

FMDP Task 3.1 – Reactor Conceptual Testing Reference Design NETS 2021

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Space Technology Mission Directorate
Technology Demonstration Mission Program
Space Nuclear Propulsion Project

J. Gustafson | April 27, 2021

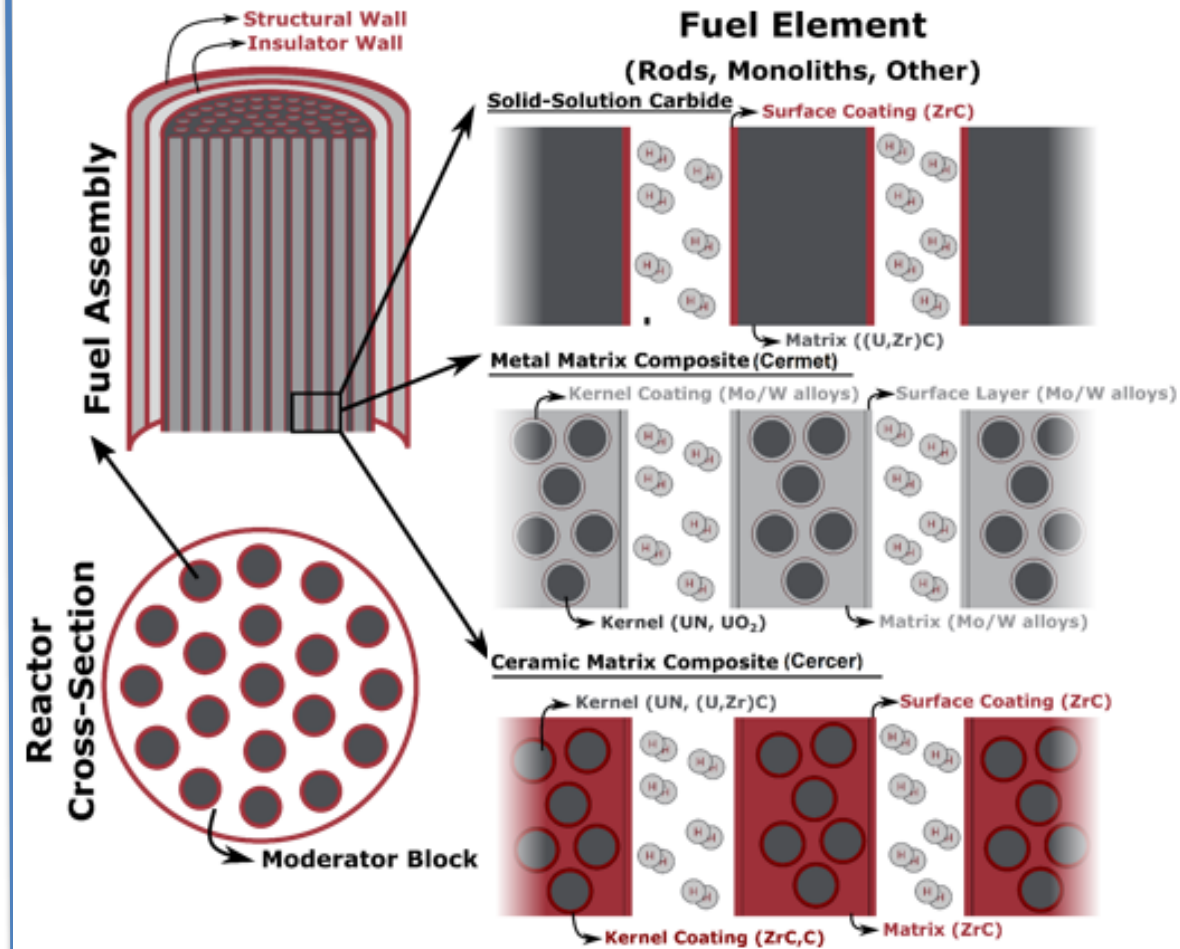
Fuel and Moderator Development Plan (FMDP) - Overview

