National Aeronautics and
Space Administration

Space Technology Mission Directorate

Nuclear Thermal Propulsion Update

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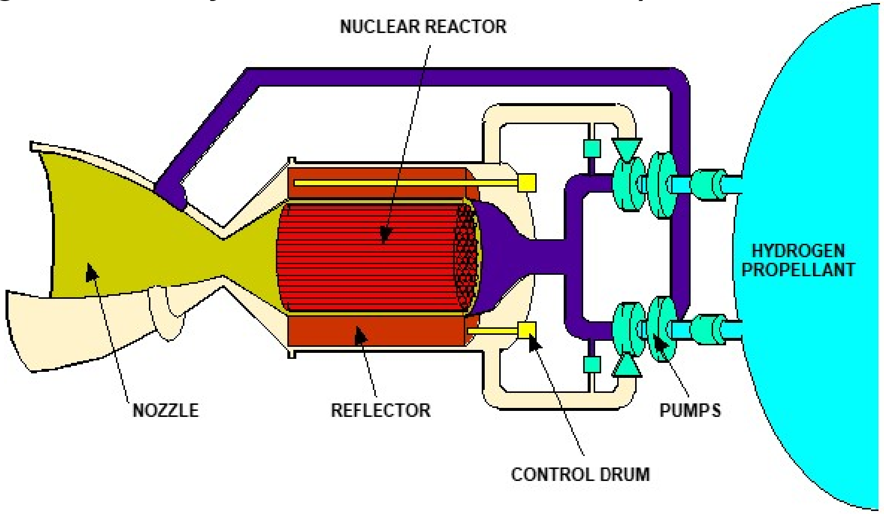
30 April 2019

Background

How A Nuclear Thermal Propulsion (NTP) Engine Works

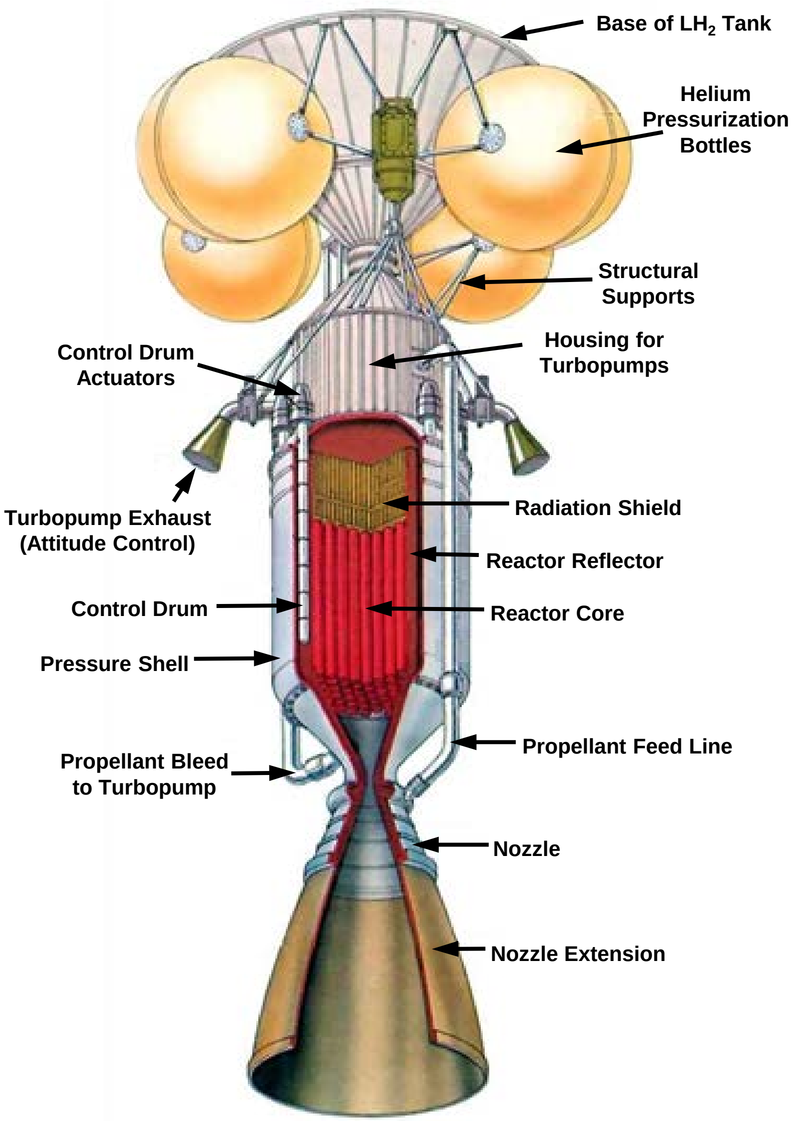
- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: 100,000 N ≈ 450 MW_{th} at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O_2/H_2 engine actually runs hotter than NTP)



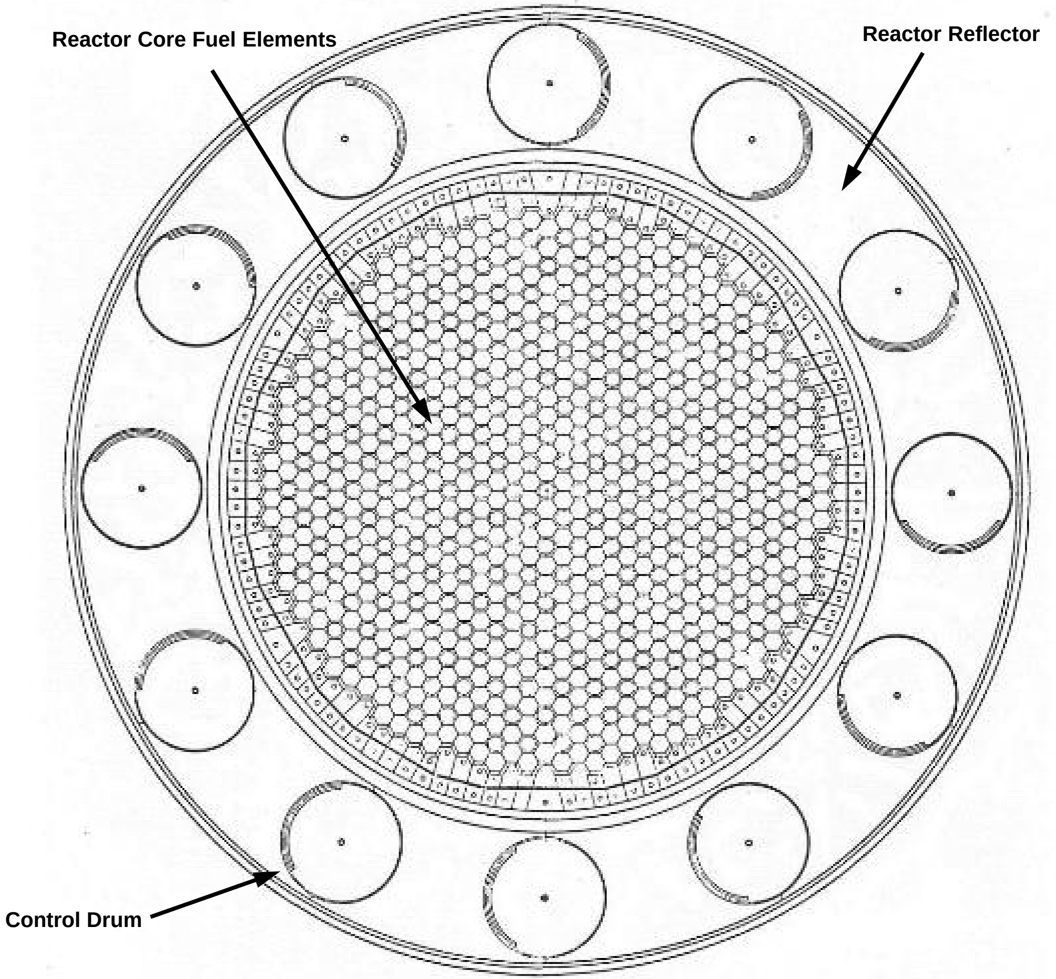
Major Elements of a Nuclear Thermal Rocket

