

MODERATOR CONSIDERATIONS FOR SPACE NUCLEAR POWER AND PROPULSION SYSTEMS

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Nuclear reactors have the potential to provide high energy density to enable sustainable surface power and advanced propulsion methods needed for human exploration activities at the moon and mars. Current mission planning is surveying different reactor types for space power and propulsion application. Of these reactor types, the use of a moderator within the reactor can enable reduced enrichment, reduce overall fuel loadings, and minimize the critical size of the reactor compared to unmoderated reference systems. This proceeding summarizes some moderator materials identified for space reactor applications: zirconium hydride, yttrium hydride, beryllium, and beryllium oxide, and the unique design considerations inherent to surface power and nuclear thermal propulsion reactor designs. It was found that there are four key considerations during the moderator selection and design process: nuclear properties, thermophysical & mechanical properties, manufacture & readiness, and environmental compatibility. Surface power reactors can benefit from moderators which minimize overall system mass and are capable of surviving high temperature irradiation environments for years with little degradation. Nuclear thermal propulsion reactors can benefit from moderators which are capable of retaining structural integrity under multiple burns while being exposed to a wide temperature range ($40 < T < 500+ \text{ K}$). Moderator materials which exhibit good stability under irradiation and high temperature operation, minimize fuel pitch, and are high readiness are desirable for near term implementation.

I. INTRODUCTION

In space nuclear power and propulsion systems, the reactor acts as a heat exchanger by transferring the heat from fission to heat a working fluid to high enough temperatures to power a turbine (power) or be expanded out a nozzle to produce thrust (propulsion). Reactor design is typically proposed as a unit cell configuration of fuel, structural, and moderator components assembled into an active core which is surrounded by a reflector to form a finite volume for heat generation. Fuel provides the nuclear material needed to generate fission, while the moderator, if incorporated into the design, provides material with nuclear properties to enable criticality of the reactor design and better utilization of the neutrons produced from fission. Better utilization of neutrons allows the designer to minimize reactor volume (mass) or reduce required fuel material while enabling the same operating performance. Therefore, for high assay low

enriched uranium (HALEU) systems, moderation can be a key component to enable criticality and reduce the mass of the reactor subsystem.

Moderator design and material selection is inherently a multi-physics-based problem. Material selection and related geometries used in component design control the overall nuclear and thermal performance of the system based upon fundamental nuclear and thermophysical properties. In addition to enabling criticality and nominal performance, the moderator must retain structural integrity under extreme operating conditions (irradiation, temperature, etc.) to enable reliable operation of the reactor. When selecting the optimal moderator for the system, four categories are traded during the design process:

1. Nuclear Properties
2. Thermophysical & Mechanical Properties
3. Manufacture & Readiness
4. Environmental Compatibility

Nuclear properties desired to be optimized for the moderator primarily concern optimizing the neutron economy under nominal conditions. The probability of a nuclear interaction is highly dependent upon the average energy of the neutron population. For example, fission cross section, a measure of interaction probability, is greatest at low energies ($\sim 0.025 \text{ eV}$ or less). Neutrons, typically born from fission at high energies ($\sim 1-2 \text{ MeV}$, i.e. fast), can be “slowed down” to lower energy by scattering interactions which result in a loss of kinetic energy. By maximizing the portion of the neutron population slowed down to thermal energies ($\sim 0.025 \text{ eV}$), the probability fission is significantly improved, thereby enabling the designer to minimize core mass or fuel loading within the reactor. Moderators should correspond to nuclear properties which maximize the moderator ratio (ratio of scattering to absorption probability) and slowing down power (neutron energy loss per collision) while minimizing Fermi age (proportional to physical distance required to slow down neutron to thermal energy). These properties minimize parasitic neutron losses in the moderator and reduce the volume of moderator needed to thermalize the neutrons. For nuclear space systems, the latter can be a key driver to minimizing system mass.

Thermophysical and mechanical properties of interest to moderator design include minimizing density (reduces overall mass), maximizing material melting temperature or useful operating temperature (enables higher operating

margins or performance), maximizing thermal conductivity (efficient heat transfer out of the moderator), and providing desirable mechanical properties. Mechanical properties, such as strength and ductility, ensure component reliability and must be accounted for in the design to prevent structural failure during operation. Material property evolution may be expected during service lifetime depending on operating parameters of the system. Several thermophysical properties are generally degraded during service due to neutron bombardment (particularly thermal conductivity and ductility). Embrittlement, high temperature grain growth, recrystallization, or secondary phase formation can also result in undesirable property evolution during operation.