- Activities are coordinated by NASA and the Department of Energy (DOE).
- Project primary focus is to develop a high-temperature HA-LEU solid fuel form moderator-block reactor design
 - Building-block strategy to fuel development is key to maturing critical technology path
 - Optimizes ability to advance fuel fabrication capability and reactor design simultaneously
 - Nuclear testing with Idaho National Laboratory:
 - PRIME-1 a UN cermet with flowing hydrogen in FY2022
 - PRIME-2 a UN cermet with flowing hydrogen in FY2023
 - Ground Rules for FMDP Reactor Subsystem (RSS) Testing Reference Design Concept:
 - The reactor uses a HA-LEU Uranium Nitride (UN) fuel kernel embedded in zirconium carbide (ZrC), referred to as cermet fuel, or molybdenum/tungsten (Mo/W), referred to as cermet, matrix material in a moderator block arrangement.
 - The gas (hydrogen) nozzle chamber temperature must be sufficient to reach an engine specific impulse (Isp) of 900 sec. This is analogous to an approximate fuel channel exit gas temperature of ~2700 K.
 - The engine thrust is in the range of 12,500 to 15,000 lbf.
 - The dry RSS mass limit is ~3,800 kg. This does not include turbomachinery, nozzle or external shielding mass allocations. This mass limit does include the necessary internal shielding.
 - The fuel elements are circular in shape with internal cooling channels.

Benefits of Moderator Block Configuration

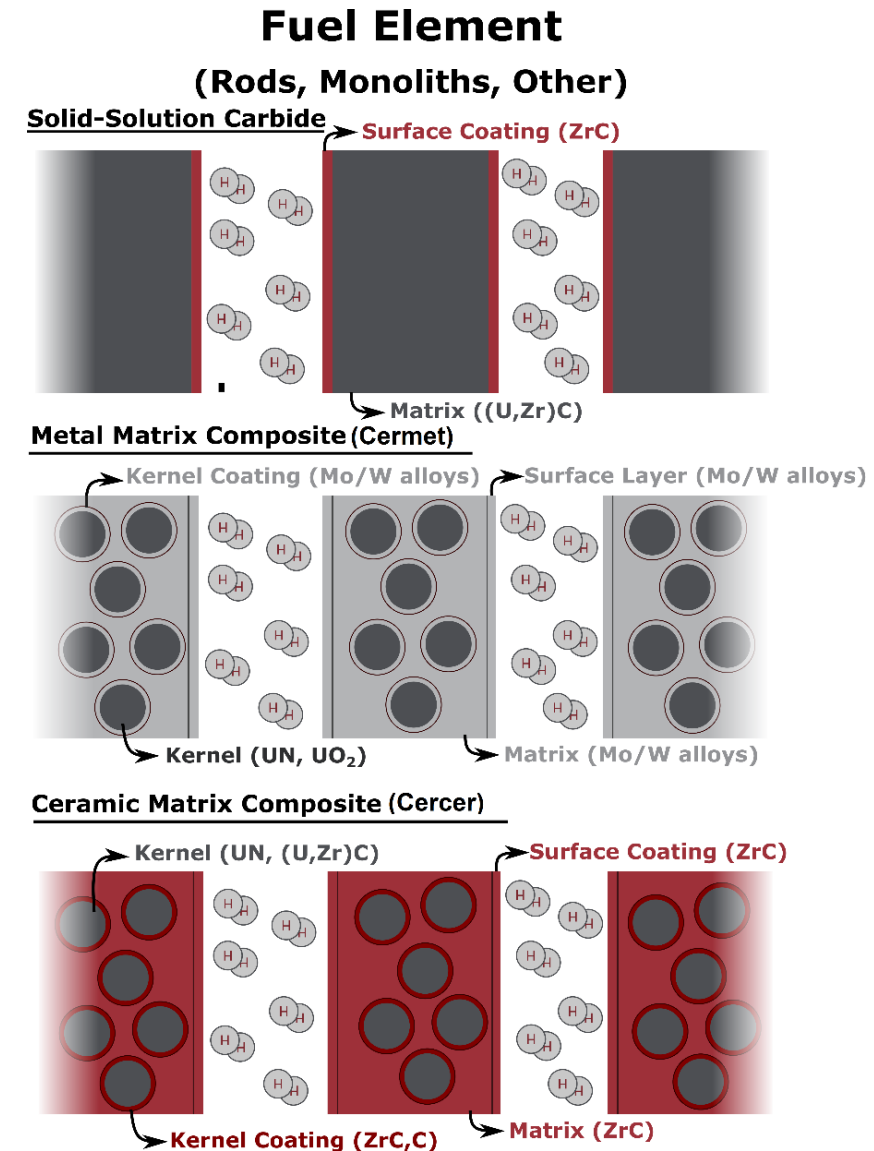
- **Improved moderation of neutrons**
 - Allows for reduced core radius and core height → **Smaller, lighter cores**
 - Requires less ^{235}U kg loading for criticality due to better neutron utilization
 - Less structural material required, so less parasitic neutron absorptions
- **Reduced element and intra-element power peaking and easier fuel loading optimization**
 - More uniform moderation around fuel
 - Supports higher ISP (chamber gas temperature) with lower temperature gradients, and Lower ^{235}U loading
- **Core arrangements that can accept different fuel compositions and geometries**
 - Fuel regions can be more easily arranged to address core radial power peaking
 - Can support different fuel types and fuel element shapes (rods or internally cooled cylinders)
- **Simplified Design and Core Assembly**
 - Easier to plumb single pass cooling flow through the moderator block
 - Less heat transfer to moderator through insulator flow tube wall
 - Opportunities to reduce manufacturing cost