NERVA Nuclear Thermal Rocket Prototype

How An NTP Engine Works (continued)

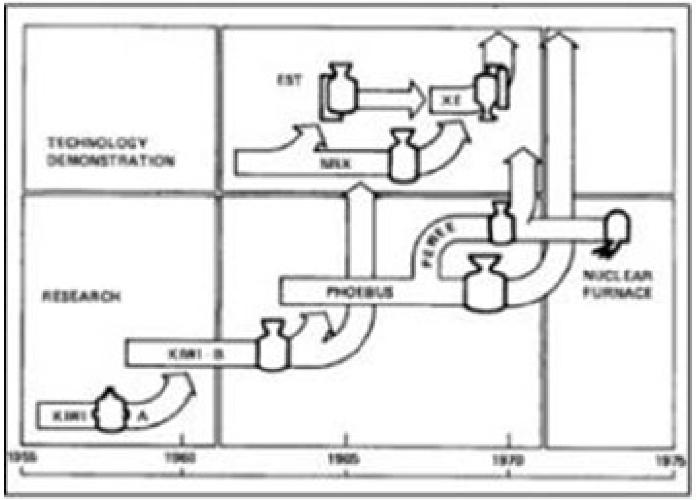


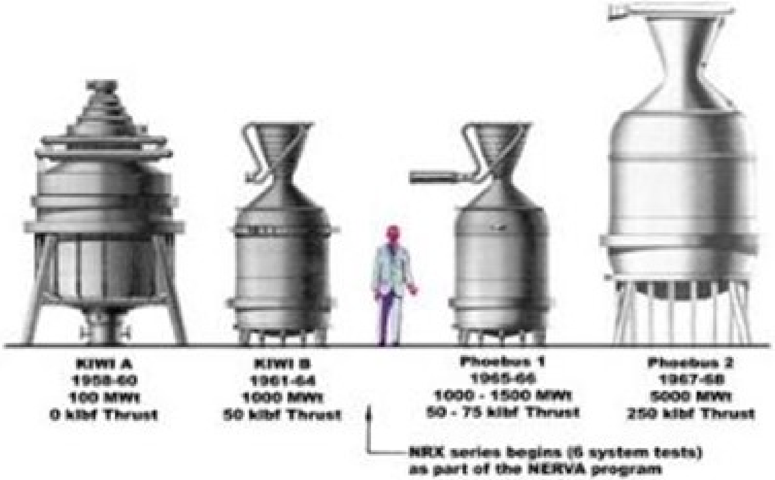
Cross Section

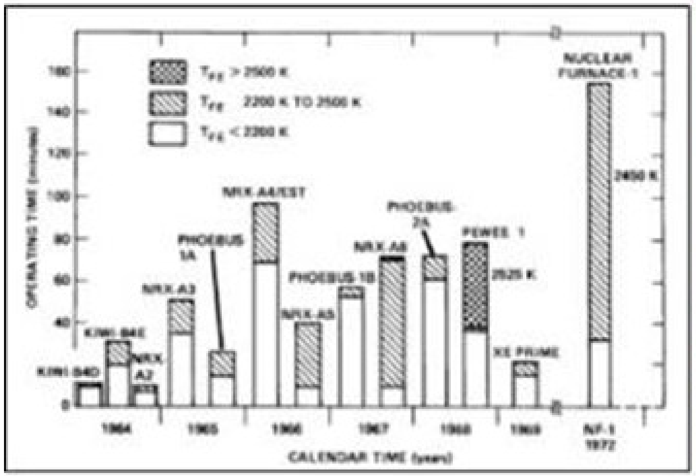


Note: Control drums rotate to control reactivity. Part of circumference covered with absorber and the rest is a reflector.

20 NTP Engines Designed, Built, Tested During Rover/NERVA, 1955-1972







Today’s NTP Development

- Past to Present: Changes since Rover/NERVA
  - Increased regulation and cost associated with nuclear operations and safeguards
    - Extensive development of non-nuclear engine components and extensive experience with various types of nuclear reactors
- Emphasis on Low Enriched Uranium (LEU) Fuel
  - Political and international acceptance
  - Programmatic flexibility (optimum mix of NASA, Department of Energy (DOE), industry, and universities)
  - Eliminate significant cost, schedule, and security impacts from attempting to develop and utilize a system containing highly enriched uranium (HEU)
  - Options for real-time exhaust processing or exhaust capture as a method of nuclear rocket engine testing

- 55430 lbs thrust
- 1140 MW power using NRX-A5 type fuel
- 28 restarts in 1969
- 11 minutes at full power
- Optimum startup/shutdown sequence

XE’ at MSFC

Why NTP?
Architectural Robustness

Architectural Robustness: An insensitivity to required mission energy (the combination of payload mass and DV)

- **Numerous studies have shown that NTP has better system performance than other in-space transportation alternatives**
  - Due to NTP's combination of **high thrust** (~25K lbf/engine) and **high Isp** (~900s)
  - Chemical systems have **high thrust** (~25K lbf/engine) but **low Isp** (~460s)
  - SEP systems have **very high Isp** (~3000s) but **very very low thrust** (~1.5-3 lbf/stage)
- **The robustness offered by NTP can be used to provide flexible mission planning by trading objectives including:**
  - Enables faster trip times for crew
  - More payload
  - Fewer SLS launches
  - Enable off nominal mission opportunities and wider injection windows
  - Enable crew mission abort options not available from other architectures

NTP is a safe, affordable 'game changing' technology for space propulsion that enables faster trip times and safeguards astronaut health.

Current Project

Nuclear Thermal Propulsion (NTP) Project Overview

Project Objective:

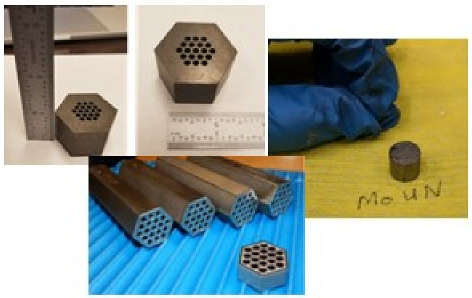
Determine the feasibility and affordability of a Low Enriched Uranium (LEU) - based NTP engine with solid cost and schedule confidence

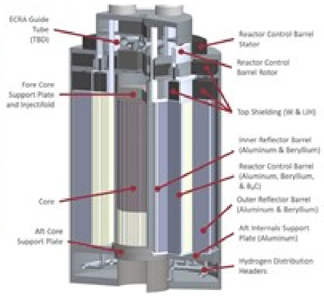
Approach:

