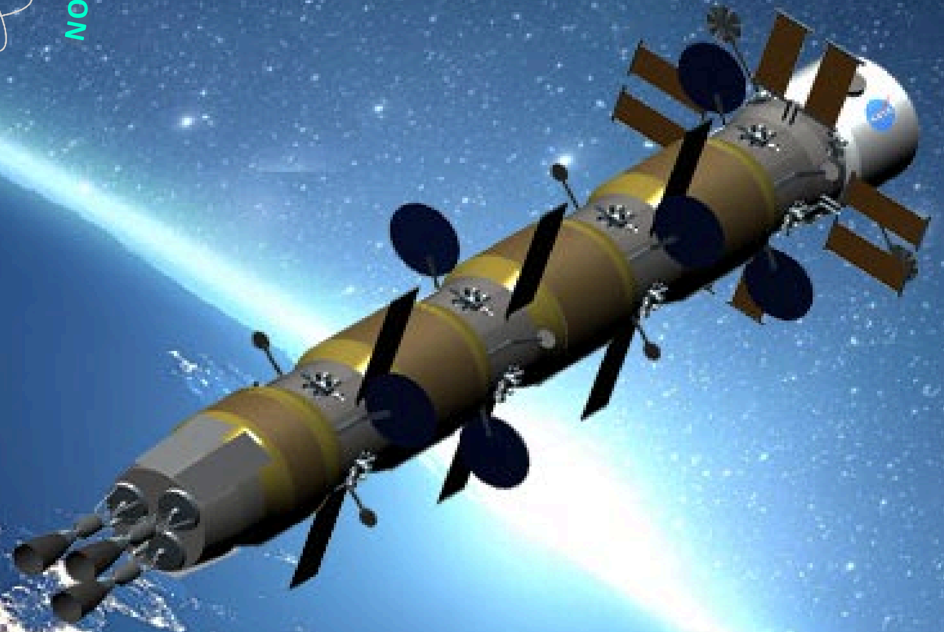


A System Design Process For NASA NTP Testing Reference Design Concepts (NETS 2022)

Contract Number: BEA Subcontract 00212687
DPD Number: 1612, Issue: Basic
DRD Number: 1612CD-001

Space Technology Mission Directorate
Technology Demonstration Mission Program
Space Nuclear Propulsion Project
J. Gustafson | 5/11/22

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
    - PRIME-2 a UN cercer with flowing hydrogen
  - 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 cercer 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.

NERVA Legacy Program Design Analysis Flow Charts

Important to Leverage Past Experience to Inform Work Progression

WANL-TME-2758, Data Item S-101, Nuclear Analysis Report Nuclear Subsystem (U), February 1971.
https://www.osti.gov/servlets/purl/4219036

WANL-TME-2689, Data Item T-119, F-1 Fuel Material Development Final Report, July 1970.

https://www.osti.gov/servlets/purl/4227416-6hKxcx/

Design Analysis Process Is Not a New Topic – Important to Leverage Past Knowledge