Moderator block configuration offers practical and proven solution to design challenges



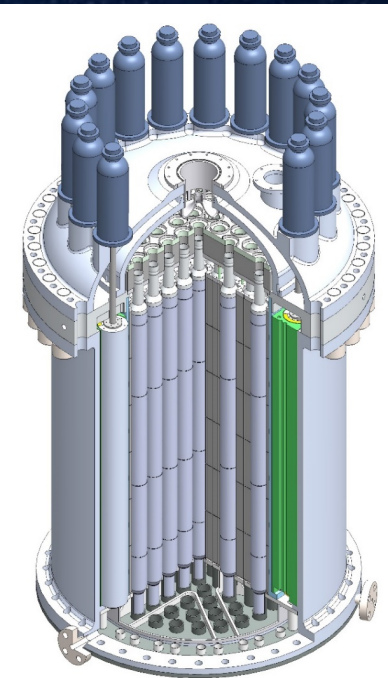
Transition from GCD NTP to Technology Demonstration Mission Project

- NASA Game Changing Development (GCD) Feasibility Assessment recommendations used to focus development efforts on optimization.
 - I&C, Reactor and Fuel materials and design, CFM and low leakage components.
- For the reactor and fuel optimization, pivoted arrangement to fuel assemblies in a moderator “block”
 - Fuel and moderator arrangement can be more easily tuned to optimize moderation and power distribution
 - Gas flow paths inside reactor vessel are simpler to allow better reactor assembly and operation
 - Modular fuel assemblies provided flexibility to support the entire program lifecycle from early development, fabrication, and testing to final mission objectives, while allowing phased implementation of fuel type
 - Scalability to different thrust levels by increments of fuel assemblies and core length while staying within the thermo-mechanical limitations of the fuel type

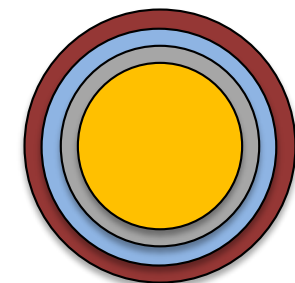


Assumptions - Technical

- Moderator block core arrangement considered pathway for higher performance.
- Provisional material properties for fuel, structures, and moderator are being used.
- The target to maintain fuel meat outer diameter with 91 coolant channels is kept.
- Fuel particle architecture starting point remains informed by initial study (i.e., fuel kernel with 1-3 thin TRISO-like overcoats).
- Fuel meat coating on cooling channel walls and outer surfaces.
- Fuel assembly gaps can be maintained as intended. Gaps are needed for different reasons whether assembly, thermal expansion, or heat transfer.
- Fuel form as an internally cooled monolith can work for thermal hydraulic performance/Isp.



