [63, 120]. The thermodynamic stability of UN (the mononitride phase) has shown to be stable under NEP reactor operating conditions. At approximately 2073 K, UN begins to dissociate at a rate that is dependent on the nitrogen partial pressure of the system, however dissociation is expected to be negligible at 1400 K even under vacuum conditions. Verification measurements can be carried out under reactor conditions to validate the stability of UN fuels for NEP reactors.

2. Re-Establish Fuel Irradiation Performance Database for NEP Operating Environments

There exists an extensive database for UN irradiation data established under the SP-100 program, however, data gaps do exist. When evaluating the existing database, testing conditions should be compared to that required for the HALEU NEP reactor design to match critical parameters such as: operating temperature, fuel pellet geometry and cladding, total burnup (or fluence), irradiation spectrum and power density.

3. Refractory Cladding and Liner Materials Development

This risk is shared with FSP systems. Please refer to UO_2 Technology Gap 1 for a full description. Additional considerations unique to NEP applications include confirming chemical compatibility with the cladding and the working fluid.

4. Demonstrate Production Scale Fabrication Processes and Infrastructure

A UN production line will need to be secured to support reactor demonstration activities. Production scale processes for UN are less established than UO_2 fuel forms. In historic development programs, fabricability and repeatability was a challenge. This has been overcome with recent experience base for laboratory scale equipment. However, scaling these processes may present new, unanticipated challenges. Verification that there are no differences laboratory and production scale fabrication processes will be necessary. Existing infrastructure may be leveraged for research and development activities, but a dedicated fabrication process line will likely be desired by industry to ensure full quality and process control is maintained during the fabrication of fuel for the demonstration and flight reactors.

5. Development of Quality Assurance / Quality Control Techniques

Historically, repeatability / fabricability of UN pellet fuels has been a challenge. This has been overcome with recent experience base (scale up may present new challenges). The fuel development program should include the development of quality assurance and control techniques and the development of a fuel specification based on newly generated data from the NEP testing program.

6. Integrated Reactor System Behavior

This is a universal risk for all reactor fuel systems. A reactor operations database will need to be established and fuel performance demonstrated as an integrated component within the reactor system. Unique considerations for NEP reactors include considering all operating conditions and the interface for working fluid exchange with other critical technology elements within the NEP system. For pumped Li systems, this includes operating modes associated with Li freeze-thaw. For pumped HeXe systems, this includes considering impurities that may be transferred in the working fluid from other subsystems (such as power conversion) if a common working fluid is used.

7. Moderator Development and Integrated Fuel / Moderator Performance Demonstration (Thermal Reactor Only)

This risk is shared with FSP systems. Please refer to UO_2 Technology Gap 4 for a full description.

UN-modified TRISO for NEP Applications

A modified TRISO was assessed for NEP applications. This variant would be beneficial to reducing the reactor volume and mass for a particle fueled reactor but would require a full fuel development program as it is expected to deviate in both operating conditions as well as fuel materials and geometries compared to the AGR TRISO. The limiting factors associated with UN TRISO fuels are low fuel volume loading, UN dissociation at high operating temperatures, and demonstration that the maximum time / temperature capability can be achieved under NEP conditions. A core based on this fuel type would likely have a larger core mass than UO_2 or UN but would be less than that of the AGR TRISO. Technology development activities can be done with existing equipment and facilities. A dedicated HALEU coated particle production line would allow for full fabrication process control.

UN-modified TRISO Performance Assessment

This assessment has identified that a custom modified TRISO-fuel form should be targeted for NEP applications. While a fuel form of this type has not been demonstrated through historic programs, there have been several TRISO related fuel development activities which have tested higher operating temperature or higher uranium density TRISO variants. A summary of the performance database gathered under these programs is presented in **Table E.3** [69, 36]. Due to the lack of an existing fuel performance database for modified TRISO fuel forms and unestablished fuel failure modes under NEP operating conditions, UN-modified fuel performance potential is unknown. Fuel operating temperatures comparable to UN and UO_2 pellet fuels are anticipated, and maximum fuel operating temperature is expected to be limited either by UN dissociation phenomena or, if coatings act to stabilize UN and prevent loss of free N formed by dissociation, SiC-PyC coating interactions and SiC coating stability [117]. Both the graphite matrix and UN-TRISO fuel forms are not expected to have any reaction with a HeXe working fluid that would limit fuel operating duration although they may interact with impurities within the working fluid [118]. Graphite and silicon carbide are not compatible with molten lithium at high temperatures and would require protective coating development to operate in a LMR NEP system [119, 76]. TRISO fuel forms are anticipated to exhibit favorable behavior under irradiation, with irradiation effects primarily constrained to the coated particle level. The TRISO failure modes identified under the historic TRISO development programs (see Appendix D, Section "FSP Fuel Form Overview, AGR TRISO for Fission Surface Power Applications") are expected to be applicable to this fuel type, however NEP operating durations are shorter making high burnup phenomena less important for fuel design compared to FSP systems.

Table E.3 Comparison of the Existing Fuel Performance Database for Modified TRISO Fuel Forms to NEP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	**Working Fluid**	**Interfaces**	**Power Density (W/cm^3)**	**Burnup (or Fluence)**	**Reactor Operations**
Study Reference	1400	HeXe or Li	Graphite Matrix	100	5 years operating duration (2.5×10^{25} n/m^2)	-
Existing Performance Database						
US TCR Program (UN TRISO)	733 K	-	Particle Only	Not reported	6% FIMA (target)	No
Japan TRIZO Program (UO_2 TRIZO)	1923 K	He	Graphite Matrix Compact	Not reported	4.6% FIMA (2.2×10^{25} n/m^2)	No
US TRIZO Program (UC_2 TRIZO)	1523 K	He / Ne	Graphite Matrix Compact	Not reported ($6.5\ kW_{th}/ft$)	28.8% FIMA (10.7×10^{25} n/m^2)	No

UN-modified TRISO Technology Gap Assessment

1. Development of Fuel Fabrication Processes for Modified UN TRISO Fuel Forms

To increase uranium densities for NEP applications, it is recommended that the AGR TRISO be modified to a custom NEP fuel form. This would include establishing fabrication processes to allow for the production of UN kernels (preferably high density, > 90% TD), larger kernel diameters, custom coating thicknesses and greater fuel volume loadings within the pellets. It is expected that existing infrastructure may be utilized to meet this need with some modification for additional processing equipment (conversion furnace) for UN kernel production, technology development will be required to optimize existing coating parameters to meet the needs for NEP fuel production.

2. Demonstrate Acceptable Modified UN TRISO Stability Under High Temperature Operating Conditions

Similar high temperature testing should be performed for the Modified UN TRISO fuel form as UN pellet fuels (see UN Technology Gap 1). Additional consideration for the TRISO fuel form includes confirming acceptable chemical compatibility between the UN kernel and coating layers.

3. Establish Fuel Irradiation Performance Database for NEP Operating Environments

NEP applications will require higher power densities than the established coated particle fuel performance database. Further, the modified UN TRISO fuel form is a custom fuel form for NEP applications and modifications are expected to impact fuel performance (material properties and irradiation performance database). A full test program will require the development of the fuel performance database under separate effects and combined effects conditions. Existing fuel performance models may be used to predict fuel performance and should be benchmarked with data generated through the test program.

4. Working Fluid Compatibility

Chemical compatibility between the fuel element and working fluid must be demonstrated. This may result in the need to develop protective coatings or diffusion barriers.

5. Moderator Development and Integrated Fuel / Moderator Performance Demonstration

This concept requires moderation. Please refer to UO_2 Technology Gap 4 for a full description.

6. Demonstrate Production Scale Fabrication Processes and Infrastructure

A dedicated modified UN TRISO production line will need to be secured to support technology development and demonstration activities. Verification that there are no differences laboratory and production scale fabrication processes will be necessary.

7. Development of Quality Assurance / Quality Control Techniques

This fuel form is a custom fuel for NEP applications; therefore, the fuel development program will need to include the development of quality assurance and control techniques. These likely can be based upon existing techniques for AGR TRISO fuel production. Similar to UN pellets, based on data generated from the testing program, the development of a fuel specification is needed.

8. Integrated Reactor System Behavior

This is a universal risk for all reactor fuel systems. Please refer to UN Technology Gap 6 for a full description for NEP systems.