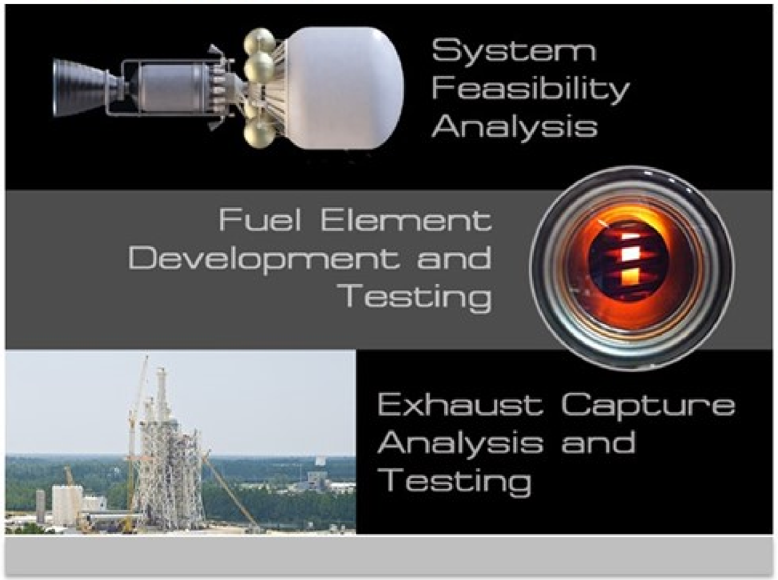
- Evaluate the implications of using LEU fuel on NTP engine design
- Fuel element, reactor, and engine conceptual designs and feasibility analyses
- Mature critical technologies associated with LEU fuel element materials & manufacturing
- Develop a method to facilitate ground testing
- Develop relevant cryogenic propellant management technologies

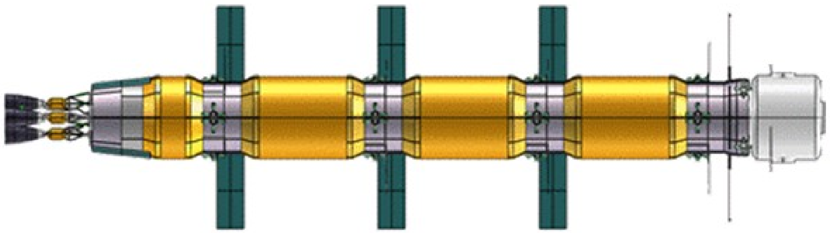
Roles and Responsibilities

- **MSFC**: PM, SE & Analysis Lead, Cryo ConOps Lead, FE Testing
- **GRC**: Cryocooler Testing, Cryo ConOps Support, Sys. Analysis Support
- **SSC**: Engine Ground Testing Analysis
- **KSC**: Ground Processing ConOps / Propellant Densification
- **Aerojet Rocketdyne**: LEU Engine Analysis
- **AMA:** Engine Cost Lead; Cryogenic Fluid Management Support
- **Aerospace:** Engine Cost Independent Review
- **BWXT:** Fuel Element (FE) / Reactor Design/Fabrication
- **DOE:** FE / Reactor Design and Fabrication Support







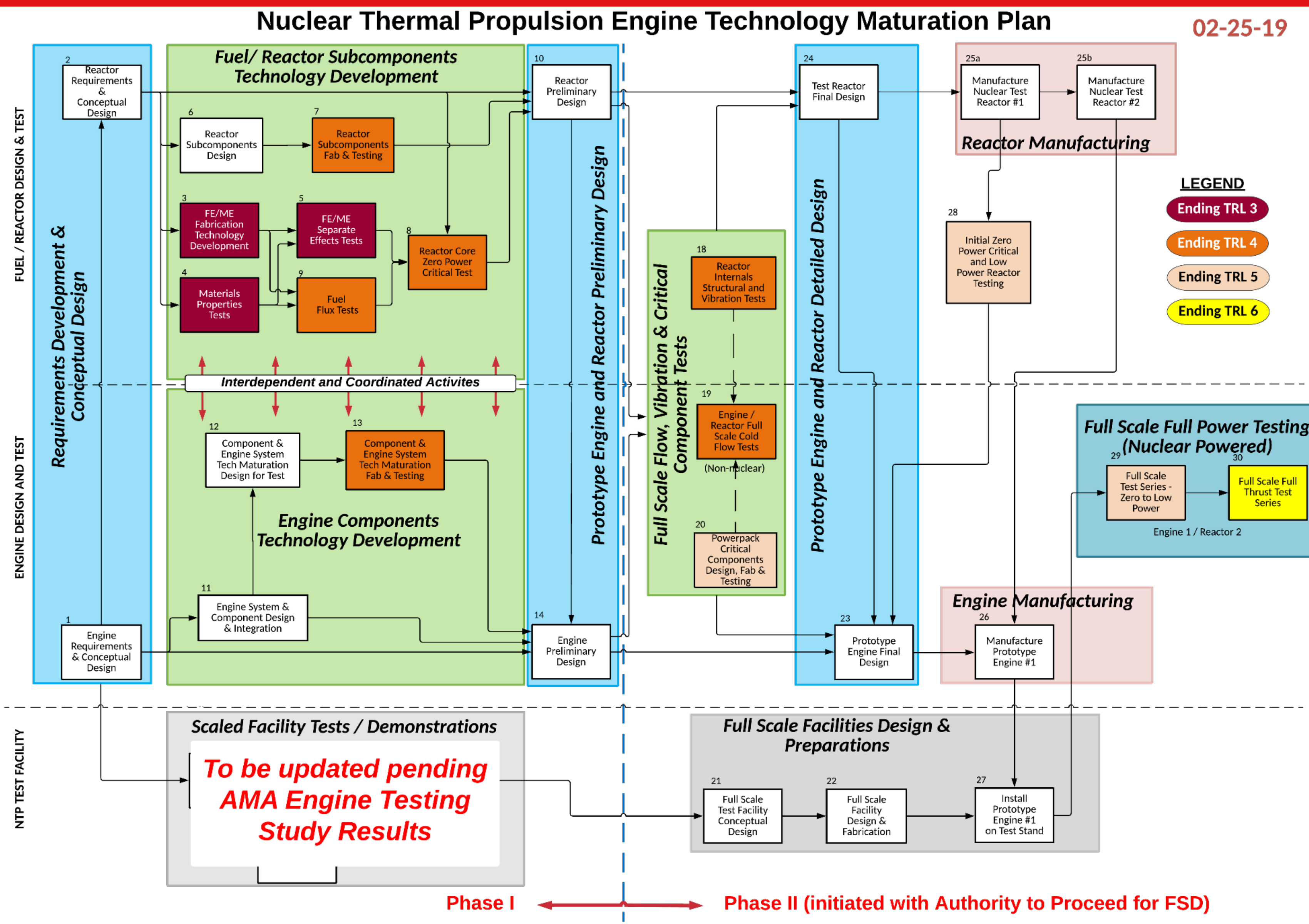


NTP Technology Development Challenges

- **Nuclear Fuels / Reactor**
  - High temperature/high power density fuel
  - Unique moderator element/control drums/pressure vessel
  - Short operating life/limited required restarts
  - Space environment
- **Integrated engine design**
  - Thermohydraulics/flow distribution
  - Structural support
  - Turbopump/nozzle and other ex-reactor components
  - Acceptable ground test strategy (technical/regulatory compliant)
- **Integrated stage design**
  - Hydrogen Cryogenic Fluid Management
  - Automated Rendezvous and Docking

NTP can provide tremendous benefits. NTP challenges comparable to other challenges associated with exploration beyond earth orbit.

