National Aeronautics and
Space Administration

Space Technology Mission Directorate

Nuclear Thermal Propulsion Update

Richard Ballard
NTP Project Manager (Acting)
Marshall Space Flight Center

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NTP Overview Outline

Project Overview

- **Key Team Members**
- **System Feasibility Analysis**
  - Scope and Approach
  - High Level Results
- **Fuel Element (FE) Fabrication and Test Status**
  - Approach 1: Packed Powder Cartridge (PPC) Fuel Element
  - Approach 2: Spark Plasma Sintering (SPS) Fuel Element
  - Approach 3: TRi-structural ISOtropic (TRISO) or Coated Mixed Carbide (CMC) (New Work)
  - Fuel Development Design Independent Review Team (DIRT) Recommendations
  - Transient Reactor (TREAT) Facility Testing at Idaho National Laboratory
- **NTP Technology Development Challenges**

NTP Flight Demonstration Formulation Study

- **Objective**
- **Options**
- **Design Collaboration Team**
- **Flight Demo 1 (FD1) Study Results**
- **Schedule**

Project Summary

Nuclear Thermal Propulsion (NTP) Project Overview

Key Benefits

Provide NASA with a robust in-space transportation architecture that enables faster transit and round trip times, reduced SLS launches, and increased mission flexibility

Current Strategy and Investments

Risk Reduction: Determine the feasibility of an low enriched uranium (LEU)-based NTP engine with solid cost and schedule confidence.

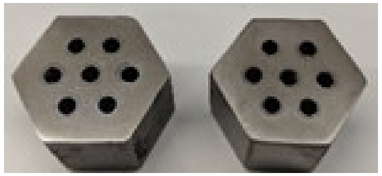
Flight Demo Study: Evaluate NTP concepts to execute a flight demonstration mission to include potential users and missions and additional fuel forms. This study is inviting industry participation

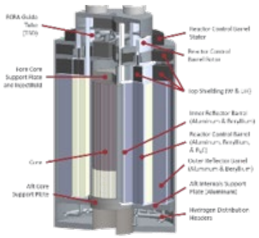
Partnerships and Collaborations

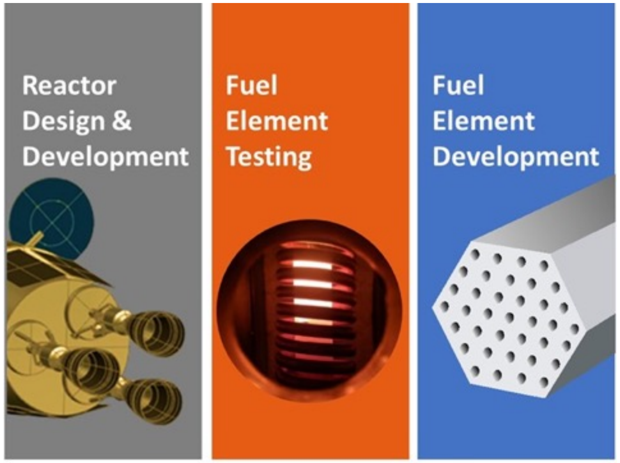
NASA and Department of Energy (DoE) (Idaho National Lab, Los Alamos National Lab, and Oak Ridge National Lab) are collaborating on fuel element and reactor design and fabrication for LEU-based NTP feasibility. DoE provides indemnity to industry.

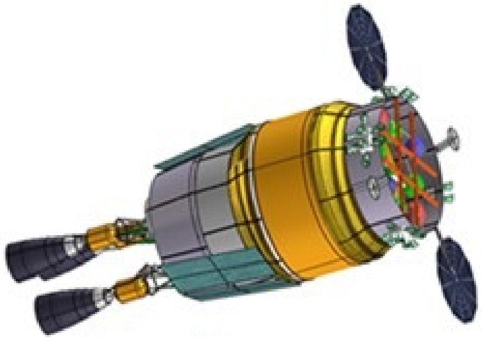
NASA, DoE and Department of Defense (DoD)/Strategic Capabilities Office (SCO) are working to develop a common fuel source for special purpose reactors including NTP and "Pele". Shared investments will address key challenges of the TRIstructural ISOtropic (TRISO) fuel form that will inform both the NTP risk reduction and flight demo formulation.

DoD, DoE, and NASA are formulating a collaborative effort that utilizes and benefits each organization. Specific areas include: Indemnification, mission requirements, design, analysis, facilities and testing.