Cost and Schedule

No perceptible differences were found among the three fuel forms with respect to long term cost difference. NEP fuel development is expected to require moderate cost investment. There exists laboratory fabrication and testing equipment which can be leveraged early in the program to support fuel prototyping and separate effects testing. Additional investment will be needed for technology development of high temperature fuel variants and modifications to testing infrastructure to enable combined effects testing. No perceptible difference was assessed between the required fuel development schedule as well. Similar to FSP applications, refractory metal cladding development (pellet fuels) and moderator development (coated particle fuels, optional pellet fuels) will be needed for the system.

UO_2 Assessment

UO_2 fuel can be readily produced and obtained from commercial or Government facilities at quantities acceptable to meet development needs for phase I and II testing. A refractory metal cladding and moderator fabrication process line will need to be established and demonstrated.

Cost: Moderate

Schedule: Moderate

UN Assessment

UN fuel can be readily obtained from Government facilities at quantities acceptable to meet development needs for phase I and II testing. The same development needs identified for FSP reactors will be required for NEP applications.

Cost: Moderate

Schedule: Moderate

UN-modified TRISO Assessment

TRISO fuel can be readily obtained from commercial and Government facilities and HALEU coated particle production lines are currently in the process of being established. Due to the desire to increase the uranium density of the fuel form for NEP applications, increased cost and schedule is expected for fuel form development compared to FSP applications. Existing fabrication and testing equipment can be leveraged for NEP coated particle fuel development; however, some modifications may be required.

Cost: Moderate

Schedule: Moderate

Other NEP Fuel Development Considerations

NEP System Scalability Considerations

An integrated technology demonstration program aimed specifically toward a NEP system operating at more than 1 MW_e has not been undertaken and no prior NEP reactor has been developed that is representative of that needed to meet the NEP reference parameters of this study. Although preliminary design studies for MW_e-class NEP systems have been conducted, there have not been any significant detailed design, hardware development, or model and simulation (M&S) advances for the full, integrated NEP system. Other technologies which could be included in an integrated system demonstration, such as thrusters and heat rejection, also require technology development to demonstrate performance, lifetimes, and reliability for a MW_e class system.

Increased reactor power level can also result in increased complexity for the reactor design in the areas of thermal fluid interactions and reactor control. The need to extrapolate from existing technologies to a MW_e system required for the baseline mission results in considerable uncertainty which may impede test and facilities planning.

Advanced reactor test facilities are currently under development, but the extent to which those facilities would be able to contribute to the development of MW_e-class NEP systems remains to be determined. The major challenges for testing and facilities planning that must be addressed include evaluation of whether or not system testing must be performed under vacuum environments, high power level operations, and heat rejection. System testing under vacuum environments to verify in-space performance and lifetime, will challenge existing vacuum facility capabilities. Because of all these considerations identified, it is recommended that any NEP development be initiated at a small power and thrust level to gain and understanding of the system performance and system issues. This should be done in keeping with systems and technologies that can scale up to MW_e levels for both performance and lifetime goals. Following initial demonstration and validation of the design, the system can be demonstrated at increasing power levels.

FSP and NEP Extensibility

Both FSP and NEP systems benefit from a low weight, compact reactor design. Both systems have many common fuel, operation, and performance requirements which could allow for a common power reactor fuel form to be developed. For the testing program, much of the testing could be leveraged to benefit both programs and separate effects testing of fuels could largely be shared. Fuel operating temperatures and power densities would be approximately the same for each system. Operating duration is longer for FSP systems, this would require extending the irradiation and high temperature property database compared to NEP fuel development. When developing the testing program, reactor design must be considered for both systems so that the database is comprehensive. Because a NEP system is larger, (50 kW_{th} to 10 MW_{th}) more integrated fuel / moderator demonstration tests (phase II) may be needed for thermal NEP systems to ensure dimensional changes of the fuel and moderator element (as well as hydrogen retention for hydride moderators) do not impact reactivity or thermal performance of the reactor. Additionally, due to the size of the NEP core, internal (in-core) control rod drives may be needed which will impact the power profile in the core and peak fuel temperatures / locations. Reactor power profile optimization could be used to counterbalance this effect and keep the fuel within allowable limits. Working fluid compatibility must also be considered for NEP applications which will impact material selection as well as temperature and stress gradients through the unit cell due to the heat transfer interface.

If it is desired that the FSP fuels be extensible to human mars NEP needs, UN is more extensible than both UO_2 and TRISO fuel forms assessed for FSP. UN pellet fuels would provide for the smallest reactor design for both NEP and FSP systems. UN fuel also has an extensive existing NEP performance database to support fuel fabrication and the reactor design. Use of a single fuel form for both systems would:

- Allow for a common NASA/DOE/DOD fuel production capability for FSP and NEP reactors
- Reduce the design and testing needed to flight qualify hardware and reactor designs for launch which would in turn reduce cost and schedule for obtaining both FSP and NEP systems when considering overall NASA mission goals.

Metallic fuels and $UZrH_x$ fuels are candidates for low temperature FSP systems but are not extensible to high performance NEP applications due to operating temperature limitations. Beyond fuel development, moderator technology development is also extensible between FSP and NEP applications.

Appendix F: Nuclear Thermal Propulsion Fuel Assessment

Nuclear thermal propulsion (NTP) systems are the last space reactor system considered in this assessment. NTP systems are an alternate propulsion technology to NEP that is being considered for crewed missions to Mars. NTP reactors function much differently than NEP and FSP reactors and therefore have much different requirements and design constraints. NTP reactors do not generate power, instead, the thermal power generated through fission is directly transferred to heat a propellant, typically hydrogen, to very high temperatures. At very high temperatures, the hydrogen propellant is expanded through a nozzle to allow for high I_{SP} ($\geq$ 900s) and thrust (typically $\geq$ 15,000 lbf). High I_{SP} and thrust allow NTP systems to enable fast transit times, similar to NEP systems, with a simplified reactor-engine system. The system parameters for an NTP system used for this study are as follows:

- Reactor power - 500 MWth
- Reactor outlet temperature - 2700 K,
- Reactor coolant / heat transport – H_2 propellant,
- Operating duration - 10 hours

In NTP systems, the fuel is the critical technology to ensure the overall performance of the system. A very high temperature fuel form is desired for this application to maximize the achievable exit temperature of the reactor (critical importance to enable the desired I_{SP}). NTP systems require fuels capable of operating temperatures much beyond that demonstrated through terrestrial development programs, but only for short operating durations. While there exist numerous materials with melting temperatures above 2700 K, many of these materials may not be compatible with hydrogen or have desirable nuclear properties which limits the overall fuel design options. Like FSP and NEP systems, the mass of the reactor is still important to minimize, this ensures the overall thrust to engine mass ratio is maximized which reduces propellant requirements to satisfy the mission. The total thermal power of the system directly corresponds to the overall thrust of the system. Therefore, in order to minimize mass, high power densities ($\geq$ 5 MW/L), much beyond that typical of terrestrial or space power reactors, are required for the reactor / fuel form. The specific attributes desirable for NTP fuels are:

- **High melting temperature / high temperature thermal stability.** High melting temperature, much exceeding 2700 K, is typically an indication that the fuel will be thermodynamically stable (no compositional evolution) at high operating temperatures. The fuel must be capable of operating at high temperatures while maintaining margin to melting and resisting significant phase change or material property evolution during operation in order to maintain performance and design margin.
- **Hydrogen compatibility.** Due to the use of a hydrogen propellant for propulsion, fuel forms must be capable of operating in a high temperature hydrogen environment. Required high pressures ($\geq$ 2.5 MPa typical) and flow rates (scales with thrust) may exacerbate corrosion rates if fuel materials are incompatible with the hydrogen propellant.
- **High uranium fuel density.** Like other space reactor applications, high uranium density can be used to minimize the overall volume / mass of the reactor. Fuels that have a low uranium density will typically require more fuel elements, more moderator elements and / or more reflector material to sustain criticality through the reactor operating duration and minimize reactor critical volume.