Astronuclear Laboratory

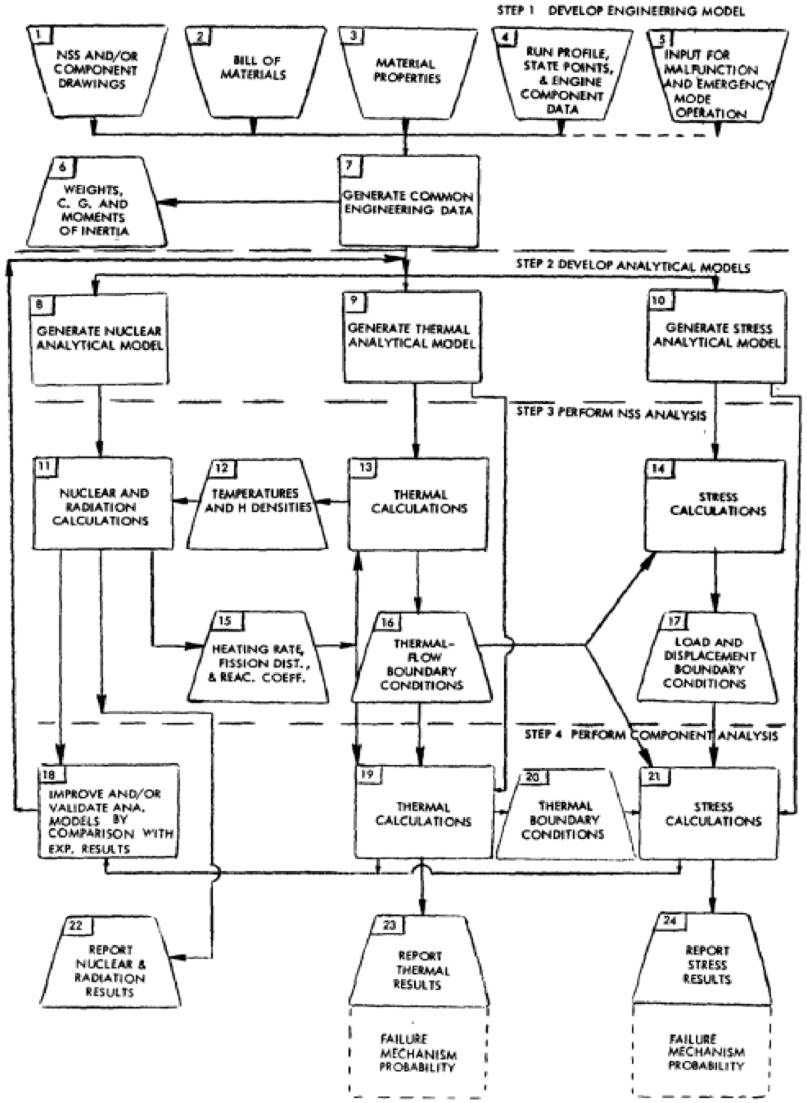


Figure 2-1. Flow Chart for Nuclear, Thermal, and Structural Analysis

NASA Systems Engineering Handbook and Feasibility Considerations

NASA SP-2016-6105 Rev. 2, NASA Systems Engineering Handbook, https://ntrs.nasa.gov/citations/20170001761

TABLE 2.2-1 Project Life Cycle Phases

Phase		Purpose	Typical Outcomes
Pre-Formulation	**Pre-Phase A** Concept Studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mock-ups
Formulation	**Phase A** Concept and Technology Development	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition
Formulation	**Phase B** Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mock-ups, trade study results, specification and interface documents, and prototypes
Implementation	**Phase C** Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
Implementation	**Phase D** System Assembly, Integration and Test, Launch	To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
Implementation	**Phase E** Operations and Sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
Implementation	**Phase F** Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

Feasible System Outcome Expected
Important to Have Criteria (Some examples below – Credit NASA Game Changing Development NTP Feasibility Conceptual Design)

Criteria Title	Criteria Statement
High Assay Low Enriched-Uranium (HALEU) Reactor	Design a reactor concept using a HA-LEU fuel system that will go critical, achieve full rated thermal power conditions, and meet endurance lifetime within the given engine system allocated reactor mass and volume constraints while balancing the power density and ability to cool the reactor.
Material Selection - Reactor	Design a reactor concept capable of operating in a combined thermal and radiation environment.
Reactivity Swing	Design a reactor concept that will be controllable from cold dry vacuum conditions to steady state hot pressurized full thrust conditions vacuum thrust.
Operational Modes	Design a reactor concept that will be controllable for stable defined transients for engine startup, shutdown, and coast cooling.
Reactor Fuel Region Exit Gas Temperature	Design a reactor concept that will deliver a fuel element exit gas temperature adequate for the engine to deliver an I_{sp} required, while staying within the fuel thermal limits under the operational conditions for endurance, burn time, and multiple starts.
Reactor Total Thermal Power	Design a reactor concept that will provide enough total thermal power [that meets the thrust requirements] while staying within the fuel thermal limit for endurance, burn time, and multiple starts.
Operating Environments	Design a reactor concept capable of operation for the expected duration