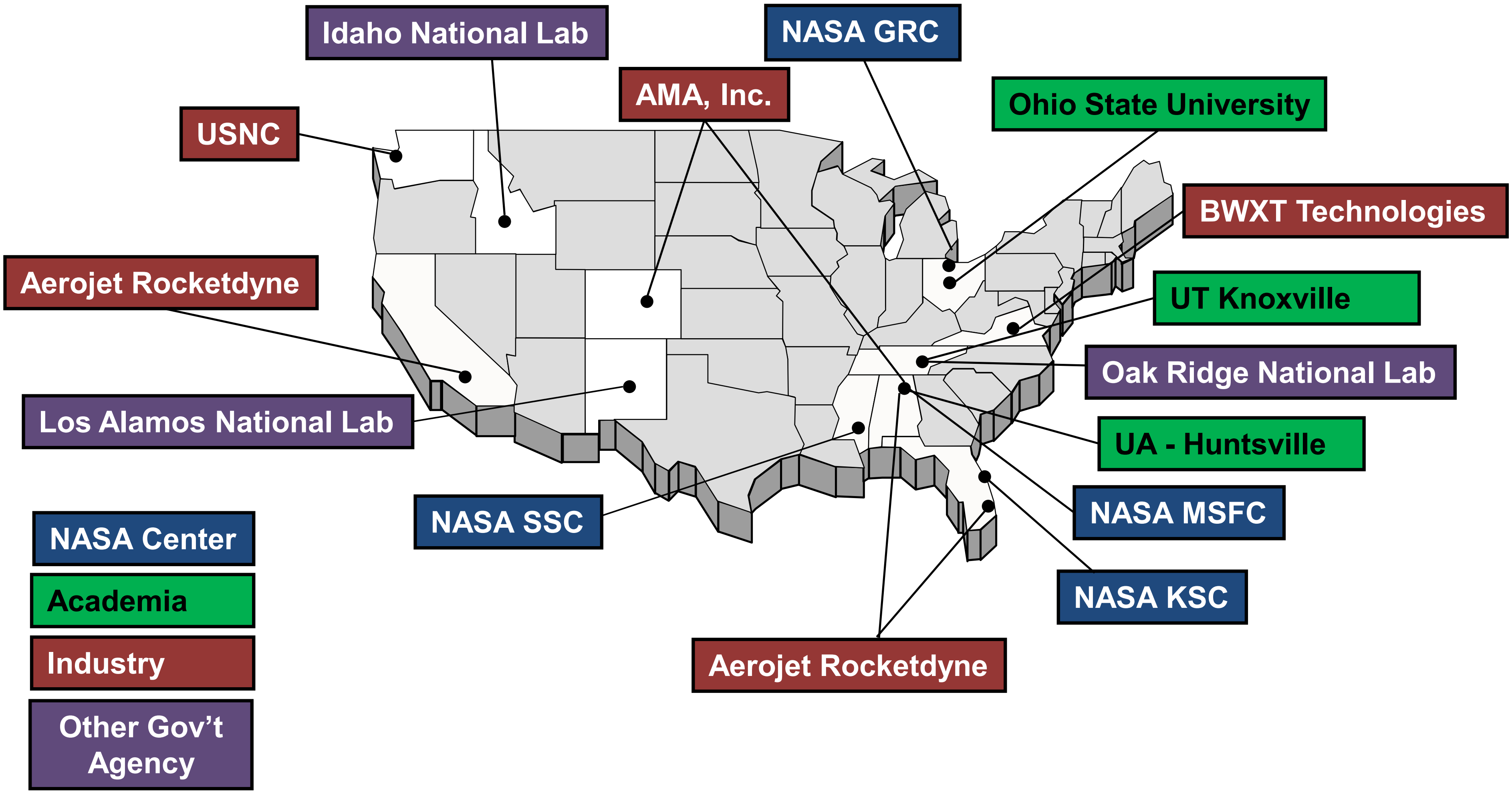








NTP Organization and Key Members



System Feasibility Analysis

- **Project Goal**
  - Determine the feasibility of a LEU-based NTP engine
- **System Feasibility Analysis Scope**
  - 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, fabricate and test prototypical fuel elements for a nuclear thermal rocket reactor
      - ❖ Fuel Element (FE) Test Facilities: No one facility provides everything needed – multiples facilities are leveraged to obtain needed feasibility assessment data
        - *Compact Fuel Element Environmental Test (CFEET)* System, Marshall Space Flight Center, (MSFC)
          - Small (≤2") specimens, RF induction heated to prototypic temperatures (≤2850 K) in non-flowing hydrogen
        - *Nuclear Thermal Rocket Element Environmental Simulator (NTREES)*, MSFC
          - Larger (≤20") FEs, RF induction heated to prototypic temperatures, (≤2850 K), pressures (≤1000 psia) in flowing hydrogen
        - *Transient Reactor Test (TREAT)* Facility, Idaho National Laboratory (INL)
          - Small (≤2") specimens, heated by nuclear fission: prototypic temperatures (≤2850 K)
    - ➢ Identify robust production manufacturing methods for a LEU fuel element and reactor core
- **System Feasibility Analysis Approach**
  - Technical Feasibility: A systems engineering approach
    - ➢ Assessment defines 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

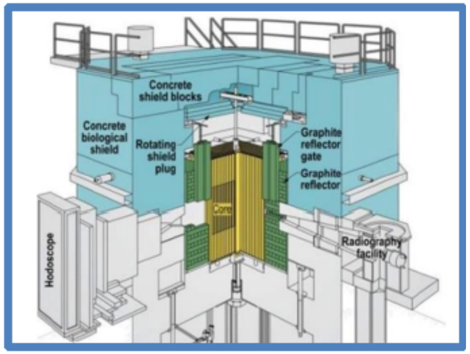
NTP Fuel Element Test Facilities

	CFEET	NTREES	TREAT
Location	MSFC	MSFC	DOE INL
Heating	Radiative (RF induction coil coupled with tungsten susceptor)	Test Article Internal Resistance (Current induced by RF Coil)	Nuclear Fission (tailored power)
NTP Test Fuel	YSZ, ZrN, and dUN	ZrN and dUN	High Assay LEU UN
NTP Test Specimen	C0, C7 (0 or 7 cooling tubes)	N19 (19 cooling tubes)	C7 (7 cooling tubes)
NTP Test Specimen Size	0.75" hex, 2" length	1.15" hex, 20" length	0.75" hex, 2" length
NTP Test Article Temperature	$\leq$ 2850 K	$\leq$ 2850 K	$\leq$ 2850 K
Test Chamber Pressure	20 psia	$\leq$ 1000 psia	~ 20 psia
Test Chamber Gas	Hydrogen – Cover	Argon or Nitrogen	Safe Gas Cover
Test Article Gas Flow	~none	Hydrogen - Full FE Scaled Flow Rate	~none