- **Thermal shock resistance and thermal cycle stability.** Unlike power reactors which operate continuously through the mission, NTP systems operate for short durations (burns) on the order of minutes for multiple total burns throughout the mission. Startup and shutdown are achieved as quickly as possible to maximize effective I_{SP} and prevent damage to engine components. Fast transients may result in thermal shock to the fuel and other reactor components. Operation for multiple burns will result in thermal cycling of the components which can have adverse impacts to fuel performance, such as crack formation, crack propagation or formation of undesirable secondary phases during transients.
- **Slow degradation mechanisms.** It is acceptable and expected that NTP fuel will evolve and degrade throughout its operating duration due to the demanding operating environment. However, fuel degradation should be slow enough to allow the fuel to maintain operation and performance throughout the mission.
- **Existing fuel property, performance, and reactor operations database.** If fuel properties and performance under relevant conditions is well characterized, there is increased confidence in predictive modeling data and reduced technical risk in the fuel qualification program for a given design. Existing reactor operations data reduces risk for system level demonstrations and can bolster related safety analyses required for ground demonstration test facilities.
- **Fabrication process readiness and availability.** Leveraging existing fabrication processes can reduce the technology development efforts pursued in support of fuel qualification. Availability of fabrication process equipment allows for immediate prototyping of required test articles to be used in demonstration / testing activities.
- **Testability of the fuel form.** Fuel / reactor design may result in increased complexity in the development of required fabrication, assembly, and test facilities if the fuel contains high amounts of enriched uranium, unique cooling configurations (such as axial inflow), large or complex and delicate fuel geometries.

Two fuel forms were surveyed in this assessment for NTP applications. The first was an industry modified fuel form based upon coated particle technologies. This fuel type included a zirconium carbide-matrix ceramic ceramic (cercer) fuel with dispersed coated UN particle fuels. The second fuel option was a fuel form representative of a NTP fuel developed through historic programs. The NERVA / Rover fuel form, a graphite matrix fuel with dispersed coated UC_2 particles was evaluated, modifications to the fuel form due to study ground rules of HALEU enrichment and reference system parameters were identified. The Rover / NERVA fuel form was assessed to require operation beyond the fuel kernel melting temperature (~2750 K) to enable the desired system parameters, however this fuel form has a large and proven operational database to reduce risk during reactor technology maturation. The cercer fuel form was identified to have the potential for highest operating temperature due to the theoretical melting point of UN and acceptable compatibility with a hydrogen propellant. Both reactors were anticipated to enable approximately the same reactor mass and had potential for meeting operating duration requirements although additional technology development would be needed. Technology development cost and schedule would be approximately the same for either type, as testing facilities were assessed to be the cost and schedule driver for NTP fuel development. The cercer fuel form was perceived to have a slight cost penalty due to low manufacture readiness, more complex fabrication methods, and lack of an existing performance database.

NTP Fuel Form Overview

NERVA / Rover Derivative for NTP Applications

The NERVA / Rover fuel is a graphite matrix prismatic fuel form with dispersed PyC-coated UC_2 particles for heat generation and ZrC coated channels for heat transfer. These materials have desirable high melting temperatures and good nuclear properties, however the major challenge for this fuel form is incompatibility between the structural graphite matrix and hydrogen propellant. In historic development programs, primary failure modes of this fuel form included hydrogen corrosion and kernel migration. The NERVA / Rover fuel form shares much commonality with ongoing gas reactor development programs including the same matrix material (graphite) and similar coated particle design to the BISO. Much of the existing infrastructure for TRISO-based fuel forms could likely be leveraged for the production and prototyping of this fuel type, although additional technology development would still be needed. To adapt this reactor / fuel technology for modern missions with the reference system parameters of this study and a HALEU enrichment, the fuel uranium loading would need to be increased and moderation would be required as a component of the reactor design. Due to the use of graphite as a structural component within the reactor, fuel forms of this type would be best suited for a thermal (moderated) reactor design. A 2700 K exit temperature would require operation of the fuel particles at a temperature exceeding the melting point of UC_2. While higher melting temperature alternatives do exist, i.e., UO_2, UN, (U,Zr)C, these fuel types were not considered in this evaluation.

NERVA / Rover Performance Assessment

Throughout the NERVA / Rover testing program, nearly 20 ground test reactors fueled with a graphite matrix prismatic fuel form with dispersed PyC-coated UC_2 particles and ZrC coatings were tested. Many lessons related to NTP fuel performance and controlling failure modes were learned through this program. Testing spanned short duration burn tests with multiple burns (up to), long continuous burn durations up to 60 minutes, peak fuel temperatures analyzed to exceed 2500 K, and power densities exceeding 5,000 W/cm^3 [38, 61, 60]. The NERVA / Rover program culminated in the testing of higher performance solid solution carbide, (U,Zr)C, and composite, (U,Zr)C-C, fuel forms at temperatures up to 2500 K for 109 minutes [123]. In addition to the NERVA / Rover program, the SNTP program also tested a high temperature coated particle-based fuel forms for high performance, short operating duration NTP applications [66]. This program was cancelled prior to any reactor operations testing. While the reactor design of the SNTP program was different than the NERVA program, the SNTP program used a similar coated particle type (UC_2 kernel with PyC and ZrC coatings) and testing data could be applicable. A summary of the historic NTP fuel performance database gathered under NERVA and the SNTP programs is presented in **Table F.1** [61, 123, 66].

Table F.1 Comparison of the Existing Fuel Performance Database for Historic NTP Ceramic Coated Particle Fuel Variants to NTP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	Working Fluid	Interfaces	Power Density (W/cm^3)	Operating Duration (Fluence)	Reactor Operations
Study Reference	> 2850	H_2	ZrC Matrix	≥ 5,000	10 hrs (3.6 x $10^{23} n/m^2$)	-
Existing Performance Database						
US NERVA Program (UC_2 BISO)	2500+ K	H_2	Graphite Matrix Element	≤ 5,200	Up to 60 minutes (~5.5 x 10^{22} n/m^2)	Yes
US NERVA Program (UC-ZrC-C)	2500 K	H_2	Graphite Matrix Element	4,500	Up to 109 minutes (8.5 x 10^{22} n/m^2)	No
US NERVA Program (UC-ZrC)	2400 K	H_2	-	4,500	Up to 109 minutes (8.5 x 10^{22} n/m^2)	No
US SNTP Program (UC_2 TRIZO)	> 3000 K	H_2	Particle Only	≤ 1,000	-	No

Fuel performance of NERVA / Rover fuel forms are limited by two key phenomena: hot hydrogen compatibility and UC_2 migration. Fuel endurance curves have been established for this fuel type based on historic Rover / NERVA fuel performance data [61, 64]. These curves show that for 10-hour operating durations, maximum fuel operating temperature would be limited to 2200 K or less due to fuel cracking and corrosion during operation which lead to a loss of structural integrity and reactivity of the fuel over time. Higher operating temperatures and longer operating durations have been proposed (ultimately limited by the sublimation point of graphite) to be achievable with the development of superior fuel coatings which are more resistant to cracking and fully protect the graphite matrix during operation [124, 125]. Another limiting factor for NERVA / Rover fuel operating temperature is UC_2 melting temperature (~2700 K). To meet NTP system performance parameters of this study, peak fuel operating temperatures of 2850 K or greater are anticipated. This would require the UC_2 to be operated in the molten state. Operation above the melting point of UC_2 has been studied in prior programs and is limited by the migration of molten kernels which lead to loss of core reactivity if they are mobile enough to leave the fuel system.

NERVA / Rover Derivative Technology Gap Assessment

1. Hydrogen Compatibility: Development of Fuel Channel Coating Technologies

The graphite matrix is incompatible with hydrogen and a robust high temperature protective coating is required to enable NTP fuel form operation for the desired operating duration.

2. Modification of Historic Fuel Fabrication Processes for Higher Fuel Volume Loadings
HALEU reactors will require either increased fuel volume loadings compared to historic NERVA / Rover designs or increased moderation. Increasing fuel volume loading may reduce the manufacturability of the fuel form. It is expected that existing infrastructure may be utilized to meet this need with some modification for additional processing equipment (conversion furnace) for UC_2 kernel production. Additional technology development will be needed to modify existing fabrication processes or recapture historic fabrication processes for net-shape element production.

3. Demonstrate Molten Kernel Operation
UC_2 melts at ~2700 K, therefore, this fuel form would need to operate at a molten state in the hottest regions of the reactor to meet the performance parameters proposed in this study. Molten kernel operation was investigated and demonstrated in historic programs, however not for the temperatures and operating durations proposed in this study. Alternatively, reduced performance requirements (2300 – 2400 K exit temperature) would allow for higher confidence in fuel performance and avoid molten kernel operation.