Technology Maturation Plan



NTP Fuel Element Fabrication and Test Strategy

	Testing at MSFC	Testing at INL – SIRIUS 1	Testing at INL – SIRIUS 2
Welded Cans (*with packed powder)*	1 dUN in Mo or Mo/W; Tested in CFEET. dUN in Mo or Mo/W; Tested in NTREES		4 <20% enriched UN in Mo or Mo/W; Tested in TREAT
Traditional Cermet *(SPS)*	2 dUN in Mo or Mo/W; Tested in CFEET. dUN in Mo or Mo/W; Tested in NTREES		5 <20% enriched UN in Mo or Mo/W; Tested in TREAT
Traditional Cermet *(SPS)*		3 Uncoated 21% enriched UN in W/Re; Tested in TREAT	

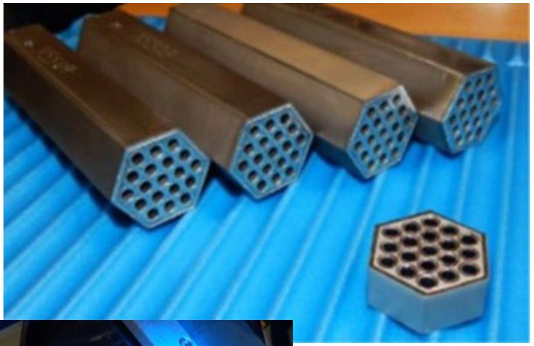
CFEET – Compact Fuel Element Environmental Tester
dUN – Depleted Uranium Nitride
NTREES – Nuclear Thermal Rocket Element Environmental Simulator
SPS – Spark Plasma Sintering
TREAT – Transient Reactor Test Facility
UN – Uranium Nitride

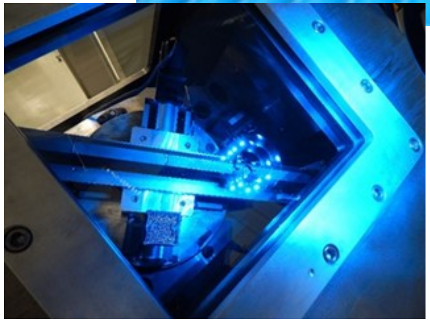
Notes:

1. All Cans and Traditional Cermets have 19 channels
2. UN fill of cans performed at MSFC

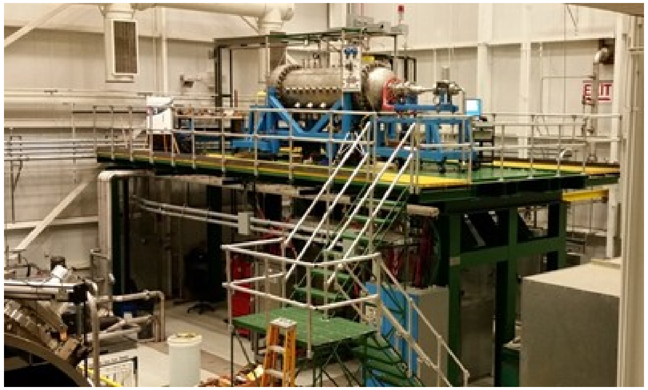
Fuel Element Development Status

- **Packed Powder Cartridge Development**
  - Continuing “cold end” Mo/depleted uranium nitride (dUN) fuel element (FE) fabrication
    - Completed laser butt welding mods for test articles and butt welds on ½” cold end development articles
    - Worked plug weld issues
    - Preparing for cold end, 19 hole element test in the MSFC Nuclear Thermal Rocket Element Environmental Test Simulator (NTREES) Facility in May, 2019
  - “Hot end” Mo/W/dUN fuel element NTREES test schedule for September, 2019

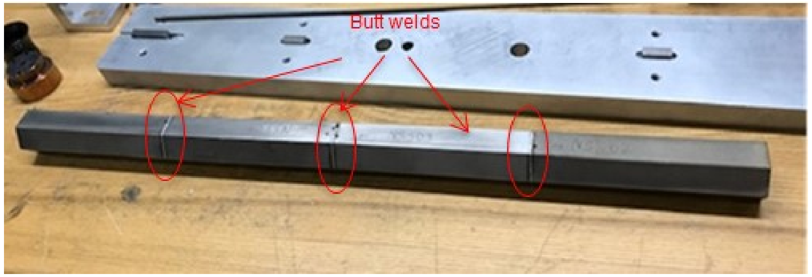




Above: Cold end FE welding process development cartridges; Left: Installed rotisserie fixture for cartridge butt welds (BWXT)



NTREES Test Facility, MSFC



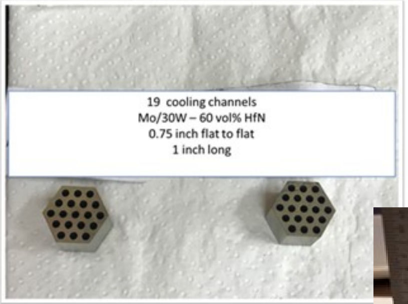
Butt weld development of stainless steel NTREES N-19 article: May possibly use as an additional fit-up article for NTREES testing

Pursuing multiple manufacturing options for fuel element development
Option 1: Packed Powder Cartridge

Fuel Element Development Status, continued

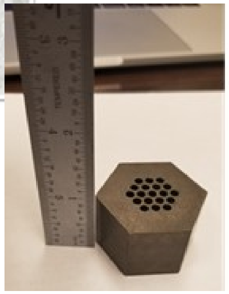
- **Spark Plasma Sintering (SPS) Cermet FE Development at MSFC**
  - SPS process rapidly (~5 min.) consolidates powder material into solid components
    - Fabricated the first SPS Mo/dUN specimen at MSFC, 2/22/19
    - Fabricated 2 hexagonal molybdenum tungsten-hafnium nitride (Mo/W/HfN) ceramic-metal (CERMET) fuel wafers
      - First major milestone and suitable for testing in the MSFC Compact Fuel Element Environmental Tester (CFEET)
    - Next milestone is to duplicate the Mo-W fabrication process using dUN instead of HfN
    - Goal: Deliver a surrogate 16-inch fuel test article by the end of FY19 for NTREES testing

Above: First SPS Mo-dUN specimen, ~10 mm in diameter by 12.7 mm long



Above: 2 hexagonal Mo/W-surrogate CERMET ~.75" by 1" in length

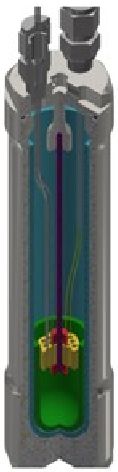
Below: Mo-HfN FE specimen: fabricated to demonstrate feasibility and scalability




Pursuing multiple manufacturing options for fuel element development
Option 2: Spark Plasma Sintered (SPS)

Transient Reactor Test Facility (TREAT)
Idaho National Laboratory (INL)

- **SIRIUS-1 Experiment Plan**
  - Demonstrate TREAT's ability to simulate prototypic stresses on NTP fuel and evaluate fuel performance during rapid heat up and thermal cycling conditions
    - Experiment will use a hexagonal, 19-hole, Mo-W Cermet sample containing 21% enriched UN
    - Sample will be housed in a stainless steel canister equipped with refractory metal liners to protect canister from sample heat
    - Test Description
      - Calibration runs will be performed using low power transients to confirm amount of reactor power needed to achieve desired temperatures
      - Fission heating will be used to raise sample temperature at 95 K/sec ramp rate (consistent with NERVA testing)
      - Sample temperature will be held at 2600 – 2850 K for approximately one minute, then reactor will be shut down and sample will be allowed to cool
      - Sample will be heated and cooled for six cycles
    - Post Irradiation Examination
      - Following irradiation, sample will be examined for cracking, hydriding, UN dissociation, and other temperature effects