No one test facility provides everything needed, so multiple existing facilities are leveraged to obtain needed feasibility assessment information

Compact Fuel Element Environmental Test (CFEET)

Nuclear Thermal Rocket Element Environmental Simulator (NTREES)



Transient Reactor Test Facility (TREAT)

FY19 System Feasibility Results

- **System Feasibility Data Tracking**
  - The matrix which tracks feasibility data uses a color-coding system (green, yellow, and red) to visually indicate the status of feasibility for each item
    - ❖ Green indicates the criteria is met
    - ❖ Yellow indicates that the criteria are close to being met with some planned work remaining
    - ❖ Red indicates that significant further work is required to determine if the criteria can be met
  - Determined 34 of 42 criteria to be green
  - Assessed the remaining 8 as yellow (shown below):

Title	Statement
Fuel Element Designs, Fabrication and Testing	Design, develop and test fuel elements that will meet the neutronic, thermal hydraulic and structural performance requirements of a reactor conceptual design.
High Assay Low Enriched Uranium (HALEU) Reactor	Design a reactor concept using a LEU fuel system with a refractory metal based fuel element 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.
Fuel (UN) Performance – Thermo-Physical Character	Performance behavior of fuels in reactor application are understood to give confidence fuel form will function for the endurance lifetime (starts/duration).
Material Selection - Reactor	Design a reactor concept capable of operating in a combined thermal and radiation environment.
NTPE Health & Status Monitoring	Design a NTP engine concept that will monitor the health and status of the engine
CFM Thermal Performance	Show that CFM system performance will limit LH2 boil-off sufficiently to close the reference mission architecture.
Propellant Loss due to Leakage	Show that a path exists to develop valves and couplings that provide sufficiently low leakage rate to meet the CFM ConOps needs.
Cryocooler Performance	Show that a development path exists to advance cryocooler performance to meet the CFM ConOps needs.

More detailed table in backup section

Fuel Element Development Status

- **Fuel Element Development and Test Status**
  - **Approach 1: Packed Powder Cartridge (PPC) Development**
    - BWXT designed and developed the fuel form and cartridge consisting of Molybdenum (Mo)-depleted uranium nitride (dUN) “cold end” and Mo-tungsten (W)-dUN “hot end”
    - Mo-dUN “cold end” FE development and testing
      - Complex fab and assembly: 20” NTREES FEs consisted of 23 parts and 41 welds
      - Challenges to cartridge welds delayed testing approximately 2 months
      - Fuel element butt welds and flow channels showed cracks prior to testing
      - Completed “cold end” Mo-dUN fuel element (FE) test in NTREES, 6/27/19
        - Fuel element failed during testing
    - Mo-W-dUN “hot end” FE delivery delayed from September 2019 to December 2019 due to materials availability and fabrication issues. NTREES test scheduled for January 2020.
      - “Cold end” FE failure precipitated formation of a Design Independent Review Team (DIRT) to evaluate design and technical risks associated with PPC FE concept as well as provide recommendations for NTP forward path.
      - DIRT recommended cancelling further PPC development and test, and focus resources on alternate FE development activities.

Mo-dUn cold end: pre-NTREES test

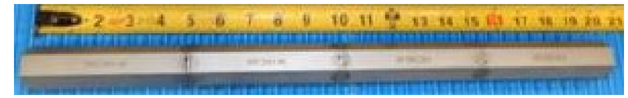
Centerline crack on side with weld overlap

Fuel Element Development Status, (cont.)

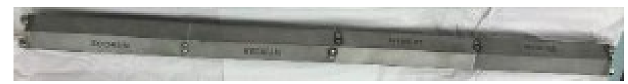
- **Packed Powder Cartridge (PPC) Fuel Element Development**
  - Results: Mo-dUN "cold end" FE testing in the NTREES Test Facility on 6/27/19 (API Milestone)
    - During a planned hold at 1850K the NTREES facility experienced a power system fault resulting in in an unintended cool down rate
    - FE separated into two pieces along a butt weld; no dUN was released in the chamber
    - The resulting rate of cooling (≈ 80-90 K/sec) was not greater than predicted for an actual nuclear fuel element in service
    - Determined that the cooling rate did not initiate nor was it sufficient to induce breakage of a properly designed FE

Fit Check

SS 304 Development Article



N19C-A1 Surrogate Test Article (S1)



N19C-A2 dUN Test Article (Cold End)

Flow tube to end cap welds show centerline cracking for outer portion of outer tube row for test N19C-A1

Above Images from here – N19C-A1

Separation at in-coil butt welds due to thermal stresses

Design Independent Review Team (DIRT) Established Following 2nd NTREES PPC FE Failure

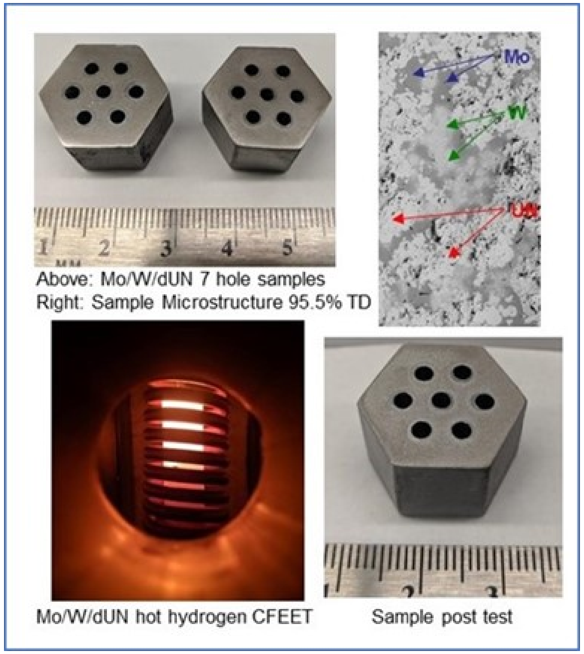
Fuel Element Development Status, (cont.)