4. Demonstrate Transient Performance under NTP Start Up Conditions
NTP start-up transients (~100 K/s) require a fuel form capable of retaining structural integrity for multiple cycles. The fuel form must be demonstrated to be capable of resisting cracking due to thermal stresses during the transient as well as crack propagation under multiple thermal cycles.

5. Moderator and Insulator Development
In NTP systems, the fuel and moderator are in close proximity in the core, thermal insulation and cooling of the moderator is important to ensure moderator integrity is maintained throughout reactor operating duration (consider both normal operations and cooldown / decay heating). Therefore, for NTP systems, moderator and insulator technology development is needed including development of fabrication processes and a material performance database. The impact of moderation will also impact reactor dynamics during start up and care should be taken in the design to avoid the chance of a reactivity excursion due to required reactivity insertion.

6. Fuel Performance Demonstration under Combined Effects Conditions
One of the biggest technical risks for a NTP reactor-engine demonstration is NTP fuel performance under prototypic conditions (combined effects). High power densities (≥ 5 MW/L) desired for NTP fuel form operation results in significant thermal stresses during operation. However, due to facilities limits, there is an inability to test fuels under NTP environments (consider power density, neutron spectrum, hot hydrogen).

7. Demonstrate Production Scale Fabrication / Assembly Processes and Infrastructure
Production scale fuel fabrication, including fuel-tie tube assembly methods were demonstrated during the NERVA program. These techniques need to be recaptured and effects of altering historic processes may impact fabrication process scalability. Existing infrastructure may be leveraged for research and development activities, modification of existing infrastructure is needed to fabricate net shape fuel elements and protective coatings. A dedicated fabrication process line will likely be desired by industry to ensure full quality and process control is maintained during the fabrication of fuel for the demonstration and flight reactors.

8. Development of Quality Assurance / Quality Control Techniques
This fuel form will require modified fabrication process and operating conditions compared to historic predecessors. Therefore, the NTP fuel development program will need to include the development of quality assurance and control techniques. These likely can be based upon historic

techniques, as well as those developed in support of the AGR TRISO program. Similar to NEP fuel types, based on data generated from the testing program, the development of a fuel specification is needed.

9. Integrated Reactor System Behavior

This is a universal risk for all reactor fuel systems. A reactor operations database will need to be established and fuel performance demonstrated as an integrated component within the reactor system. Unique considerations for NTP reactors include considering the reactor-engine interface during operation and the impact of moderation on the NTP start up. Additional considerations may be given to the need for anti-criticality devices, including the impact of their integration on fuel design and assembly. NERVA / Rover Derivative fuel forms may be able to leverage the existing NERVA / Rover operations database to limit required testing.

ZrC matrix-Cercer for NTP Applications

Cercer fuel designs have not been previously pursued in any historic U.S. NTP development program. However, with advances in manufacturing technologies and increased performance needs for modern missions, the usefulness of a fuel form of this type was identified for modern NTP applications. For high performance ($\geq$ 900 s), HALEU NTP applications, ZrC-matrix cercers are attractive candidates due to the low thermal neutron absorption cross section, high melting point, and good hydrogen compatibility of ZrC. For this study, a ZrC-matrix cercer fuel with dispersed coated UN particles was assessed. Fabrication processes required for the production and assembly of net-shape components are not well understood and have a limited experience database. Similar to NERVA / Rover fuel forms, the ZrC-matrix cercer fuel form has synergies with ongoing TRISO-based fuel form development activities. While the matrix material is different than that used in terrestrial gas cooled reactor designs, much of the existing infrastructure for coated particle production could likely be leveraged for the production and prototyping of this fuel type. Additional technology development and infrastructure investment would still be needed for net shape cercer fuel production and to ensure that all required feedstocks were available at the required quantity for the development program.

ZrC Cercer Performance Assessment

ZrC cercer fuel forms are novel fuels not previously developed through major historic space reactor or power reactor development activities. Therefore, the fuel performance database for this fuel type does not exist. However, there has been UN-kernel and other high temperature coated particle fuel development activities which have led to the development of some test data that may be applicable to initial cercer fuel design activities. A summary of the performance database gathered under these programs is presented in **Table F.2** [36, 69, 126, 66]. The first three of the programs listed in this table were also reported in Appendix E, Section "NEP Fuel form Overview, UN-modified TRISO for NEP Applications" and are applicable to modified TRISO fuel forms for NEP applications.

Cercer fuel performance potential is unknown due to the lack of an existing fuel performance database for cercer fuel forms and unknown fuel failure modes. Cercer operating temperatures up to 3100 K (theoretical melting temperature of UN) have been proposed and fuel operating duration identified to be possibly limited by UN-PyC interactions which could lead to the formation of lower melting temperature UC_2, UC, or U(C,N) [127]. Kinetics of the rate of this reaction is unknown. Cercer fuels are anticipated to exhibit acceptable hydrogen performance due to low reactivity of ZrC with H_2 at temperatures of interest to this study [128]. If cercer operating duration is limited by hot hydrogen compatibility, fuel endurance similar to solid solution carbide fuel forms is expected (operating temperatures exceeding 2800 K for 10-hour durations) [64].

Table F.2 Comparison of the Existing Fuel Performance Database for Other Coated Particle Fuel Variants to NTP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	Working Fluid	Interfaces	Power Density (W/cm^3)	Operating Duration (Fluence)	Reactor Operations
Study Reference	> 2850	H_2	ZrC Matrix	≥ 5,000	10 hrs (3.6×10^{23} n/m^2)	-
Existing Performance Database						
US TCR Program (UN TRISO)	733	-	Particle Only	Not reported	-	No
Japan TRIZO Program (UO_2 TRIZO)	1923	He	Graphite Matrix Compact	Not reported	- (2.2×10^{25} n/m^2)	No
US TRIZO Program (UC_2 TRIZO)	1523	He / Ne	Graphite Matrix Compact	Not reported (6.5 KW_{th}/ft)	- (10.7×10^{25} n/m^2)	No
US SNTP Program (UC_2 TRIZO)	> 3000	H_2	Particle Only	≤ 1,000	-	No
US (U,Zr)C Programs (UC-ZrC BISO)	2923	-	Graphite Matrix Compact	n/a	n/a (no irradiation data)	No

ZrC Cercer Technology Gap Assessment

1. Development of Fuel Fabrication Processes for Cercer Fuel Particles

Similar to technology development needs for coated particle NEP reactors (modified TRISO technology gap 1), ZrC-fuel development will require technology development to establish methods to fabricate custom UN coated particle fuel forms. This would include design activities to define coated particle geometries / coating design as well as demonstrating the fabricability of the selected coated particle geometry. It is expected that existing infrastructure may be utilized to meet this need with some modification for additional processing equipment (conversion furnace) for UN kernel production, technology development will be required to optimize existing coating parameters to meet the needs for NTP fuel production.

2. Establish Hot Hydrogen Fuel Performance Database

ZrC is anticipated to demonstrate acceptable hot hydrogen behavior, but thermal cycling performance of a composite fuel based on a ZrC-matrix is unknown. Additionally, the impact of hydrogen interaction on ZrC-fuel properties (mechanical and thermal properties) is unknown. Establishing a hot hydrogen performance database for this fuel form through non-nuclear separate effects testing should also allow for some insight into controlling fuel failure modes of this fuel type. Test data gathered under this phase may be used to validate fuel performance models.

3. Establish Fuel Irradiation Performance Database for NTP Operating Environments

ZrC-cercer fuel response under NTP irradiation conditions is unknown. Separate effects testing of ZrC cercer fuel forms under prototypic power densities, irradiation temperatures, burnups, and nuclear transients should be used to develop the fuel irradiation performance database. Test data gathered under this phase may be used to validate fuel performance models.

4. Establish low Hafnium Content ZrC Feedstocks

Natural Zr contains hafnium impurities, ZrC feedstocks with low hafnium impurities would need to be developed to the appropriate quantity and quality to support the NTP fuel development program.

5. Demonstrate Net Shape Fuel Element Fabrication Processes

ZrC-matrix fuel forms are currently low readiness and net shape fuel fabrication processes are not yet established. Net shape fuel element fabrication processes that must be developed include net-shape sintering with any channel forming methods which may be needed, channel and exterior coating or cladding methods, and methods to assemble / bond full scale element.