Nuclear materials are often specialty materials which will require an established supply chain and development of relevant net-shape manufacture processes prior to system implementation. Therefore, proposed conceptual designs should consider materials availability, special handling considerations, fabricability, as well as manufacture and performance readiness of the technology. Established materials with a known supply chain, fabrication processes, and pre-existing performance database for basis of acceptable design windows are desirable. The selected moderator must also be able to ensure reliable performance under the unique operating conditions posed for nuclear space systems. Material stability under operating environment, including total lifetime, number of thermal cycles, operating temperature and pressure, total irradiation experienced over operating lifetime (i.e. burnup or fluence), imposed heat fluxes and thermal stresses, expected transients, chemical compatibility, as well as other functional considerations should be assessed. Each of these categories contribute to the overall complexity of the design and feasibility to mature the moderator (TRL > 4) at a reasonable cost and schedule. Optimal moderator designs maximize the desirable attributes of each of these categories at the lowest reasonable cost, schedule, and risk.

II. OPERATING CONSIDERATIONS FOR SPACE NUCLEAR POWER AND PROPULSION SYSTEMS

For both space nuclear power and propulsion, the figures of merit within the four defining categories: nuclear properties, thermophysical & mechanical properties, manufacture & readiness are shared. However, different figures of merit may be driving for environmental compatibility. For nuclear thermal propulsion and nuclear power systems, different operating conditions of the reactor are required (Table 1). A moderator design which can enable reliable operation for long duration high temperature irradiations without requiring active cooling will be most desirable for a fission power design. For a thermal propulsion design, moderators should enable reliable operation for short

duration hydrogen exposures under thermal cycling conditions. For both designs, enabling increased moderator operating temperatures reduces the demands on insulating components which can enable more design flexibility for higher performance or better operating margins. Additional compatibility with physical interfaces in the system, such as reactor structure, required insulation, or fuel assemblies (chemical and CTE) should also be considered during the design¹. Materials which enable the best blend of performance properties to enable reliable operation while minimizing additional technology development under each of the unique environments will look most advantageous for selecting a common moderator design for nuclear space power and propulsion.

TABLE I. Comparison of operating conditions for ongoing space fission system reference designs^{1,2,3}

	Fission Power	Space Nuclear Propulsion (NTP)
Operating Atmosphere and Pressure	Vacuum (Space) OR equilibrium with reactor environment	Flowing Hydrogen > 3.5 MPa
Operating Temperature	> 1000 K	Minimum: 40 – 250+ K Maximum: goal to minimize (dependent on fuel assembly interface)
Total Reactor Thermal Power	~50 kWth	~330 MWth
Typical Heat Generation Rate/ Flux	0.09 W/cm ³	85 W/cm ³ 0.6 – 6 W/cm ²
Total Lifetime	up to 15 years (740 kWth-year)	~2 hours (75 kWth-year)
Requires Active Cooling?	No	Yes
Largest Anticipated Implementation Hurdles	Retention of dimensional, compositional, and structural stability under long duration, high temperature irradiation	Retention of compositional and structural stability under intense heat fluxes and reducing environment

III. SUMMARY OF CANDIDATE MATERIALS

Moderator material selection requires consideration of many competing design attributes to optimize a design to meet performance goals. Moderators which can enable low reactor masses and higher system operating temperatures (driven by fuel temperature) will be more likely to meet performance goals. However, materials with higher readiness and manufacturability may be beneficial to reduce required technology development and associated risk. A survey of applicable high temperature moderators was performed, and figures of merit related to the four categories were gathered for a relatively wide range of material candidates⁴. Two classes of moderators were identified as highest potential candidates for space nuclear power and propulsion systems: metallic hydrides and beryllium-based alloys (Table 2).

The first moderator class includes the metallic hydrides, of this category, yttrium hydride (YH_x) and zirconium hydride (ZrH_x) are promising as they provide excellent hydrogen densities, low absorption properties, high slowing down power, and relatively high operating temperatures, 950 - 1150 K and 673 - 800 K respectively. This combination of properties can enable the smallest critical core sizes if temperatures within the core can be managed below hydride use temperature limits. Because of this metallic hydrides have significant development history for space nuclear power and propulsion designs^{4,5}. YH_x can enable higher operating temperatures than ZrH_x designs, but at the cost of higher