Must Keep Systems Engineering Phase Of Work in Mind

System Design Process For NASA NTP Testing Reference Design Concepts

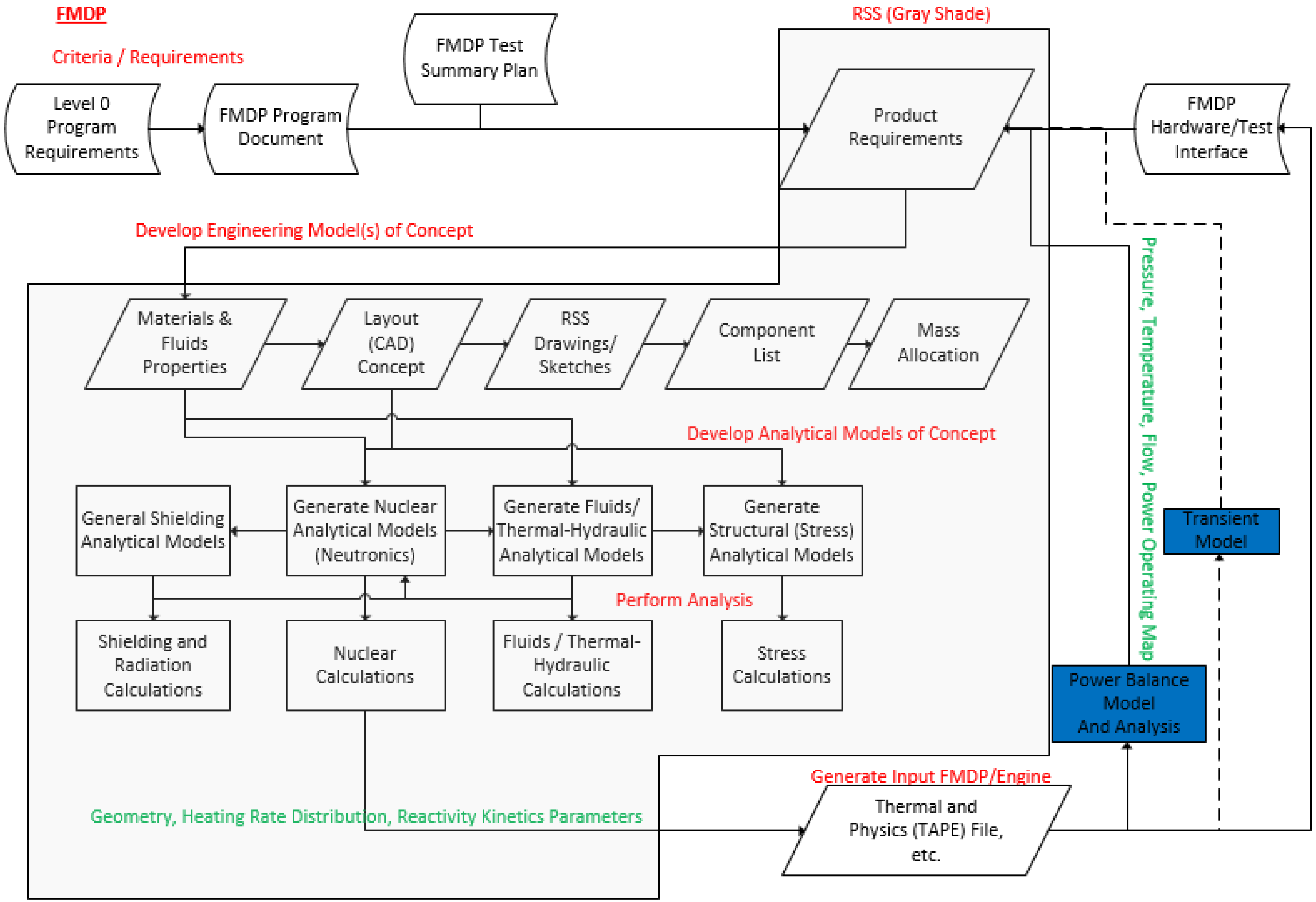
Develop Engineering Model
- Material Properties, Layout, Drawings, List, Mass