6. Cercer Fuel Performance Model

Predictive fuel performance models do not currently exist for cercer fuel forms being developed for NTP applications. These models may be established by modifying existing models. However, controlling failure modes of cercer fuel forms are not currently known. Therefore, newly developed models will require benchmarking and validation based on results of fabrication and performance (separate effects and combined effects testing) demonstration activities.

7. Moderator and Insulator Development

This is a common risk for NTP systems. Please refer to NERVA / Rover Technology Gap 5 for a full description. Additional considerations for cercer reactor development are related to the possibility of deviations from historic moderator designs and how that may introduce new technology gaps. If an alternative moderator is proposed (from historically demonstrated designs), additional evaluation may be needed to confirm moderator behavior under relevant NTP environments (high pressure hydrogen, thermal gradients, irradiation environment). The integrated reactor system may also require more extensive critical testing to confirm / resolve dynamic behavior of the reactor.

8. Fuel Performance Demonstration under Combined Effects Conditions

This is a common risk for NTP systems. Please refer to NERVA / Rover Technology Gap 6 for a full description. ZrC-matrix cercers have not been previously demonstrated under known historic US NTP development programs. ZrC property evolution or fuel behavior of ZrC-cercers under prototypic irradiation environments is unknown for NTP.

9. Demonstrate Production Scale Fabrication / Assembly Processes and Infrastructure

This is a common risk for NTP systems. Please refer to NERVA / Rover Technology Gap 7 for a full description. For ZrC matrix cercers, existing infrastructure may be leveraged for research and development activities, modification of existing infrastructure is needed to fabricate coated fuel particles, net shape fuel elements, and protective coatings. A dedicated fabrication process line will likely be desired by industry to ensure full quality and process control is maintained during the fabrication of fuel for the demonstration and flight reactors.

10. Development of Quality Assurance / Quality Control Techniques
This is a common risk for NTP systems. Please refer to NERVA / Rover Technology Gap 8 for a full description.

11. Integrated Reactor System Behavior
This is a common risk for NTP systems. Please refer to NERVA / Rover Technology Gap 9 for a full description. For ZrC-cercer reactors, no critical or reactor operations data exists, and a more extensive integrated reactor-engine test program is expected to be required.

12. Cost and Schedule Assessment
Overall cost and schedule were anticipated to be approximately the same for reactors based on either fuel type. Testing facilities were assessed to be the cost and schedule driver for NTP reactor development. The cercer fuel form was assessed to correspond to a slight cost increase due to low manufacture readiness, more complex fabrication methods, and lack of an existing performance database. Laboratory scale infrastructure exists for the fabrication and testing of subscale fuel sample prototypes under separate effects conditions desired for Phase I testing. Future investment is needed to establish full scale fuel element and moderator production lines and infrastructure to enable combined effects (Phase II) and integrated system testing.

NERVA / Rover Assessment
Coated particles and subscale fuel compacts may be obtained using existing commercial and Government equipment. Some technology development may be required to recapture UC_2 kernel fabrication and coating processes with acceptable quality as well as develop net shape sintering methods which allow for higher fuel volume loadings. There likely exists equipment to perform coating activities but additional technology development may be required to develop a coating approach which resists hydrogen corrosion at design temperatures under expected thermal cycling conditions.

Cost: High

Schedule: Moderate

ZrC Cercer Assessment
Coated particles and subscale fuel compacts may be obtained using existing commercial and Government equipment. Some additional technology development may be required to refine UN kernel fabrication and coating processes with acceptable quality and density. Technology development is needed to develop net shape sintering methods and fuel assembly processes. The cercer fuel form is expected to require a low hafnium content ZrC feedstock which will need to be established at the appropriate scale to support technology maturation activities.

Cost: High

Schedule: Moderate

Appendix G: Facilities and Qualification Needs Assessment

Overall system readiness requires the integrated system, all subsystems, and their respective components to be matured and demonstrated to meet functional, performance, and safety requirements under operational environments. For reactors, the primary development needs include maturing component manufacture and assembly processes, establishing material performance databases, and demonstrating reactor operations and control. As the subsystem and its underlying components are matured, they must be demonstrated at increasingly representative scale and environments (**Figure G-1**, originally from [129]).

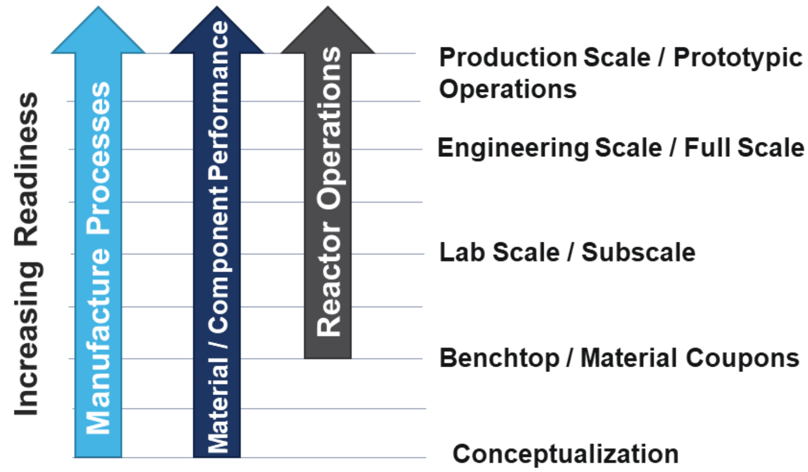

Figure G-1 Readiness considerations for space reactor development include component level manufacture and performance demonstration, as well as reactor subsystem operations demonstration.

Fuel is a critical technology to ensure the functionality and performance of the reactor. When considering development needs for space reactor fuels, again fabrication process and fuel performance readiness are two key facets to address in the fuel development program (**Figure G-2**). Important parameters to demonstrate in maturing fuel fabrication processes include demonstration of prototypic fabrication processes with increasingly representative feedstocks (consider impurity content and enrichment), geometries, and production rates. Important parameters to demonstrate in order to mature fuel performance readiness primarily centers around increasing representativeness of the test environment and test article in order to demonstrate performance under the range of operating conditions needed for service. This may include capturing inter-element effects which include interactions between a fuel component with other interfacing components, such as cladding, insulation, or moderator. Test environments should capture both the non-nuclear operating environment (heat transfer interface, temperature and stress profiles, any working fluid interactions, etc.) and nuclear environments (neutron flux, burnup, spectrum, power density, etc.). Establishing a material property and fuel performance database to benchmark the proposed reactor design and validate models is another facet of maturing fuel performance readiness.

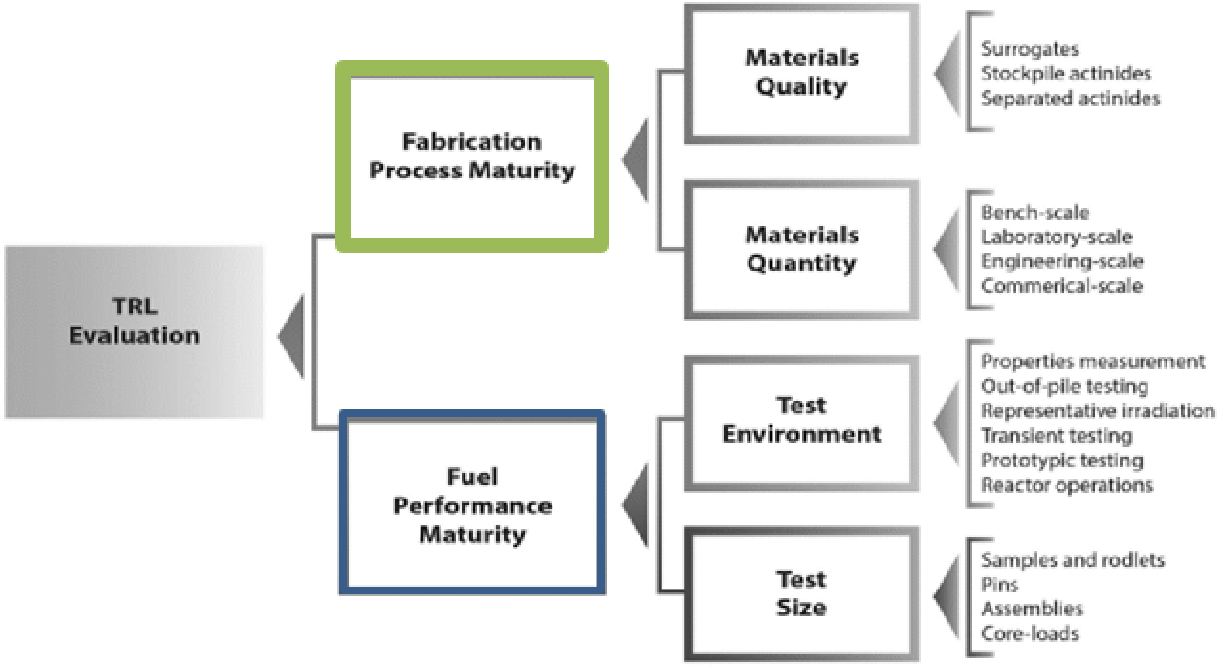

Figure G-2 Fuel maturity (TRL) is dependent upon demonstrating fabrication process and fuel performance maturity through the development program [130].