parasitic neutron losses (lower moderating ratio). Perceived limitations of the hydrides include specialized fabrication techniques which are known but not commercially available and the dissociation behavior of hydrogen at high temperatures, which must be mitigated through engineering solutions. For fission power systems, hydrogen mobility under high temperature operation must be managed to ensure hydrogen retention into the system. Development of specialty coatings or other hydrogen barriers are anticipated to be required to enable hydrogen retention over long lifetimes. For NTP systems, large temperature gradients through the moderator element may enhance hydrogen mobility and become a driving factor for hydrogen migration. This is not desirable since stoichiometry (hydrogen to metal ratio) impacts both the local nuclear and thermomechanical properties of the system and can result in phase change during operation or thermal cycling. Additional consideration should be given to the high hydrogen over pressure provided by cooling of the moderator element via pre-heating of the hydrogen propellant, both significant hydrogen loss or uptake from the system should be avoided. Hydride development will require the acquisition of irradiation data to identify if radiolysis or enhanced diffusivity accelerates decomposition of hydride candidates and radiation effects on thermophysical properties (including degraded conductivity and ductility) over relevant lifetimes and operating conditions (temperature, environment).

The second class of moderator candidates includes beryllium and its refractory compounds (such as BeO and Be₂C). While not having as desirable slowing down

TABLE II. Comparison of Selected Figures of Merit for Moderator Material Candidates (see ref. 4,9).

	ZrH _x	YH _x	Be	BeO
Theoretical Density (g/cm ³ @ RT)	5.62	4.24	1.85	3.01
Thermal Conductivity	47 @ 300 K 35 @ 600 K	70-80 @ 300 K 30 - 40 @ 773 K	190 @ 273 K 90 @ 973 K	275 @ 273 K 41 @ 1073 K
T _{melt} (K)	-	-	1558	2843
Max Use T (K)	800 - 900	1173 - 1673	823	2000 - 2300
Slowing Down Power	1.45	1.2	0.15	0.122
Neutron Fermi Age	31	27	98	110
Moderating Ratio	55	25	126	158
Manufacturability & Readiness	Some Technology Development Required (more heritage)	Some Technology Development Required (more synergy with ongoing DoE efforts)	Established and Commercially Available	Some Technology Development Required
Pros	Known manufacture process, best slowing down power	Higher temperature than ZrH _x , known manufacture process	High TRL, commercially available	High temperature, commercially available
Cons	Not commercially available, environmental stability	Not commercially available, environmental stability limiting	Requires specialty materials handling, expensive	Requires specialty materials handling, additional tech. dev.

limiting

needed

absorption properties and is an established technology with known fabrication routes and machining methods. Due to desirable structural and thermal properties, Be and BeO have been previously used and considered as a moderator material in research reactor designs^{6,7} and typically serves as a reflector material in NTP designs. BeO and other higher melting temperature alternatives provide nuclear property benefits similar to Be but allow for higher operating temperatures. This benefit typically comes at the cost of reduced supply chain availability, lower technology readiness, and poorer thermal-mechanical properties. The use of Be and BeO in fission surface power systems primarily concerns their ability to resist irradiation induced swelling at high temperatures (> 773 K Be, > 873 K BeO), which after significant (anisotropic) swelling in BeO can lead to significant stresses, microcracking, or eventual disintegration of the material. Other design considerations may be necessary to accommodate changes to the microstructure and thermophysical properties depending upon component use temperature, i.e. low temperature irradiation embrittlement (< 573 K) or high temperature ($> 0.5 T_m$) He embrittlement (see ref. 8 for more in depth review). The latter phenomena is unique to Be-based material systems compared to metallic hydride moderators due to the $(n,2n)$ reaction which results in the formation of an helium (α) reaction product. In NTP systems, lifetime is short (hours). Therefore, retention of structural and thermal properties under high neutron flux throughout lifetime is key to ensure reactor reliability and thermal performance. Similarly, development of Be-based candidates will require the acquisition of irradiation data to characterize radiation effects on thermophysical properties (including degraded conductivity and ductility) over relevant lifetimes and operating conditions (temperature, environment).

IV. CONCLUSIONS AND RECOMMENDATIONS

For any space system, the goal of subsystem design is to satisfy requirements and enable the desired nominal performance. Moderator design can enable HALEU reactor criticality and, with the right nuclear properties, reduce the mass of the reactor subsystem. Ultimately, component design requires consideration of many competing design attributes to optimize the system to meet performance goals. The optimal reactor design will be different dependent upon moderator material selection since thermal, mechanical, and reactor physics related phenomena will impact the design's thermal management and ability to enable criticality at the lowest mass. When selecting a moderator, requirements should drive the prioritization of the figures of merit with least reasonable cost, schedule, and risk. Materials which enable the best blend of performance properties while ensuring reliable component operation and minimizing additional technology development for each of the unique power and

propulsion environments will look most advantageous for selecting a common moderator design for nuclear space power and propulsion.

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