- **Fuel Development Design Independent Review Team (DIRT)**
  - Provide an assessment of the ability and confidence of NTP design approach to meet the intended purpose and survive the environments
    - Identify strengths and challenges of the design approach
    - Suggest if design concept should be altered and/or continued
    - Assess design development priorities needed to assure survivability to environments and associated technical/programmatic risks
  - The Board made the following recommendations
    1. Discontinue packed powder cartridge fuel development at the end of FY19.
    2. Focus resources on alternate Spark Plasma Sintering (SPS) reactor design development for the remainder of the project baseline
    3. Pursue a fuel form that advances the near-term design, fabrication, and testing needs of a SPS reactor design and is extensible to the Isp needs of NASA.
    4. Project should submit written rationale detailing technical reasons why graphite composite should not be pursued.
    5. Assess potential for establishing a fuel testing capability analogous to that provided by the Nuclear Furnace facility developed during NERVA.
    6. Assess benefits vs. liabilities associated with pursuing a HEU-based NTP.

Fuel Element Development Status, (cont.)

- **SPS Cermet FE Development at MSFC**
  - Process rapidly (~5 min.) consolidates powder material into solid components (no free powder)
  - Allows for built in cooling channels that optimize heat transfer
  - Met integrity and density (>95%)
- **Successfully fabricated 2 hex Mo-W-dUN fuel wafers for testing in the CFEET system**
  - Tested in CFEET at 2250K for 20 minutes under hot hydrogen with no noticeable dissociation of UN
  - Migration at Mo-UN interface confirms hydrogen is detrimental and cladding needed to mitigate attack

A NASA developed SPS Process SPS



Above: Mo/W/dUN 7 hole samples
Right: Sample Microstructure 95.5% TD

Mo/W/dUN hot hydrogen CFEET

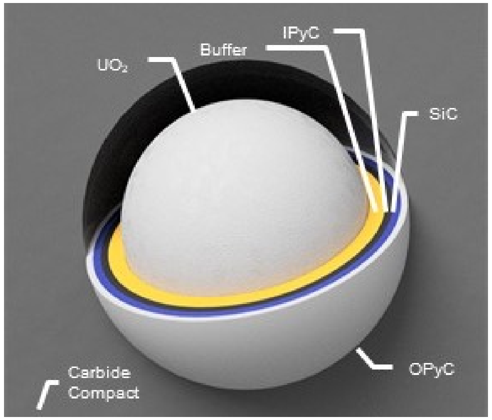
Sample post test

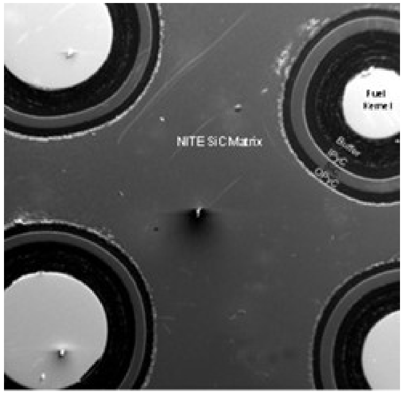
- **Current Development**
  - Will deliver a 16-inch surrogate test article for NTREES testing in November 2019
  - Fabrication and NTREES test Mo-W-dUN diffusion bonded article scheduled for March, 2020

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

Fuel Element Development Status, (cont.)

- **TRi-structural ISOtropic (TRISO) or Coated Mixed Carbide (CMC) Fuel Development**
  - STMD provided funding for an initial fuel development study and fabrication demonstration for higher temperature multi-use TRISO fuels
    - Surrogate Silicon Carbide (SiC) TRISO in a SiC matrix (2100K estimated temperature limit)
    - Zirconium Carbide (ZrC) TRISO in a ZrC matrix (3000K estimated temperature limit)
  - Joint effort with NASA and DoD Strategic Capabilities Office
    - Interest from other agencies including the DOE and DARPA
  - Evolution from High Temperature Gas Cooled Reactor (HTGR) fuels
  - Chemical compatibility with various propellants (e.g., NH_3, H_2O, CO_2, H_2)
    - Initial studies underway with hydrogen
- Began new work to initiate high temperature multi-use feasibility and development



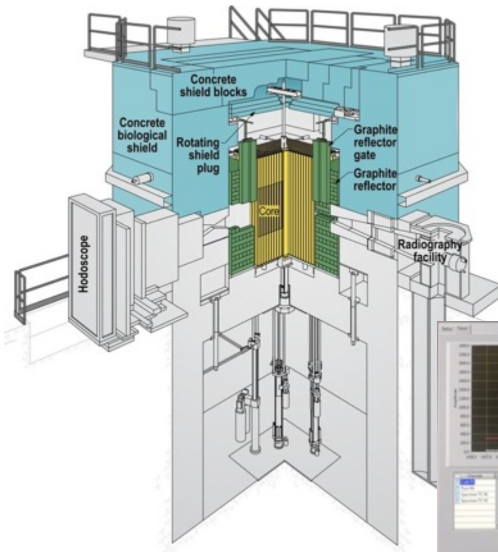


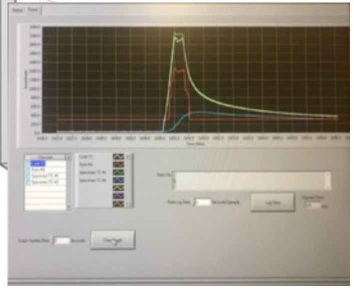
Inherently Safe	Multi-Platform Fuel
Proliferation resistant	Micro-Modular Reactors (MMR™)
Near–total fission product retention	Terrestrial mobile nuclear reactor
Engineered fuel	LEU space power and propulsion