FSP Facilities and Qualification Needs Assessment

Primary objectives of the FSP fuel qualification program will be to demonstrate the fabrication and performance of a fuel form capable of high operating temperature (>1400 K peak fuel temperature for a 1200 K reactor exit temperature) and moderate burnup capability (<10 FIMA%, 10-year operating duration). This effort will entail:

- Demonstration of the capability to fabricate and assemble full scale fuel element and heat pipe assemblies. Thermal reactor systems will also require moderator element fabrication demonstration.
- Fuel performance needs to be well understood for fuel / moderator reactor system for all operating modes (start-up, operational power transients, long term operation at temperature, cool down and restart). This will require:
  - Confirmatory fuel testing for long term, high temperature, irradiation exposure. Irradiation testing will confirm acceptable fuel dimensional stability (due to fuel swelling) and undesirable fission product interactions . Acceptable high temperature property evolution and acceptable creep behavior of structural materials may be demonstrated through irradiation or non-nuclear testing.
  - Development of predictive modeling and simulation capabilities which are validated using data from the testing program.

For each system, three phases of development were assessed to be needed to support the qualification of space reactor fuel forms. For FSP systems, these three phases are:

- **Phase I: Separate Effects Testing**. High temperature compatibility, creep, and irradiation testing demonstrate performance over the range of operational temperatures and irradiation environments. Test articles may be representative material coupons or subscale fuel samples.

- **Phase II: Combined Effects Testing**. Combined irradiation and heat transfer environments testing to demonstrate fuel performance under prototypic power densities, nuclear transient periods, and heat transfer conditions. Test articles should be a medium to high fidelity prototypes of a fuel element bundle or representative reactor core unit cell.
- **Phase III: Reactor Operations Testing.** Reactor operations testing allows fuels to be tested under the range of operating modes, including off-nominal or transient conditions. Test articles should be a medium to high fidelity (full or subscale) prototype of the FSP Reactor.

The following sections provide more detail on the development program and corresponding infrastructure needed for FSP fuel development.

FSP Phase I Development Needs

For FSP fuel forms, initial development performed in the first phase would include initial laboratory scale prototyping and testing of fuel and optionally, moderator components. Fuel and moderator development should include all relevant claddings or protective coatings and heat transfer components (heat pipe). Phase I fuel testing would include material characterization and separate effects testing of subscale fuel and heat pipe prototypes. Key outcomes of this phase would include:

- Fuel characterization that includes basic physical, mechanical, and chemical properties such as density, melting points, specific heat, thermal conductivity, tensile and compressive strengths, and the chemical compatibility between materials selected for the design. Fuel characterization should aim to close any material property database gaps (acceptable creep and chemical compatibility behavior should be confirmed).
- Gathering confirmatory test data through transient and steady-state non-nuclear tests. Non-nuclear testing demonstrates acceptable stability of the fuel form for extended durations under high temperature and compliment irradiation testing. These tests would include transient heating tests to determine thermal stresses imposed for start-up and shut down, initial heat pipe demonstration testing, and compatibility testing.
- Evaluation and down selection of candidate fabrication technologies for fuel, heat pipe, and moderator components
- Development of initial fuel performance models

For UO_2 fuel forms, there is not anticipated to be significant testing needed for development of the fuel pellets. UN fuel form development should primarily focus on demonstrating pellet fabrication technologies to the relevant geometries and purity desired for FSP applications. UN pellet fuel forms should also demonstrate acceptable high temperature stability under FSP operating temperatures through confirmatory high temperature non-nuclear and irradiation testing. AGR TRISO fuel form development under phase I will include fabrication demonstration of modified fuel particles with higher uranium densities, expanding the existing irradiation database to span any gaps between that established through AGR and what is required for the FSP design (temperature, fluence, power density), as well as confirming acceptable chemical compatibility between the fuel and heat pipe or fuel and moderator interface. For all fuel forms, transient irradiation testing may be performed to confirm fuel performance is acceptable under FSP off-nominal conditions if performance database gaps exist. There is the opportunity to perform confirmatory materials testing in coordination with fuel performance modeling to accelerate Phase I and II testing programs.

Required Phase I Testing Facilities / Infrastructure: High temperature furnaces for interfacial chemical compatibility studies and any required heat pipe compatibility testing, mechanical test equipment for high temperature material property studies (optional depending on existing property database), instrumented in-reactor capsules, and PIE equipment for any irradiation testing.

Required Phase I Fabrication Facilities / Infrastructure: Laboratory scale fuel production equipment, and sintering furnace and net-shape processing equipment for subscale or net shape fuel elements, heat pipe, moderator, and cladding fabrication line.

FSP Phase II Development Needs
Under phase II, technology development for fuel, heat pipe, and moderator (optional) technologies are completed. Phase II activities focus on demonstration of component fabrication technologies and performance under combined effects conditions (combined heat transfer and irradiation environment). Combined effects testing will allow for confirmation that fuel and related reactor technologies are capable of fabrication and assembly at prototypic length scales, show acceptable material performance under conditions representative of what they will be exposed to during prototypic operations, as well as demonstrate acceptable heat transfer from the fuel during operation to meet system performance requirements. Test articles should be a medium to high fidelity prototype of a fuel element bundle or representative reactor core unit cell (including fuel, heat pipe, and optional moderator technology). Key outcomes of this phase would include:

- Gathering statistical material properties to finalize the material property database needed for the FSP reactor design.
- A combined effects environment test facility is established for testing the representative unit cell under relevant irradiation environments (goal to match temperature and power density during irradiation).
- Demonstration and test data generation which demonstrates acceptable heat transfer from the fuel via the heat pipe technology.
- Demonstration of full-scale fabrication technologies for fuel, heat pipe, and moderator (optional) components and design of the fuel and moderator production lines for reactor fabrication.
- Fuel fabrication specification and tolerances are developed and verified by testing.
- Finalization and validation of fuel performance models with gathered test data.

For each fuel type, combined effects testing confirms acceptable fuel performance and predicted heat transfer from the fuel element to heat pipe. Overall fuel element design is demonstrated to be acceptable under representative power and temperature profiles. This testing is expected to be confirmatory for both UO_2 and UN pellet fuel forms. For the AGR TRISO fuel form, new or accelerated failure modes under combined effects conditions are identified.

Required Phase II Testing Facilities / Infrastructure: In-reactor capsule with heat rejection / heat sink for combined effects demonstration activities.

Required Phase II Fabrication Facilities / Infrastructure: Laboratory scale fuel production equipment; sintering furnace and net-shape processing equipment for subscale or net shape fuel elements; cladding fabrication line; moderator and insulator production equipment; fuel bundle and / or unit cell assembly line.