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Conceptual Testing Reference Design
(15,000 lbf)



Fuel Particle (Cercer) ~
Notional

Implications of Thrust and Isp to Nuclear Reactor Thermal Design

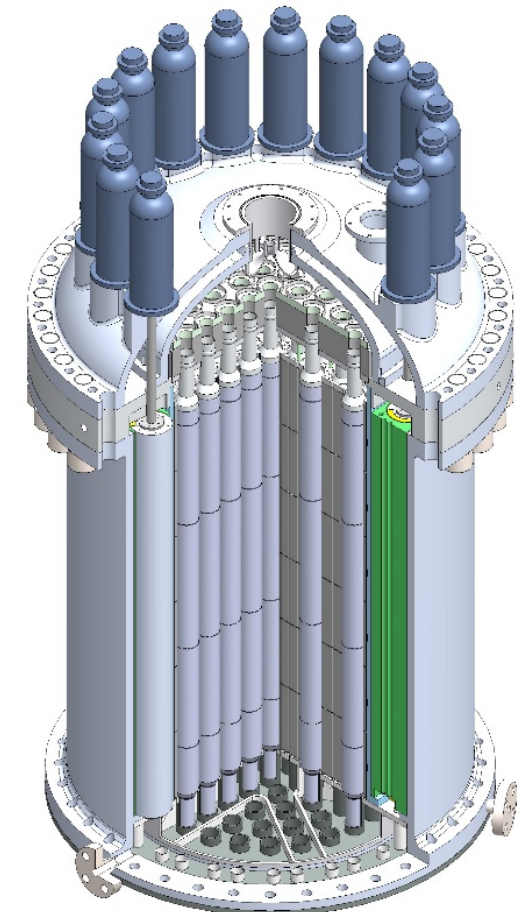
- Reactor thermal power from fission is required to heat pressurized hydrogen propellant to the temperatures required for the thrust mass flow rates and Isp

$$\frac{\partial M_{hydrogen}}{\partial t} = \frac{Thrust}{Isp * g} = W_{hydrogen} \left(\frac{kg}{s} \right)$$

$$Q_{reactor}(MWt) = W_{hydrogen} * (h_{chamber} - h_{MPT})$$

- Fission heat deposition in the solid fuel structure must be transferred to the hydrogen propellant in cooling channels
 - High power density needed for compact reactor size & mass
 - High heat transfer area and short thermal conduction paths needed for highest gas temperature (Isp) and to keep fuel temperatures and thermal stresses below design limits
 - Reduced power peaking allows higher average power density

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(15,000 lb_f)



Engine Performance Requirements Flow Down to Reactor Neutronic and Thermal Requirements

Conceptual Testing Reference Design Analysis Quad Chart

Neutronics

- Fuel and moderator assembly geometry
- Area fractions of flow, fuel, structure
- Core arrangements for criticality
- Radial, axial, and intra-element power shape
- Post shutdown decay heat loads

Thermal Assessment

- Heat transport by Convection, Conduction, and Radiation
- GH2 Flows and pressure drops
- Temperatures and pressures of fluids
- Temperatures of solids: Wall and Max
- Considered axial and radial power peaking. The effects of intra-element peaking were not included.

Radiation Transport/Shielding

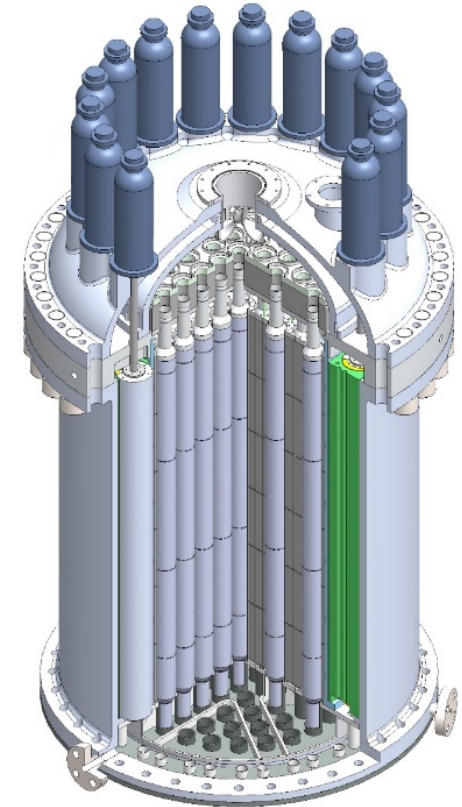
- Heat deposition in component materials
- Neutron Flux/Dose
- Gamma Flux/Dose
- Shielding thicknesses needed for dose limits
- Activation analysis