Develop Analytical Models
- Shielding, Nuclear, Thermal and Stress Models

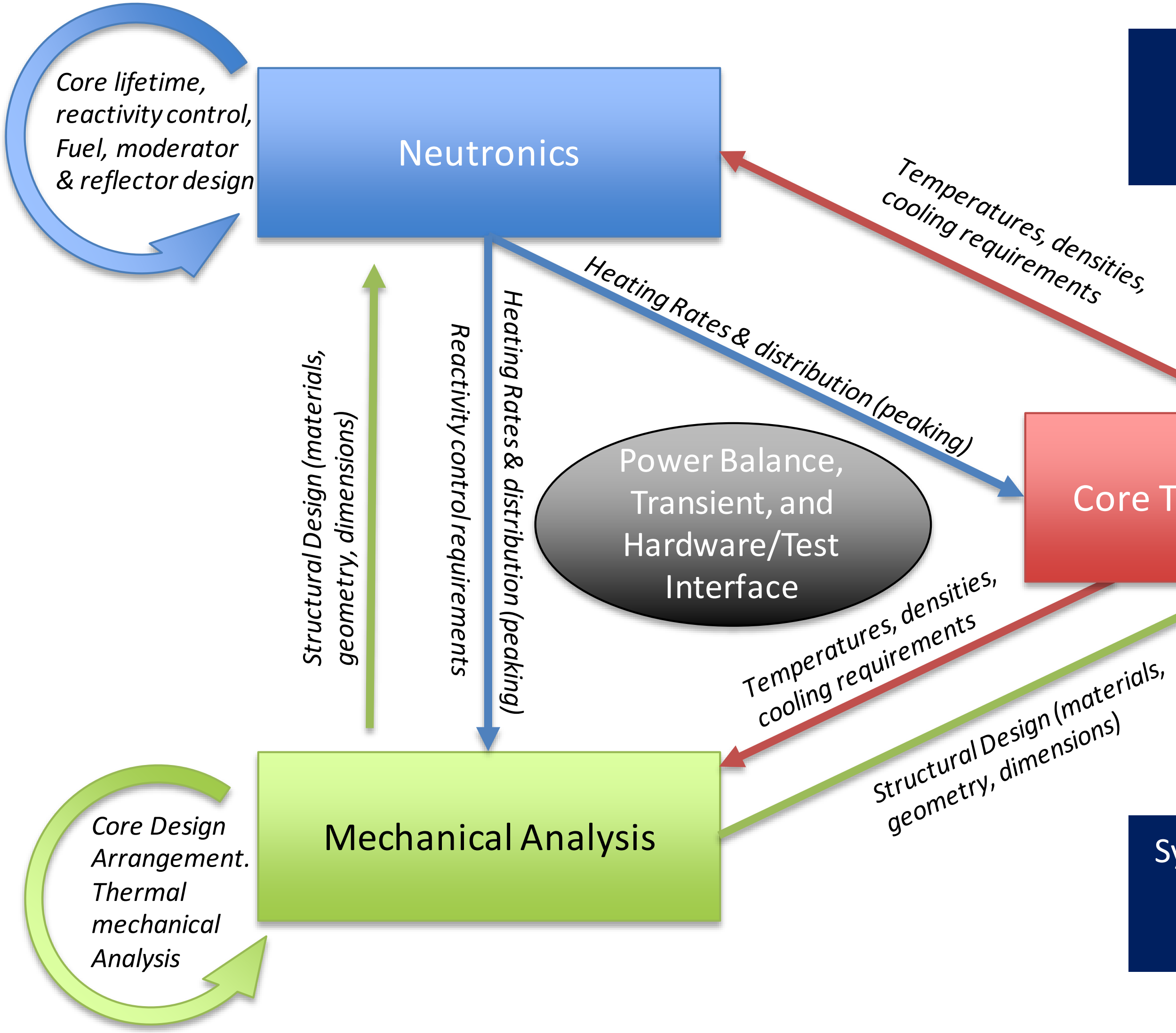
Perform Analysis
- Neutronics and Shielding Calculations
- Thermal-Hydraulic Calculations
- Stress Calculations

Document Results
- Generate input to power balance and transient modeling.
- Inform hardware and testing interfaces.

Paper Focus



Simplified View of Core Design Interactions



System Design Process pulls inspiration from NASA Systems Engineering Design Spiral

System Design Process Provides the Physics Coupling and Output Interfaces Required