FSP Phase III Development Needs

The final phase of the qualification program comprises of reactor subsystem testing. Under this phase, technical risks for the reactor and fuel are completely resolved and the qualification program of the system can commence. Reactor testing allows for the fuel, heat pipe, and other reactor components to be tested under a true prototypic environment including all loads throughout reactor operating duration. This test data also allows for a reactor operation database to be collected and for reactor physics models to be validated. The recommended test article would be a medium to high fidelity, fully assembled prototype of the FSP reactor. The design and construction of the reactor test facility must be capable of supporting long term radiation tests of the reactor at prototypic operational temperatures, durations, and environmental conditions. Key outcomes of phase III include:

- A dedicated fuel, heat pipe, and moderator (optional) production line are established. A reactor assembly facility is established. These facilities are capable of producing quality components and test articles in accordance to specifications required for the overall qualification program.
- Demonstration and test data generation which demonstrates acceptable performance of the fuel, heat pipe, and moderator (optional) under prototypic operations.
- Finalization and validation of reactor physics and reactor multiphysics models with gathered test data.
- Detailed critical experiments and analyses. Results of these evaluations will be fed back into the design since tight optimizations are necessary to minimize excess mass of flight systems.
- A ground test facility is established in support of the FSP reactor qualification campaign. For all fuel types, reactor operations system testing confirms fuel, moderator, and heat pipe reliability and ability to satisfy the FSP system power balance. Gathered reactor operations data confirms predicted reactor response of M&S tools.

Required Phase III Testing Facilities / Infrastructure: Reactor test facility (adapting an existing facility is acceptable for this application), including heat rejection and control infrastructure, "warm" to hot cell facility for examination after testing.

Required Phase III Fabrication Facilities / Infrastructure: Production scale (multiple assemblies) fuel and moderator manufacture line, reactor assembly facility, optional: integration facility for integration and demonstration with non-reactor subsystems.

Other critical reactor technologies: A number of supporting technologies will also require early development start times relative to the planned fuel and moderator development timeline. This includes the following:

- A highly reliable, fault tolerant control system with considerable diagnostic and troubleshooting capability. The control system must be capable of controlling FSP reactor response under all nominal and off-nominal operating conditions.
- Radiation hardened; high temperature instrumentation and electronics will need to be developed to support developmental testing and the eventual operational system.

- Development of multi-physics models and enhanced simulation capabilities to measure risk and performance uncertainties.

NEP Facilities and Qualification Needs Assessment

Primary objectives of the NEP fuel qualification program will be to demonstrate the fabrication and performance of a fuel form capable of high operating temperature (>1400 K peak fuel temperature for a 1200 K reactor exit temperature) and moderate burnup capability (<10 FIMA%, 5-year operating duration) while exposed to a gaseous (HeXe) or liquid metal (Li) working fluid. This effort will entail:

- Demonstration of the capability to fabricate and assemble full scale fuel elements. Thermal reactor systems will also require moderator element fabrication demonstration.
- Demonstration of reliable and predictable fuel and moderator (optional) performance under all operating modes, including conditions representative of the NEP start-up, operational power transients, long term operation at temperature, cool down and restart.

For each system, three phases of development were assessed to be needed to support the qualification of space reactor fuel forms. For FSP systems, these three phases are:

- **Phase I: Separate Effects Testing**. Working fluid compatibility, creep, and irradiation testing to demonstrate performance over the range of operational temperatures and irradiation environments. Test articles may be representative material coupons or subscale fuel samples.
- **Phase II: Combined Effects Testing.** Combined irradiation and heat transfer environments testing to demonstrate fuel performance under prototypic power densities, nuclear transient periods, and heat transfer conditions. Test articles should be a medium to high fidelity prototypes of a fuel element bundle or representative reactor core unit cell.
- **Phase III: Reactor Operations Testing.** Reactor operations testing allows fuels to be tested under the range of operating modes, including off-nominal or transient conditions. Test articles should be a medium to high fidelity (full or subscale) prototype of the NEP Reactor.

The following sections provide more detail on the development program and corresponding infrastructure needed for NEP fuel development. It is noted that NEP and FSP fuel development programs are expected to be largely similar with the exception of testing required to demonstrate fuel element, working fluid compatibility. These differences are the focus of the following discussion sections. Please refer to Appendix E for more detailed information on recommended fuel testing and other technology development considerations for power reactor maturation.

NEP Phase I Development Needs

Like FSP fuel forms, initial development performed in the first phase of NEP fuel development would include initial laboratory scale prototyping and separate effects testing of fuel and optionally, moderator components (including relevant claddings or protective coatings). Additional outcomes of this phase for NEP applications would include demonstrating working fluid compatibility of the fuel and cladding / coating system with the selected NEP working fluid. This could include high temperature static and dynamic non-nuclear testing.

For modified TRISO fuels, phase I testing should be used to identify the operating window and failure modes of the fuel form under representative irradiation environments (temperature, fluence, power density). Modification of existing TRISO coated particle fuel fabrication technologies to meet the needs of NEP reactors (higher uranium density) will be demonstrated in this phase. Acceptable high temperature compatibility / stability is confirmed for coated particle layers under nominal and off-nominal design conditions. Compared to other fuel types, this fuel form will require a more extensive characterization effort to gather fundamental material properties due to the lack of an existing database for this fuel type. Phase I development needs for each NEP fuel form beyond that identified for FSP applications for pellet (UO_2 and UN) fuel forms includes demonstration of refractory cladding technologies. This testing should focus on establishing a working fluid-cladding compatibility and creep testing database which fills any existing database gaps.

Required Phase I Testing Facilities / Infrastructure: High temperature HeXe furnaces or pumped Li loop, instrumented in-reactor capsules and PIE equipment for any irradiation testing.

Required Phase I Fabrication Facilities / Infrastructure: Laboratory scale fuel production equipment, sintering furnace and net-shape processing equipment for subscale or net shape fuel elements, and cladding fabrication line.

NEP Phase II Development Needs

Under phase II, technology development for fuel and moderator (optional) technologies are completed through combined effects testing. Key differences in combined effects testing for NEP applications compared to FSP applications include reduced operating duration requirements (limited to 5 years) and the need for demonstrating fuel performance under combined temperature, irradiation, and working fluid environment conditions. This allows for fuel material performance to be demonstrated under all relevant environments and confirmation of the heat transfer characteristics of the fuel design to meet reactor interface conditions. No additional outcomes are expected of this phase compared to FSP Phase II efforts.

For all fuel forms, combined effects testing confirms acceptable fuel performance extrapolated from separate effects testing. The testing performed during this phase demonstrates fuel stability is acceptable under representative power and temperature profiles for UO_2 and UN fuel types. For modified TRISO fuel forms, scalability of fabrication technologies to the quantities and specifications needed for full scale fuel element geometries is demonstrated during this phase. New or accelerated failure modes under combined effects conditions are identified.

Required Phase II Testing Facilities / Infrastructure: In-reactor instrumented pumped Li or an HeXe loop capable of testing the fuel at NEP operating temperature conditions.

Required Phase II Fabrication Facilities / Infrastructure Laboratory scale fuel production equipment, sintering furnace and net-shape processing equipment for subscale or net shape fuel elements, and cladding fabrication line, moderator and insulator production equipment, fuel bundle / unit cell assembly line.

NEP Phase III Development Needs

The final phase of the NEP qualification program comprises of reactor subsystem testing. The same benefits and objectives of FSP reactor testing would be required for NEP reactors. For all fuel types, reactor operations system testing confirms fuel reliability and ability to satisfy the NEP system power balance. Gathered reactor operations data confirms predicted reactor response of

M&S tools. NEP reactor testing facilities (MW_e Scale) may be significantly more difficult to implement compared to FSP due to more demanding heat rejection and control requirements. Therefore, full scale NEP systems may be unable to leverage FSP infrastructure. A scaled development approach for NEP reactor development may allow for this challenge to be addressed.

Required Phase III Testing Facilities / Infrastructure: Reactor test facility, including heat rejection and control infrastructure, hot cell facility for examination after testing.

Required Phase III Fabrication Facilities / Infrastructure: Production scale (multiple assemblies) fuel and moderator manufacturing line, reactor assembly facility, optional: integration facility for integration and demonstration with non-reactor subsystems

NTP Facilities and Qualification Needs Assessment

Primary objectives of the NTP fuel qualification program will be to demonstrate the fabrication and performance of a fuel form capable of high temperature (> 2700 K), hot hydrogen operation under thermal cycling conditions for short total durations (up to 10 hours). Key objectives of the qualification program will include:

- Demonstration of the capability to fabricate and assemble full scale fuel and moderator elements.
- Demonstration of reliable and predictable fuel performance under all operating modes, including conditions representative of the NTP start up transient and multiple burns (hot hydrogen thermal cycling).