Mechanical Assessment – Design/Structural/Stresses

- Master Equipment List – Mass Allocation
- Temperature gradient in solids
- Thermal expansion
- Component CTE mismatch

Conceptual Testing Reference Design Conclusions

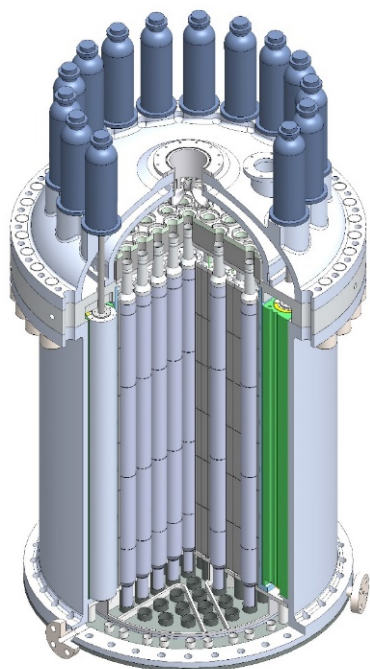
- Two reactor design concepts were developed to support the FMDP: one utilizing a cermet fuel form and the other utilizing a cercher fuel form. Both designs adhere to the FMDP ground rules detailed and meet the performance requirements.
- The supporting neutronic, thermal hydraulic and mechanical analysis demonstrates the viability of both designs and provides valuable insights to inform development and testing to progress technology maturation important for SNP NTP applications.
- The cercher needs about seven times less HA-LEU, reduced maximum fuel meat stress and is about 400 kg lighter.
- However, the cermet design leverages a previously manufactured fuel form and has the benefit of a more epi-thermal neutron spectrum.



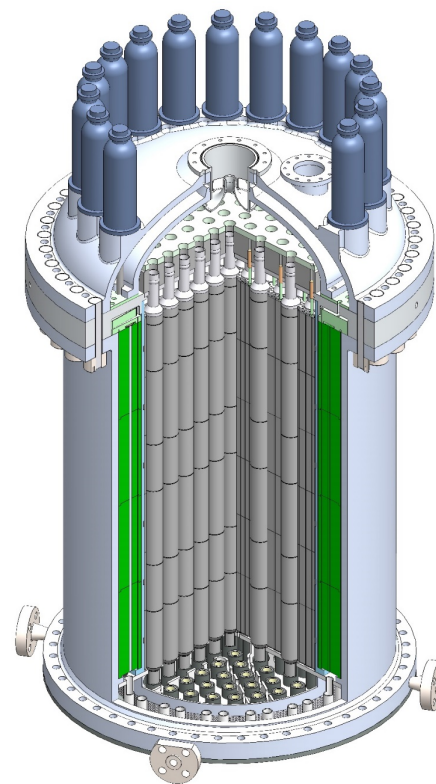
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Conceptual Testing Reference Design Reactor-Engine Integration

- Keeping in mind progression from flight/prototype to full scale mission concepts.