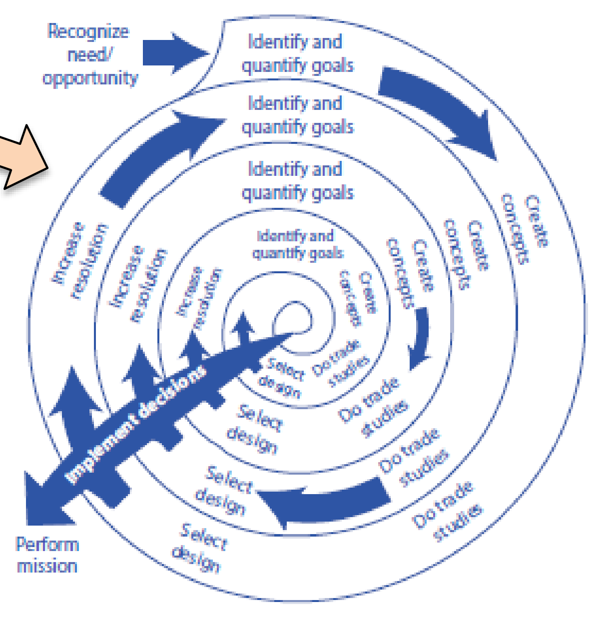


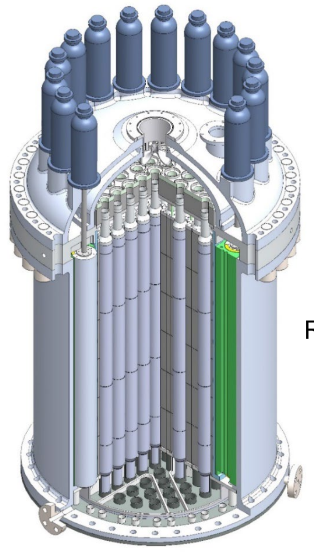
FIGURE 4.4-2 The Doctrine of Successive Refinement

NASA SP-2016-6105 Rev. 2, NASA Sys Eng Handbook, https://ntrs.nasa.gov/citations/20170001761

Conclusion

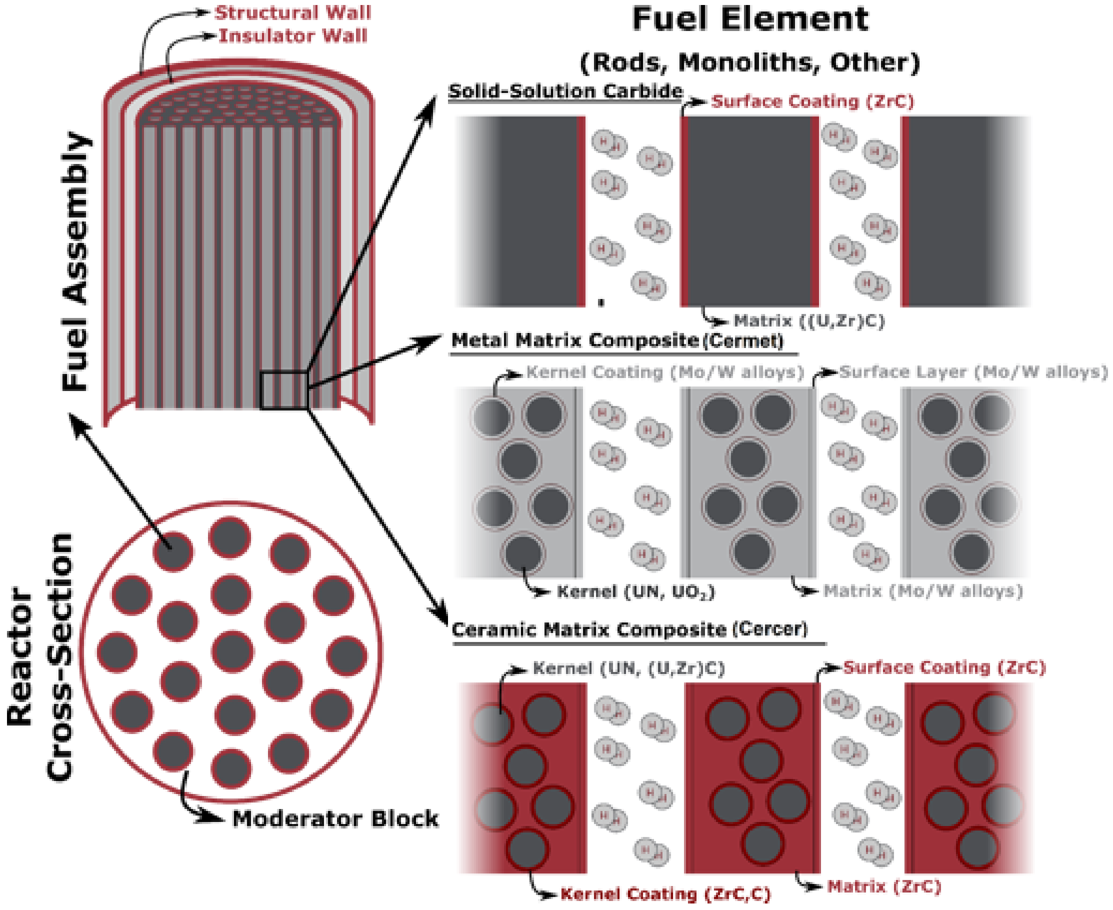
Process summarized herein facilitates production of reactor design concepts.