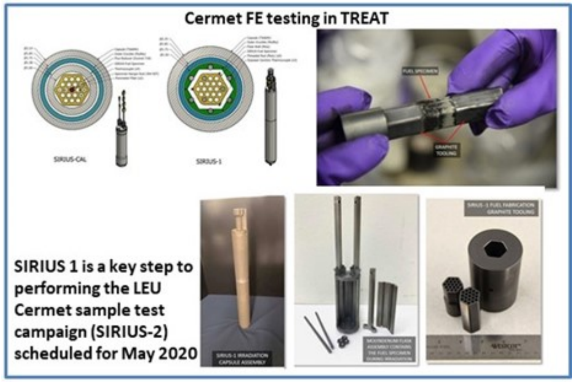
TRi-structural ISOtropic (TRISO) or
Coated Mixed Carbide (CMC) – New Work

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

- **SIRIUS-1 Experiment Plan**
  - Purpose: Demonstrate TREAT's ability to simulate prototypic stresses on fuel and evaluate fuel performance during rapid heat up and thermal cycling condition
  - Experiment uses a SPS, hexagonal, 19-hole, Mo-W Cermet sample containing 21% enriched UN
  - Test Campaign Status: (GCD milestone)
    - Completed a successful transient nuclear power test 9/10/19: NTP Project's first nuclear test
    - Reached a maximum temperature of approximately 2300 C and held a steady temperature hold for approximately 15 seconds before the reactor shut down
    - Examined sample by radiography – no cracking observed
    - Completed second transient test on 10/3/19 reaching same max temperatures as first test
    - Additional transient runs at higher temperatures are scheduled in October/November, 2019
    - Is a pathfinder for future testing of LEU cermet fuel samples in May, 2020







GCD NTP Project's First Nuclear Test –TREAT Facility, INL

NTP Technology Development Challenges

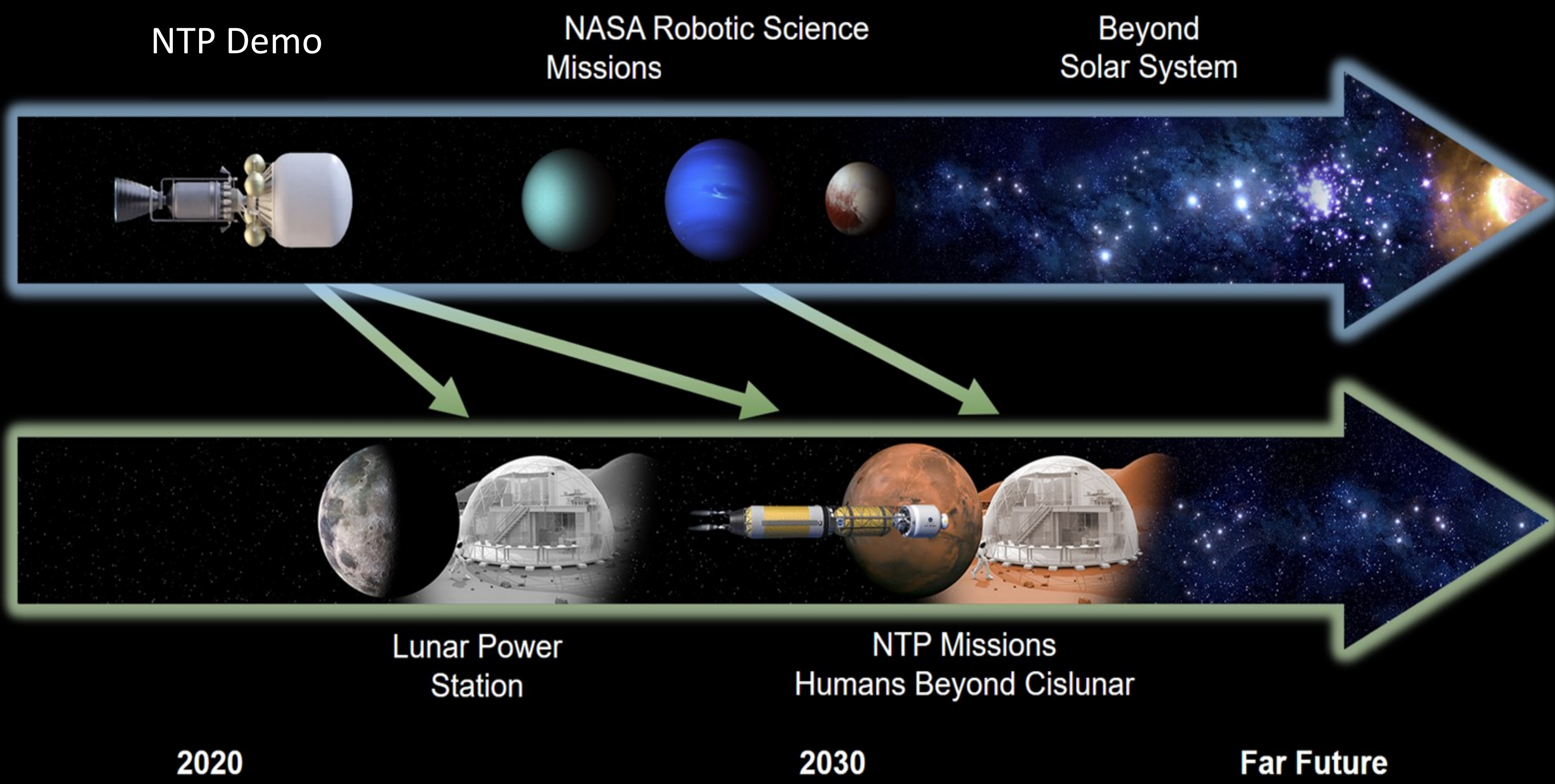
- **Reactor Design**
  - High temperature/high power density fuel
    - Logistics and infrastructure
  - High temperature material strength and durability
  - Short operating life/limited required restarts
  - Space environment
- **Engine Design**
  - Thermohydraulics/flow distribution
  - Structural support
  - Turbopump/nozzle and other ex-reactor components
  - Acceptable ground test strategy (technical/regulatory compliant)
  - Maintain alignment of design with NASA mission needs (i.e., Isp for opposition-class Mars missions)
- **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.