SIRIUS-1 Cal Capsule

SIRIUS-1 Test Capsule

Nuclear testing of fuel samples
TREAT Facility, INL

System Feasibility Analysis

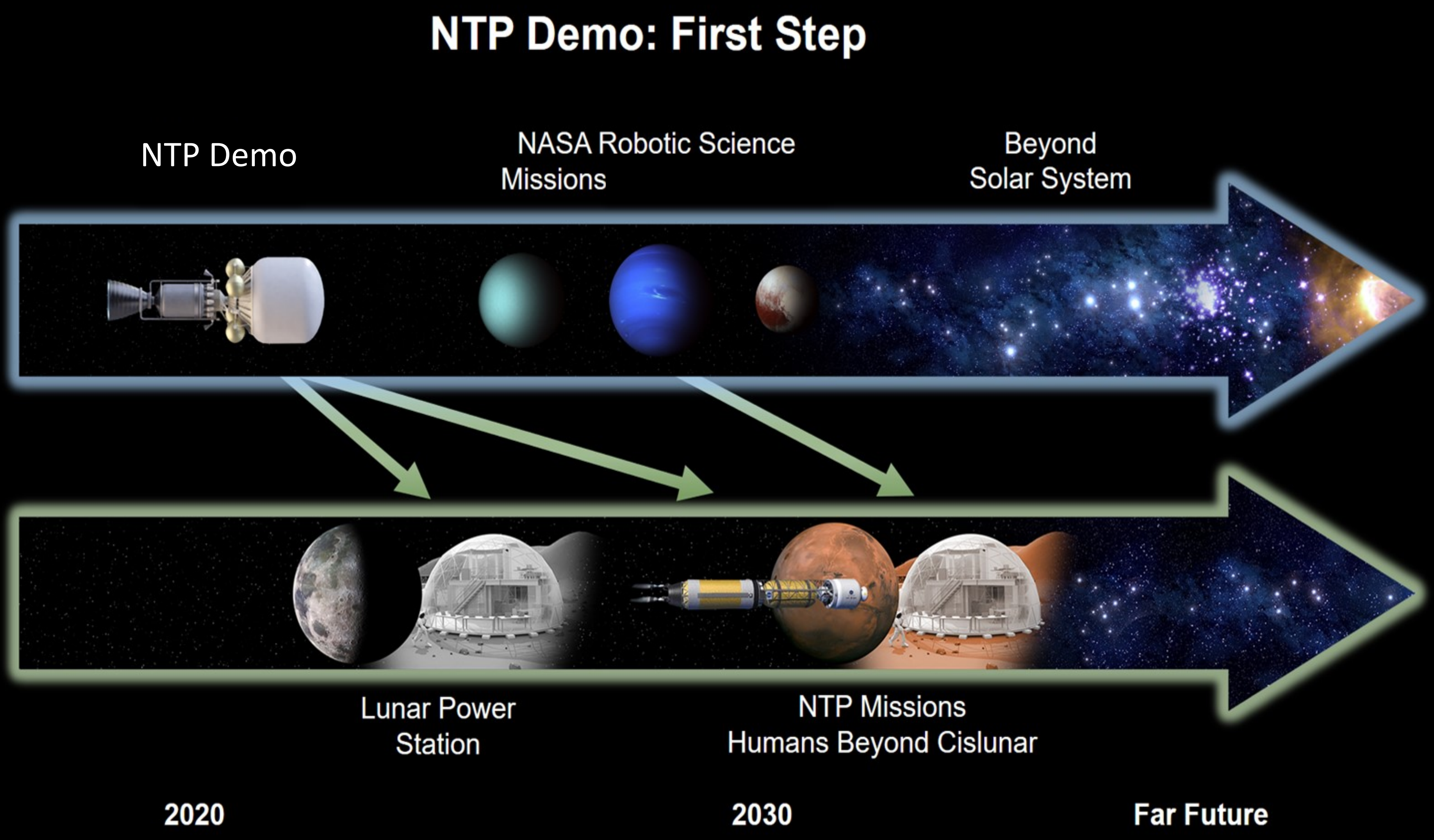
- **Project Goal**
  - Determine the *feasibility* and affordability of a LEU-based NTP engine with solid cost and schedule confidence
- **System Feasibility Analysis Scope**
  - Current assessment focuses on overall feasibility of an LEU engine/reactor/fuel and engine ground testing system based on current GCD NTP Project goals and objectives
    - Establish a conceptual design for an NTP LEU engine in the thrust range of interest for a human Mars mission
    - Design, build and test, in the Compact Fuel Element Environmental Tester (CFEET) and the Nuclear Thermal Rocket Element Environmental Simulator (NTREES), prototypic fuel element segments based on the conceptual design
    - Establish robust production manufacturing methods for a LEU fuel element and reactor core
    - Demonstrate the feasibility of a ground test method for nuclear rocket engine testing
- **System Feasibility Analysis Approach**
  - Technical Feasibility: A systems engineering approach
    - Will accomplish the assessment by defining a set of key criteria against which the engine/reactor/fuel and engine ground testing system feasibility will be judged
    - Provided for each key criteria will be a piece of objective evidence:
      - A report, analysis, test, or piece of design data, that demonstrates how the criteria item is satisfied

Summary

- **The STMD NTP project is addressing the key challenges related to determining the technical feasibility and affordability of an LEU-based NTP engine**
  - The project is maturing technologies associated with fuel production, fuel element manufacturing and testing
  - The project is developing reactor and engine conceptual designs
  - The project is performing a detailed cost analysis for developing an NTP flight system
  - An NTP system could reduce crew transit time to Mars and increase mission flexibility which would enable a human exploration campaign

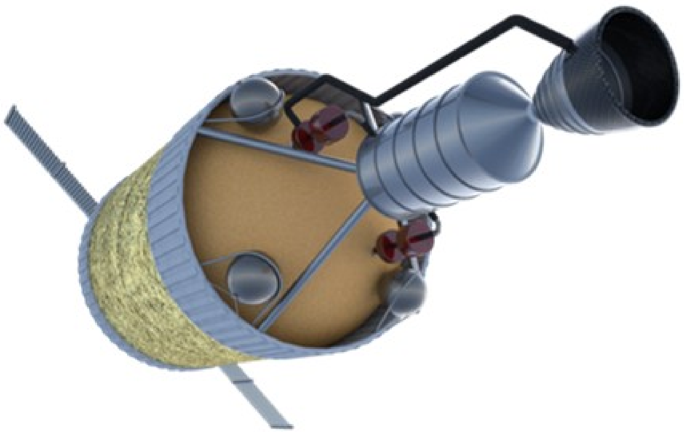
Flight Demonstration Study

NTP Flight Demo

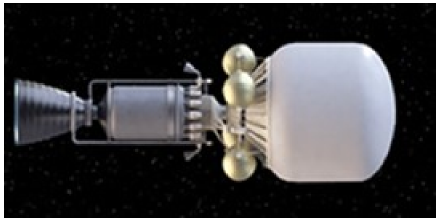


NTP Flight Demo (FD) Study

- **Objectives:**
  - Generate peer-reviewed documentation and briefings to provide enough clarity to STMD on the potential for executing a NTP flight demo so they can make an informed response back to Congress
  - The study will
    1) Evaluate NTP concepts to execute a flight demonstration mission in the immediate timeframe and later options
    2) Invite similar concept studies from industry
    3) Assess potential users and missions that would utilize a NTP vehicle
    4) Assess additional fuel form options (traceability)