Three phases of development were assessed to be needed to support the qualification of NTP fuel forms:

- **Phase I: Separate Effects Testing**. Hot hydrogen testing and irradiation testing demonstrate performance over the range of operational temperatures and pressures, thermal cycling, and steady state / transient irradiation conditions. Test articles should be a low to medium fidelity subscale fuel sample.
- **Phase II: Combined Effects Testing**. Combined irradiation and hydrogen environments testing to demonstrate fuel performance under prototypic power densities, nuclear transient periods, and hydrogen flow conditions. Test articles should be a medium to high fidelity prototype of a fuel element bundle or representative reactor core unit cell.
- **Phase III: Integrated System Testing.** Integrated system testing allows fuels to be tested under a true prototypic environment including all loads throughout fuel operating duration. Test articles should be a medium to high fidelity prototype of the NTP Engine.

In the following section, additional detail on the NTP fuel development program and corresponding infrastructure is provided.

NTP Phase I Development Needs

In the first phase, technology development of the underlying fuel and moderator components would be performed through laboratory scale prototyping and testing. In this phase, separate effects testing and material property collection would be performed on subscale fuel samples. Key outcomes of this phase would include:

- Gathering material properties to close any material property database gaps

- Gathering test data which demonstrates acceptable compatibility of the fuel form under hot hydrogen conditions
- Evaluation and down selection of candidate fabrication technologies for fuel and moderator components
- Gathering high temperature test data which confirms acceptable high temperature stability of the fuel form
- Development of initial fuel performance models

For both fuel forms evaluated, most of the activities pursued in Phase I would be the same. Critical phase I activities unique to the NERVA / Rover fuel form include development of coating fabrication techniques and demonstration of coating ability to enable acceptable compatibility in a hot hydrogen environment; as well as demonstration of acceptable high temperature stability of a fuel form at temperatures where UC_2 kernels have exceeded their melting point. At these operating temperatures, mechanical properties are expected to be degraded and molten kernels may be very diffuse resulting in migration through and possibly out of the fuel matrix. A combination of testing and analyses should show that the developed fuel design can enable required operating temperature and duration with acceptable design margin.

Unique critical phase I activities for the ZrC cercer fuel form would comprise of confirmatory hot hydrogen testing experiments of ZrC, development of fabrication processes for ZrC cercer coated particle and composite subscale fuel samples, establishment of a material property database for cercer fuel forms, and a hot hydrogen performance database for cercer microstructures including identification of failure modes and confirmatory testing to demonstrate the stability of UN at required operating temperatures. This test data in combination with analyses should allow for an identification of the allowable fuel operating window (allowable temperatures, stresses, and operating duration) for this fuel type.

Required Phase I Testing Facilities / Infrastructure: Hot hydrogen furnaces, in-reactor capsules, and PIE equipment for any irradiation testing.

Required Phase I Fabrication Facilities / Infrastructure: Laboratory scale fuel production equipment for coated particles, sintering furnace and net-shape processing equipment for subscale or net shape fuel elements, and channel coating furnace.

NTP Phase II Development Needs

Under phase II, technology development for fuel maturation is completed. Phase II activities focus on combined effects testing, i.e., representative irradiation and hydrogen environments, to demonstrate fuel performance under prototypic power densities, nuclear transient periods, and hydrogen flow conditions. Test articles should be a medium to high fidelity prototype of a fuel element bundle or representative reactor core unit cell. Therefore, full scale fabrication and assembly processes will need to be matured for both fuel and moderator components. Key outcomes of this phase would include:

- Gathering statistical material properties to finalize the material property database needed for the reactor design.
- A combined effects environment test facility is established for combined irradiation, hot hydrogen testing of components.
- Demonstration and test data generation which demonstrates acceptable performance of the fuel and moderator under representative combined effects environments.

- Demonstration of full-scale fabrication technologies for fuel and moderator components and design of the fuel and moderator production lines for reactor fabrication.
- Finalization and validation of fuel performance models with gathered test data.

Phase II outcomes are anticipated to finalize technology development for both fuel types. Combined effects testing confirms acceptable fuel performance extrapolated from separate effects testing and test data may be used to validate predictive fuel performance models. For the NERVA / Rover fuel derivatives, fuel stability is demonstrated to be acceptable under representative power and temperature profiles with molten kernel operation under the proposed NTP operating duration (including number of thermal cycles). For the ZrC cercer, acceptable UN stability is demonstrated under prototypic environments. New or accelerated failure modes for cercer fuels under combined effects conditions are identified.

Required Phase II Testing Facilities / Infrastructure: In-reactor hydrogen loop, nuclear furnace, or subscale maturation of an advanced reactor test (SMART) reactor facility with PIE capability. Combined effects transient testing may be performed in TREAT (match power density during start up transient for initial understanding of fuel performance under NTP conditions).

Required Phase II Fabrication Facilities / Infrastructure: Laboratory scale fuel production equipment for coated particles (kg quantities), large sintering furnace and net-shape processing equipment for net shape fuel elements, channel coating furnace, moderator and insulator production equipment, fuel bundle / unit cell assembly line.

NTP Phase III Development Needs

The final phase of the qualification program comprises of integrated reactor-engine system testing. Under this phase, technical risks for the reactor and fuel are completely resolved and the qualification program of the system can commence. Integrated system testing allows fuels to be tested under a true prototypic environment including all loads throughout fuel operating duration. The recommended test article should be a medium to high fidelity prototype of the NTP Engine (integrated reactor-engine). This test data also allows for a reactor operation database to be collected and for reactor physics models to be validated. Key outcomes of phase III include:

- A fuel and moderator production line are established. A reactor assembly and engine integration facility are established. These facilities are capable of producing quality components and test articles in accordance to specifications required for the overall qualification program.
- A ground test facility is established in support of the NTP engine qualification campaign.
- Demonstration and test data generation which demonstrates acceptable performance of the fuel and moderator under prototypic operations.
- Finalization and validation of reactor physics and reactor multiphysics models with gathered test data.

For all fuel types, Integrated system testing confirms fuel reliability and ability to satisfy the engine-reactor power balance. Fuel performance under designed “off-nominal” and transient conditions should also be confirmed. For NERVA / Rover derivative designs, gathered reactor operations data confirms predicted reactor response extrapolated from NERVA / Rover operations database and fuel performance data confirms predictive models. Under phase III, cercer reactor operations data confirms predicted reactor response of M&S tools, additional testing (compared to

NERVA / Rover derivative) may be required to validate reactor behavior under all engine operating modes.

Required Phase III Testing Facilities / Infrastructure: Integrated reactor-engine test stand and control infrastructure, and “warm” cell facility for examination after testing.

Required Phase III Fabrication Facilities / Infrastructure: Production scale (multiple assemblies) fuel and moderator manufacture line, reactor assembly facility, engine assembly facility, and reactor-engine integration facility.

Appendix H: Agreement with NASA / DOE FSP Reactor Technology Development Activities

Following review, the overall findings of this study were found to be consistent with recommendations from the DOE FSP team technology readiness assessment. In particular:

- Pellets of UO_2 and UN possess a sufficient technology readiness level but require confirmatory testing to assure chemical and dimensional stability.
- Coated ceramic particles form a special case under UO_2 and UN fuels category. Of these coated particle alternatives, AGR TRISO is the only fuel that possesses the necessary pedigree and readiness at this stage. Other variants, such as modified TRISO designs, will require technology development.
- Metallic UMo alloy fuel is a suitable option if the reactor temperature and burnup are sufficiently low.

Moderator development and integrated fuel-moderator performance demonstration is a technology gap that is being addressed by ongoing government led development activities. Technology maturation of metallic hydrides (such as ZrH_x and YH_x) and BeO is planned which will include testing up to and including low power criticality testing at the proposed operating temperature and neutron spectrum.

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14. ABSTRACT

This study evaluates terrestrial reactor fuel forms, with an emphasis on the coated particle fuel capability under development by interagency reactor programs, for application to space reactor systems of interest to NASA. A comprehensive review of coated particle fuel readiness and qualification status has been performed. Possible derivative fuel forms based on coated particle fuel manufacture technologies are identified and assessed for fission surface power, nuclear electric propulsion, and nuclear thermal propulsion systems. Assessments for terrestrial coated particle and historic fuels were compared for each system allowing for relative risk and common fuel qualification needs to be identified.

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