Flight Demonstration Study

NTP Flight Demo

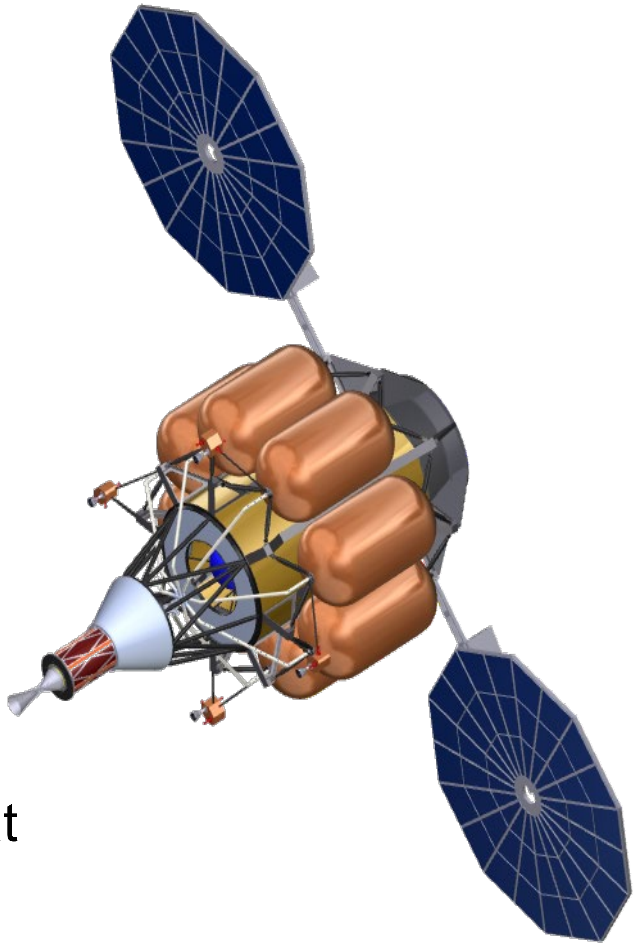
NTP Demo: First Step



NTP Flight Demo (FD) Study

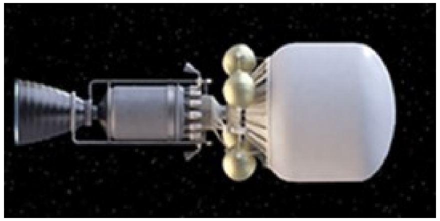
- Objective - Generate peer-reviewed documentation and briefings to provide enough clarity to STMD on the potential for executing a NTP flight demo to support an informed response back to Congress

- 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



NTP Flight Demo Options

NTP Flight Demo Development



- **Flight Demo (FD) Options to be Considered**
  - FD1 - Nearest Term, Traceable, High TRL (Target Soonest Flight Hardware Delivery)
    - Emphasis on schedule over performance
  - FD2 - Near Term, Enabling Capability (TBD availability Date)
    - Emphasis on extensible performance over schedule
- **Internal (NASA-led) and Industry-led Studies using similar GR&A**
- **Customer Utilization Studies**
  - Science Mission Directorate
  - DoD (via DARPA)
- **Outbrief to STMD will provide “MCR-like” products**
  - Including acquisition strategy, draft project plan, certification strategy, etc.

Industry Study Contributors

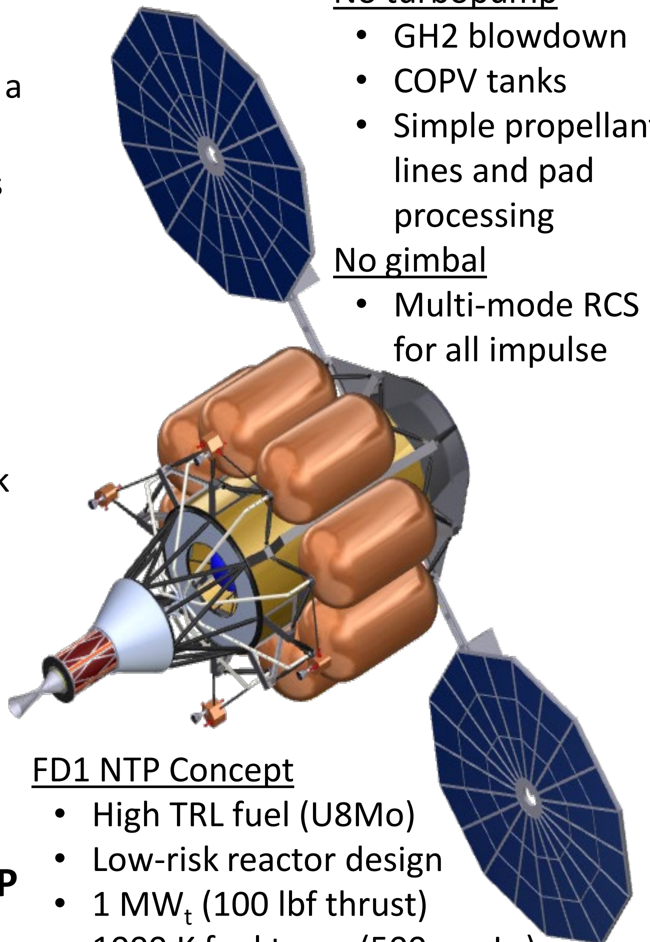
Organization		Role	Organization		Role
	NASA	Study Sponsor & Customer		United Launch Alliance (ULA)	Spacecraft Developer (informal)
	Aerospace Corporation	Reviewer		Ursa Major	Engine Developer
	Analytical Mechanics Associates (AMA)	Study Lead & System Integrator		Ultra-Safe Nuclear Corporation	Reactor Developer
	Aerojet Rocketdyne	Engines & Spacecraft Developer		X-Energy	Reactor Developer
	Blue Origin	Engines & Spacecraft Developer		BWXT	Reactor Developer
	Boeing	Engines & Spacecraft Developer		General Atomics	Reactor Developer (inputs to Spacecraft & Engine)