NTP Flight Demo Options

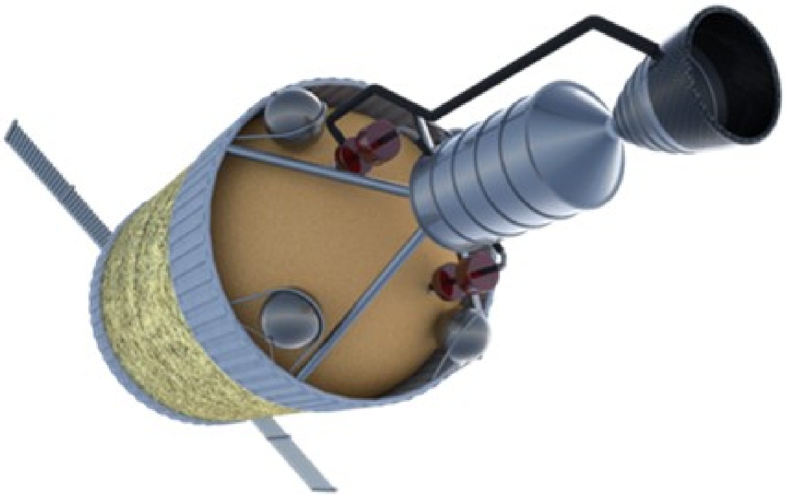


ASAP

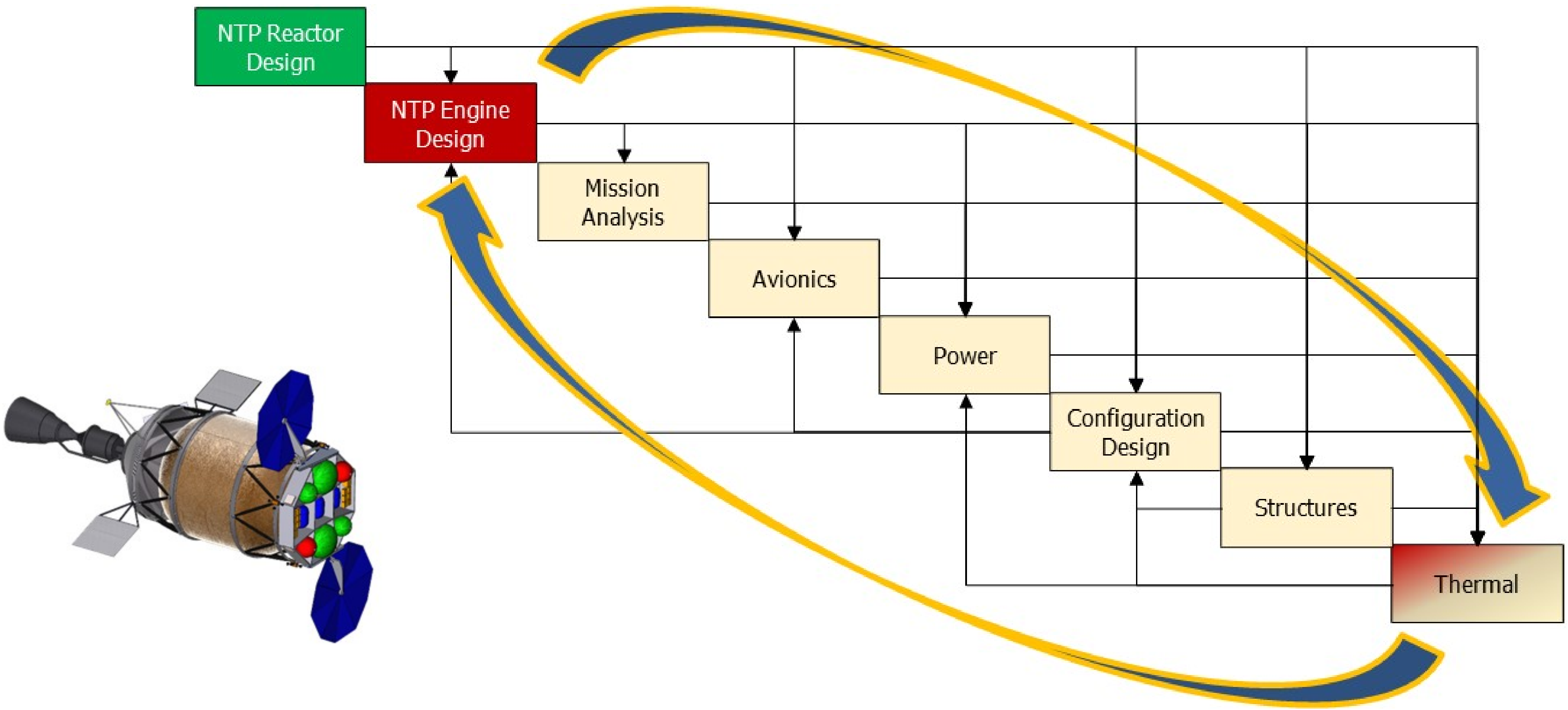
- **Flight Demo (FD) Options to be Considered**
  - FD1 - Nearest Term, Traceable, TRL Now (Target FY24 Flight Hardware Delivery)
  - FD2 - Near Term, Enabling Capability (TBD availability Date)
- **Customer Utilization Studies**
  - Science Mission Directorate
  - DoD (via DARPA)
- **Industry Perspective (Industry Day; BAA to be issued)**
- **Outbrief to STMD will provide “MCR-like” products**
  - Including acquisition strategy, draft project plan, certification strategy, etc.

NTP Flight Demo

- **NTP Demonstrator Notional Requirements (To Be Finalized)**
  1. LV Insertion into Earth escape trajectory
  2. System checkout
  3. Engine startup
  4. Steady-state operation
  5. Engine shutdown / cool-down
  6. Engine restart
  7. Steady-state operation
  8. Engine shutdown
  9. Download telemetry data
  10. End mission



NTP Flight Demo Design Team

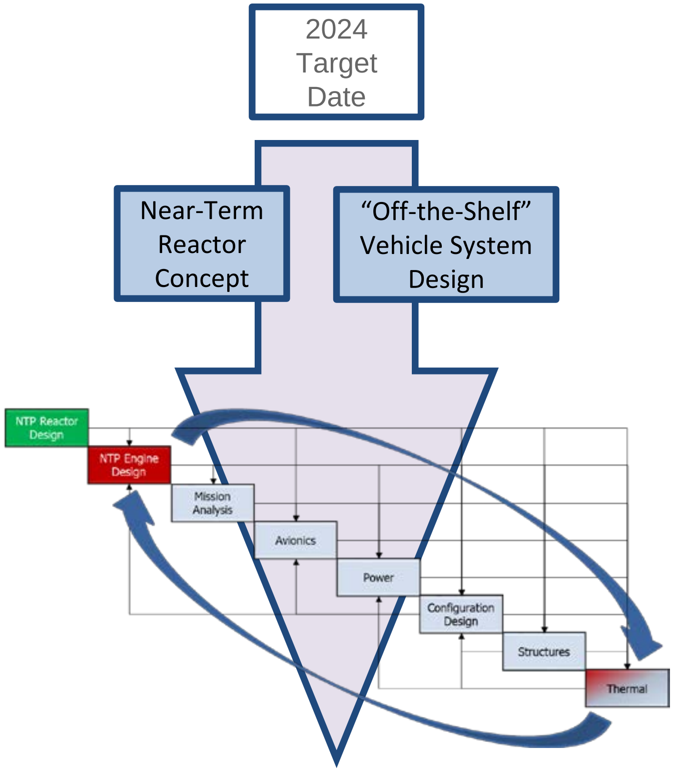


The NTP Flight Demo concept will be developed by an integrated collaborative engineering team