Elements of this process can be used to support design, neutronic, thermal hydraulic, and mechanical analysis that demonstrates the viability of reactor concepts and provides valuable insights to inform development and testing to progress technology maturation important for SNP NTP applications.



Fuel and Moderator Develop Plan Conceptual Testing Reference Design (15,000 lb$_f$)

NASA NTP Testing Reference Design - NETS 2022



Design Analysis Process Key to Supporting Concept Development

NASA's NTP Engine System is shown, of which BWXT is providing support for reactor and fuel design and analysis and AR is providing support for engine component design, analysis, and integration.(25,000 lb$_f$)

Acknowledgments

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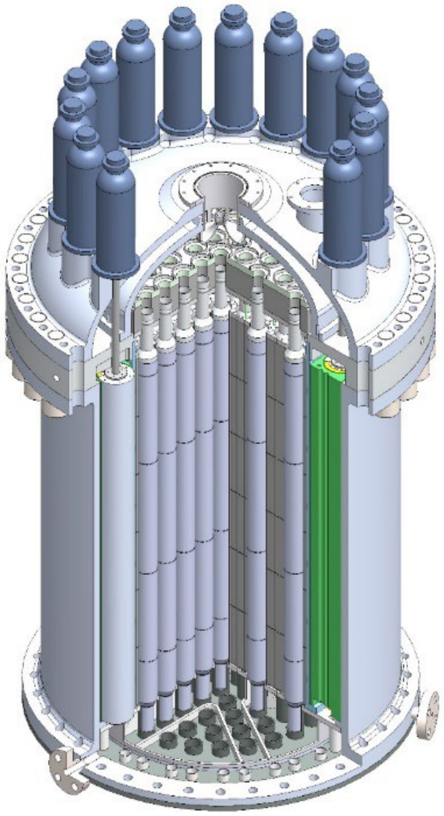


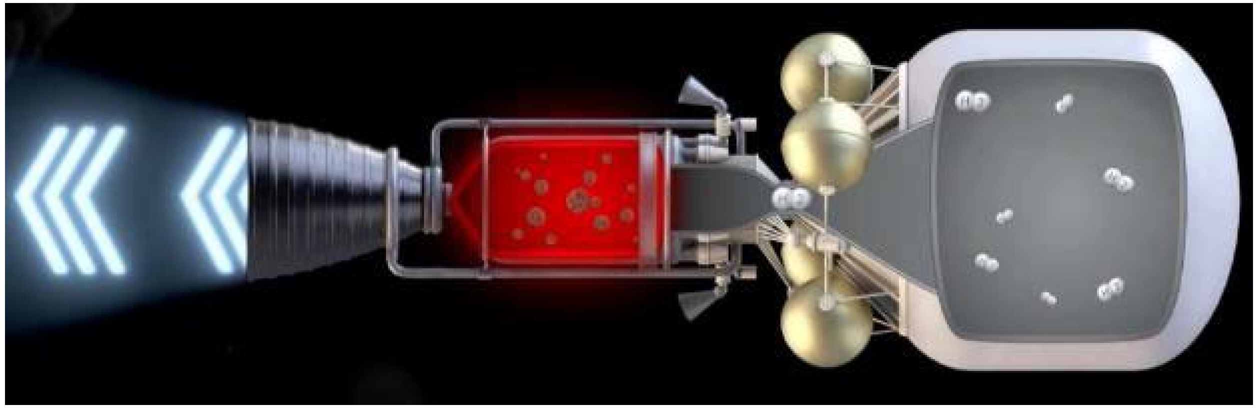
Fuel and Moderator Develop Plan
Conceptual Testing Reference Design
(15,000 lb_f)

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/miy2mbs2zAQ



Major Elements of a Nuclear Thermal Rocket Engine

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