NTP Flight Demo – FD1 Vehicle

- **<u>FD1 Mission Profile</u>**
  - Emphasis on *schedule over performance* in order to accomplish a NTP FD mission in an *immediate* timeframe and still demonstrate a propulsion functionality.
  - Vehicle design concept relies on high TRL fuel and reactor designs in order to minimize technical risk, and will emphasize using commercial off-the-shelf (COTS) hardware with minimal modifications to manage cost and streamline the acquisition strategy.
- **<u>FD1 Mission Study Results</u>**
  - 5-year project schedule considered executable with moderate risk
  - Project cost assessed to be within Category 2 regime (<$1B)
  - Mission executed in high earth orbit (>2000 miles) allows simpler onboard systems (esp. power, communications and avionics), better LV affordability.
  - All onboard systems considered to be high TRL (7) with the exception of the reactor and associated I&C.
- **Although the FD1 concept was considered low technical risk and feasible, it had limited extensibility to an operational NTP system**
  - GCD preboard considered the schedule to be optimistic and the cost to be out of balance with anticipated results
  - STMD directed no further effort to pursue the FD1 mission profile.

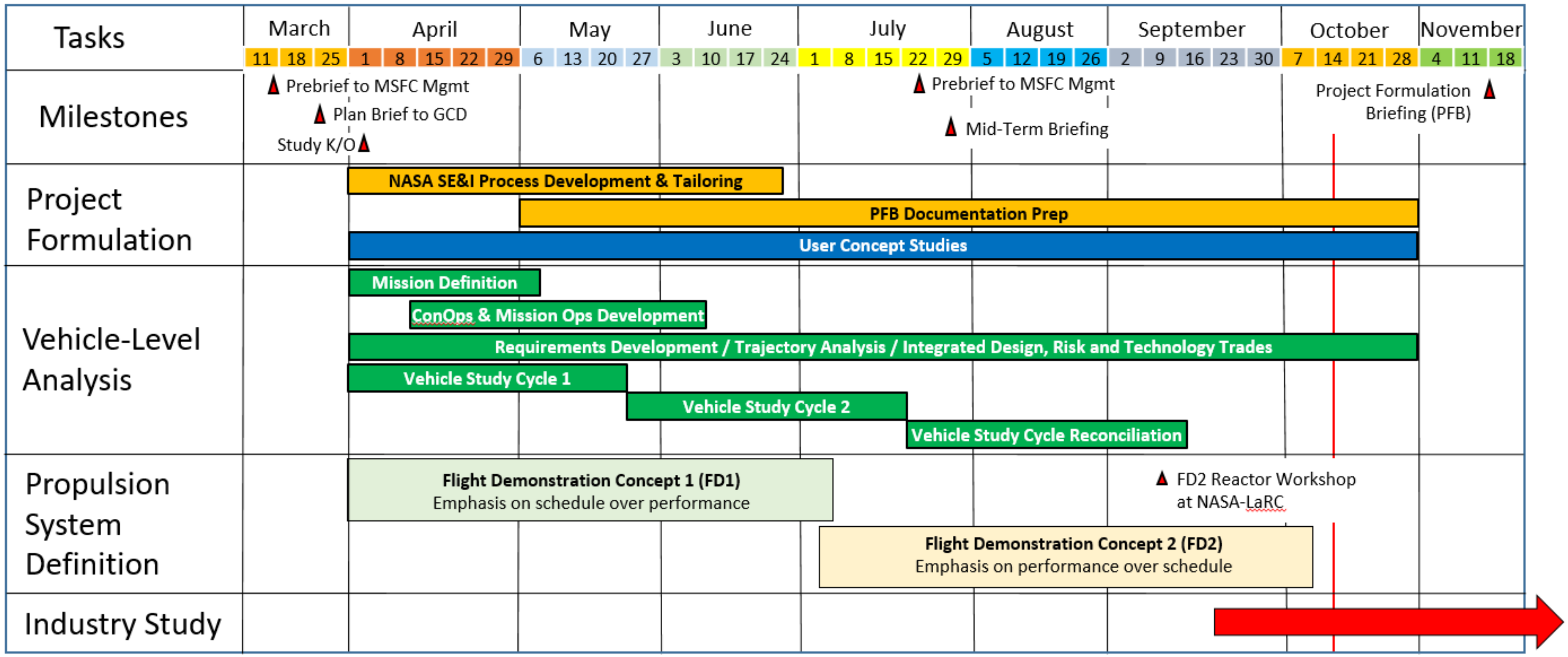
<u>No turbopump</u>
- GH2 blowdown
- COPV tanks
- Simple propellant lines and pad processing