- Vehicle design and mission analysis led MSFC Advanced Concepts Office
- Reactor design led by Department of Energy
- Engine system definition led by MSFC Propulsion Department

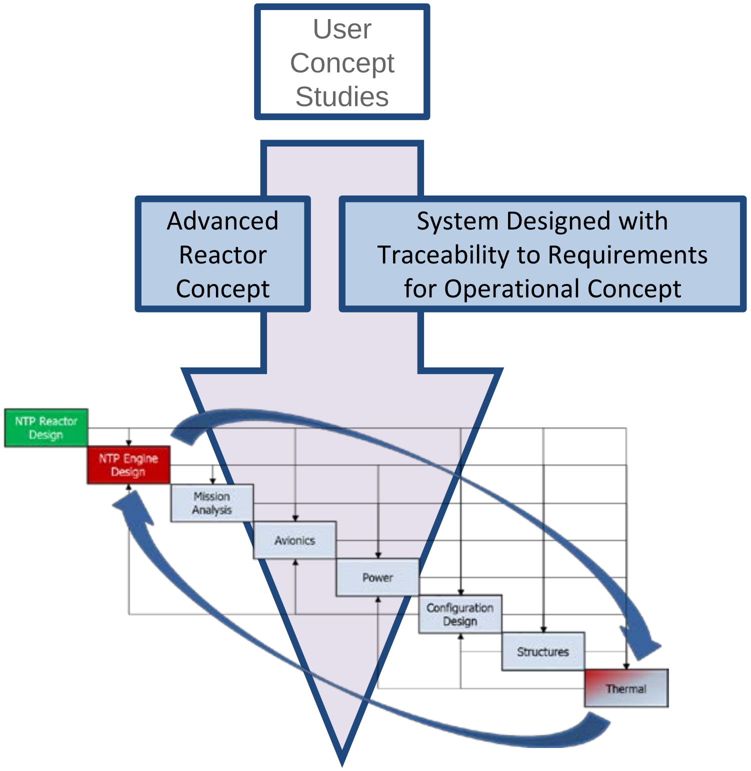
Integrated System Design Process

FD1 - Flight Demo Concept Driven by Schedule



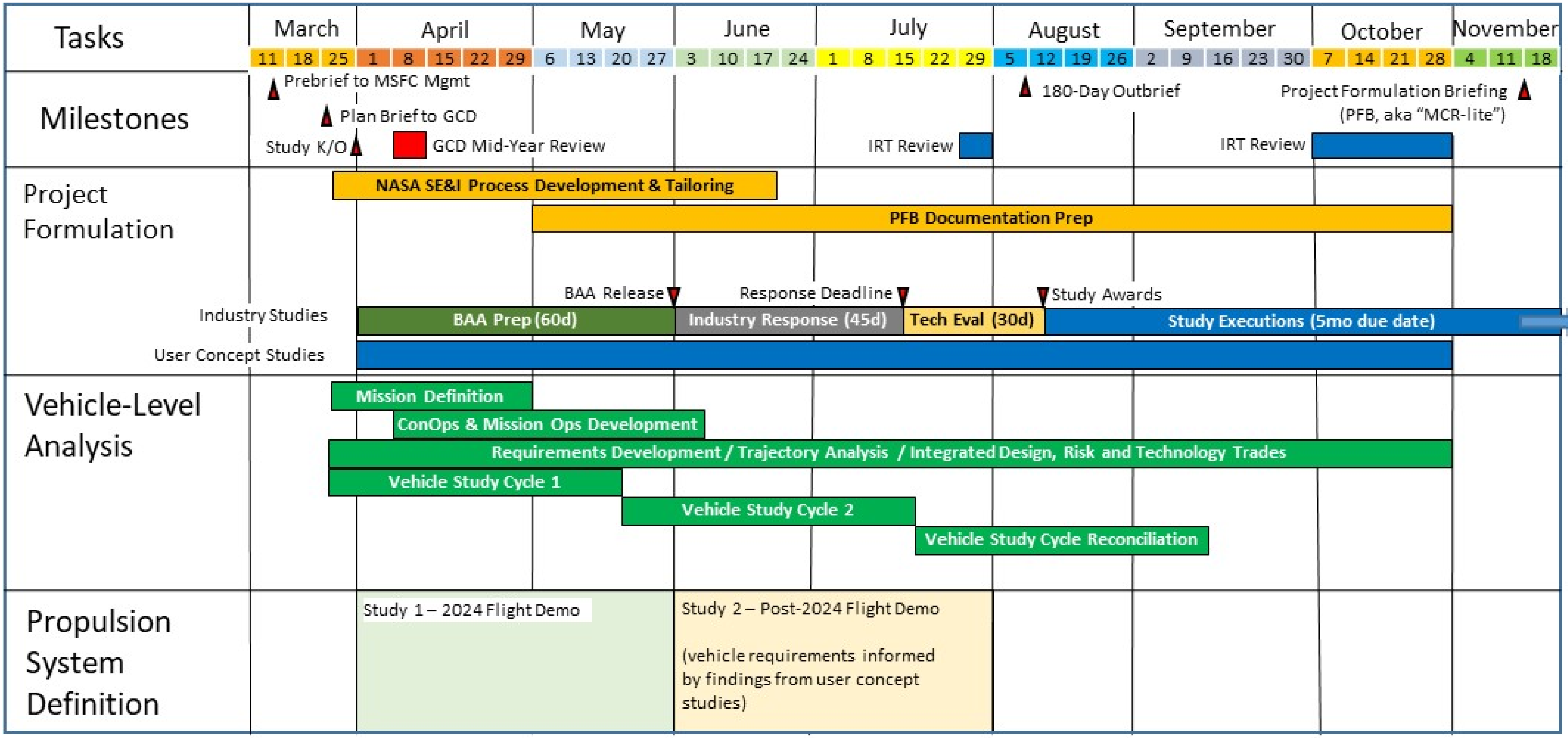
- NTP concept that can be designed, built, and **flown within required timeframe**
- Estimated program cost and schedule

FD2 - Flight Demo Concept Driven by Traceability to Real-World Use Cases



- NTP concept that **demonstrates performance** required by initial operational use cases
- Estimated flight date based on required developments
- Estimated program cost and schedule