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(900 sec Isp, 15,000 lb_f)



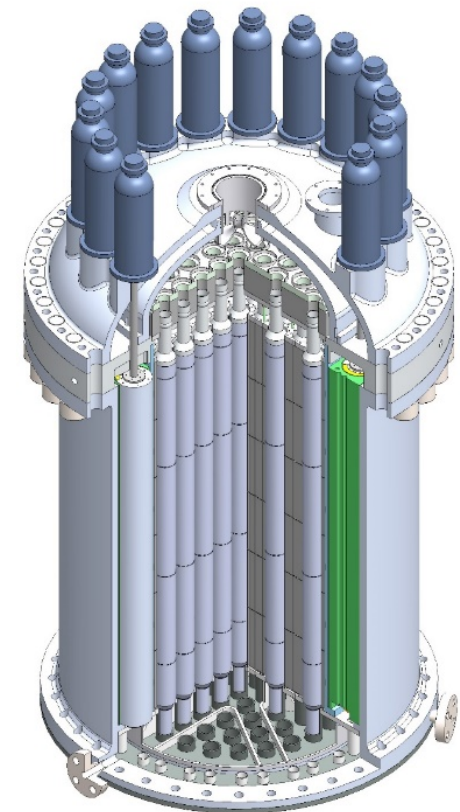
Fuel and Moderator Develop Plan
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(900 sec Isp, 25,000 lb_f)



NASA's Nuclear Thermal Propulsion Engine System (GCD – 875 sec Isp, 25,000 lb_f) is shown, of which BWXT and Aerojet Rocketdyne are providing support for engine, reactor and fuel design and analysis.

Acknowledgments

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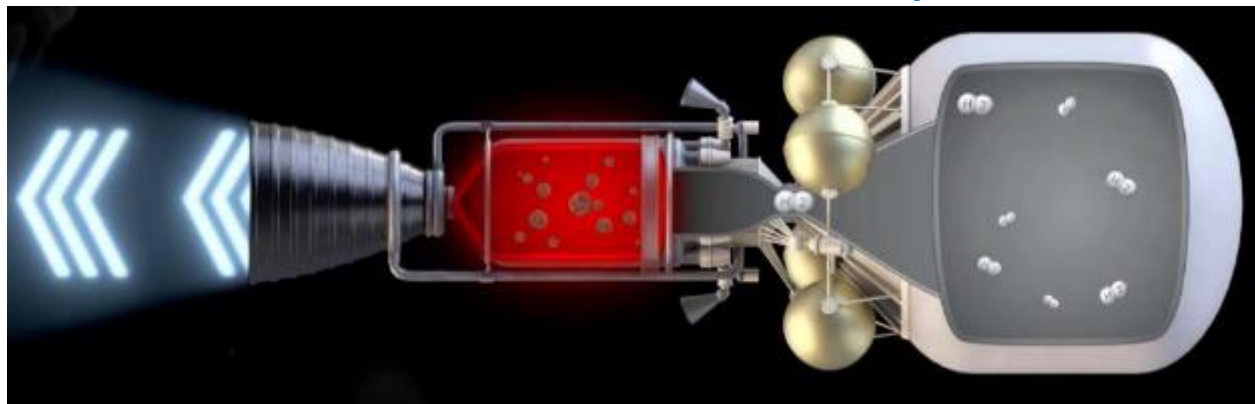
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Questions

Fundamental Performance of Nuclear Thermal Propulsion

- Propellant is heated by a nuclear reactor and thermally expanded through a nozzle
 - *No combustion of propellant, fission heat transferred to propellant gas*
- Low molecular weight (MW) propellant helps raise the Specific Impulse (Isp)
 - *Typically use lowest MW gaseous hydrogen (GH₂)*
- Specific impulse is ~2X Chemical Rockets; directly related to reactor exhaust temperature and inversely to molecular weight of propellant gas:
 - *GH₂ Impulse of 830 - 1000 sec; Nozzle Chamber Temperature ~ 2300K - 3100K*
- Thermal power of reactor is directly related to thrust via Isp (Flow Rate = Thrust/Isp):
 - *100 kN ≈ 500 MW_{th} with Isp of 900 sec*
- Amount of uranium fissioned for round trip mission to Mars is <100 gm in three reactors
 - *The fuel could be contained in the size of a toy marble or a sugar cube*

Image courtesy of NASA STMD NTP
Video: <https://youtu.be/lmy2mbs2zAQ>



Major Elements of a Nuclear Thermal Rocket Engine