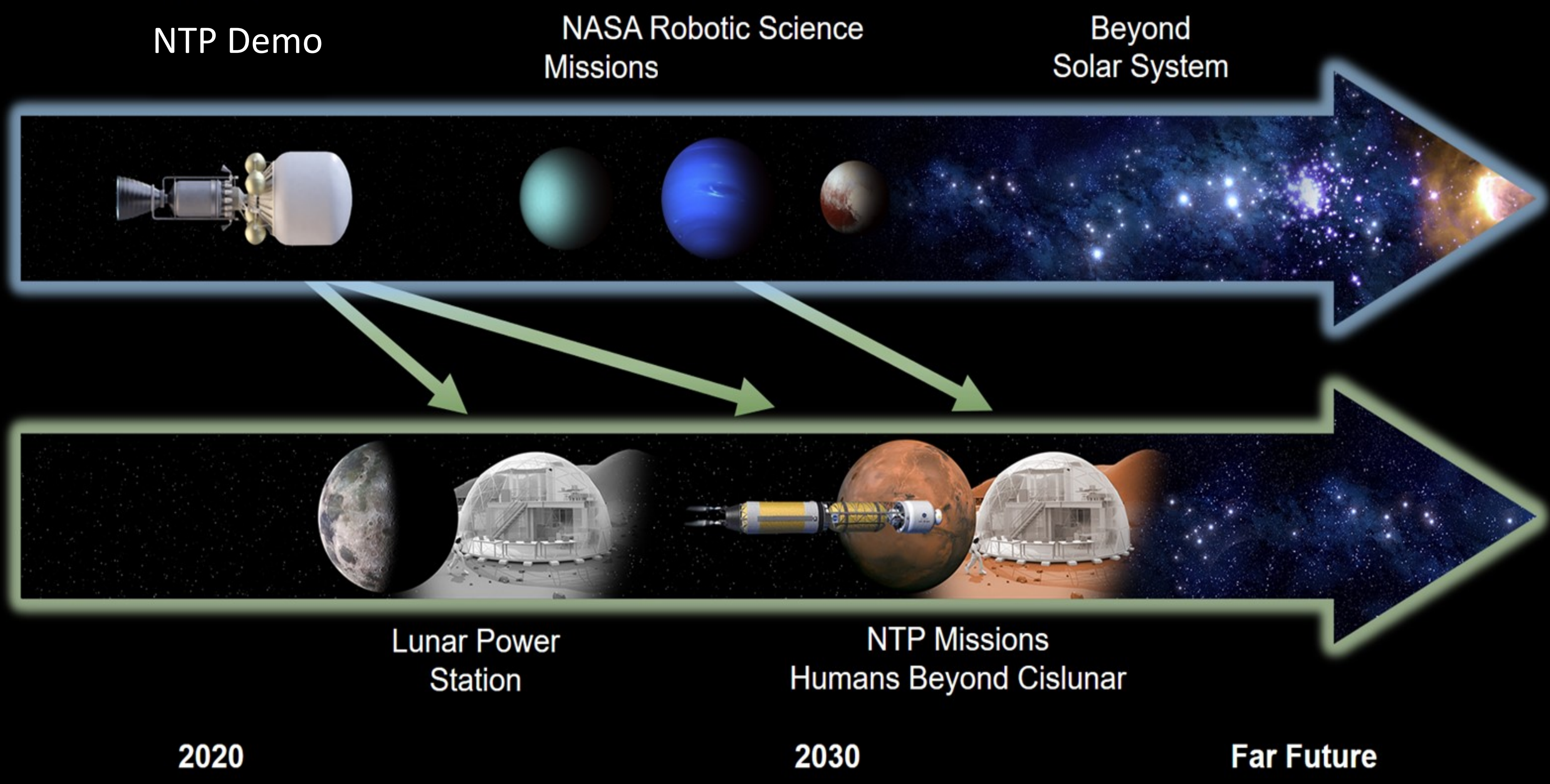
NTP FD Formulation Study Schedule



- CE and LSE will insure alignment across all ongoing study activities
- Leverage previous design work as starting point for current design work
- The first vehicle study cycle will focus on the FD1 mission concept, which will be expanded in subsequent cycles to work the FD2 mission concept studies which will be informed by findings from the user concept studies.
- BAA study responses are expected in early 2020; will work to enable earlier industry inputs via utilizing "Industry Day" approach

NTP Flight Demo

NTP Demo: First Step



Backup

Current NTP Project Architecture

Mission: 2033 Fast Conjunction

Mission Times

Earth-Mars	160 days
Mars Stay	620 days
Mars-Earth	160 days

Earth Sphere of Influence

Aggregation Orbit	NRHO
Departure / Arrival Orbit	LDHEO

Mars Sphere of Influence

Arrival / Departure Orbit	1 SOL

NTP Primary Burns (4)*

TMI ΔV / Time	622 m/s / 354 sec
MOI ΔV / Time	1,668 m/s / 823 sec
TEI ΔV / Time	1,352 m/s / 479 sec
EOI ΔV / Time	581 m/s / 181 sec

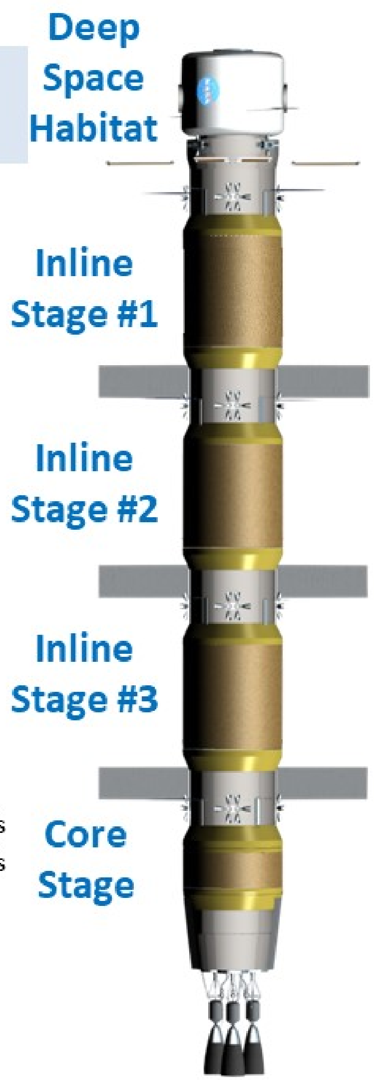
**Primary burn ΔV values do not include 4% FPR*

Earth Sphere of Influence ΔVs (RCS/OMS)

Launch to NRHO	RCS: 10 m/s / OMS: 115 m/s
NRHO to LDHEO	RCS: 95 m/s / OMS: 100 m/s
LDHEO to NRHO	RCS: 46 m/s / OMS: 70 m/s

Mars Sphere of Influence ΔVs (RCS)

Plane Changes, Apotwist	OMS: 250 m/s



Vehicle Concept Characteristics

Payload: Deep Space Habitat

Gross Mass	46,783 kg (At TMI)

Inline (each)

Propellants	LH2 Main; NTO/Hydrazine RCS
Main Usable Propellant‡	27,761 kg of LH2
RCS Usable Propellant	4,039 kg of NTO/Hydrazine
Dry Mass	10,696 kg
Inert Mass‡	13,075 kg
Gross Mass	43,875 kg
Stage Length	11.1 m
Stage Diameter	7.5 m (7.0 m Tank Diameter)

Core

Propellants	LH2 Main; NTO/Hydrazine RCS
Main Usable Propellant‡	13,449 kg of LH2
RCS Usable Propellant	3,000 kg of NTO/Hydrazine
Dry Mass	26,180 kg
Inert Mass‡	27,426 kg
Gross Mass	43,875 kg
Stage Length	19.2 m
Stage Diameter	7.5 m (7.0 m Tank Diameter)
# of NTP Engines	3
NTP Engine Thrust	25,000 lb_f
NTP Engine Isp	875 sec
OMS Isp	500 sec

‡Main Usable Propellant does not include 4% FPR. Inert Mass does.

NTP System Feasibility Assessment Process Flow Diagram