<u>No gimbal</u>
- Multi-mode RCS for all impulse



<u>FD1 NTP Concept</u>
- High TRL fuel (U8Mo)
- Low-risk reactor design
- 1 MW_t (100 lbf thrust)
- 1000 K fuel temp (500 sec I_{sp})

NTP FD Formulation Study Schedule



- NTPFD internal study Mid-Term Briefing conducted on 31 July to inform NASA response to Congress
  - Briefing was presented to the NASA/DoE Preboard and focused on the completed FD1 mission study, with a status of the FD2 study
  - The FD1 mission concept was low risk and feasible, but Preboard considered the 5-year schedule to be optimistic and the cost to be out of balance with the anticipated benefits.
- Work transitioned on to the FD2 mission study
  - Focus on extended schedule to achieve higher performance for improved traceability to an operational NTP system
  - Fuel/Reactor design team conducted a FD2 reactor workshop at NASA-LaRC on 12 September
- AMA conducted a kickoff of the NTPFD Industry-supported study on 2 October

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 performed 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
  - The project is pursuing multiple study paths to evaluate the cost/benefits and route to execute a NTP Flight Demonstration Project.

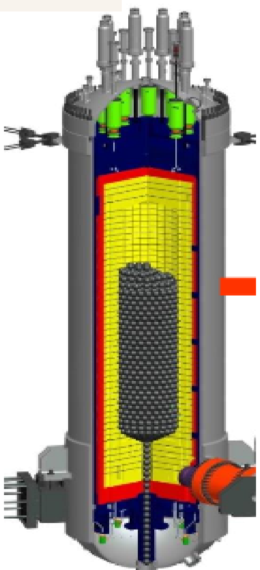
Backup

FY19 Results

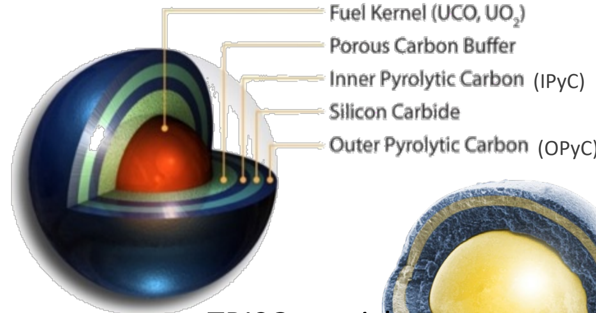
- Determined 34 of 42 criteria to be green
- Assessed the remaining 8 as yellow: criteria are close to being met with some planned work remaining in FY20

System / Subsystem	Criteria Number	Criteria Title	Criteria Statement (Capable of being done, carried out, or dealt with successfully)	Method of Compliance	RYG Assessment by CE/PM	Review and Approval Comments
Engine Systems - Integrated System						
	10	NTPE Health and Status Monitoring	Design a NTP engine concept that will monitor the health and status of the engine.	Report	Yellow	Not finished with identification of candidate sensors. This is forward work and could be done in 2020 or as part of an I&C TMP.
Reactor and Engine System Instrumentation and Control (I&C)						
Engine Subsystems						
Subsystems and Components - Valves						
Subsystems and Components - Turbomachinery						
Subsystems and Components - Reactor						
Reactor Conceptual Design						
	20	High Assay Low Enriched Uranium (HALEU) Reactor	Design a reactor concept using a LEU fuel system with a refractory metal based fuel element 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.	Analysis, Report, or Design Data	Yellow	Criteria 26 is driving color for 20.
	26	Material Selection - Reactor	Design a reactor concept capable of operating in a combined thermal and radiation environment.	Report or Design Data	Yellow	Forward work remaining to addess stress issues but have design space solutions to explore. This is also driving criteria 20 as well.
Fabrication Technology and Fuel Tests						
	28	Fuel Element Designs, Fabrication, and Testing	Design, develop, and test fuel elements that will meet the neutronic, thermal hydraulic, and structural performance requirements of the reactor conceptual design.	Test	Yellow	Test results have slipped into FY20 and have delayed the completion of Feasibility Assessment for Criteria 28 and 31
Fuel (UN) Production						
	31	UN Performance - Thermo-physical Character	Performance behavior of fuels in reactor application are understood to give confidence fuel form will function for the endurance lifetime and starts/thrusts.	Report, Analysis, and Test	Yellow	Test results have slipped into FY20 and have delayed the completion of Feasibility Assessment for Criteria 28 and 31
Subsystems and Components - Thrust Chamber Assembly (TCA)						
Subsystems and Components - Nozzle						
Engine Test Requirements						
Nuclear Engine Ground Testing Capability						
Cryogenic Fluid Management						
NTP Mars Mission CFM						
	40	CFM Thermal Performance	Show that CFM system performance will limit LH2 boil-off sufficiently to close the reference mission architecture.	Report, Analysis	Yellow	CFM CONOPS will provide analysis through all mission phases to support assessment
	41	Propellant Loss due to Leakage	Show that a path exists to develop valves and couplings that provide sufficiently low leakage rate to meet the CFM CONOPS needs.	Report, Analysis	Yellow	Work is on-going for three different valve designs at MSFC.
	42	Cryocooler Performance	Show that a development path exists to advance cryocooler performance to meet the CFM CONOPS needs.	Report, Analysis, Test	Yellow	20 W 20K cryocooler is in development under SBIR. The acceptance test has slipped into FY20 due to machanical problems with the turbomachinery elements but are not seen as presenting a critical challenge to the technical feasibility. Yellow until testing is done and evaluated.

TRISO Coated Particle Fuel in High-Temperature Gas-Cooled Reactors (HTGRs)

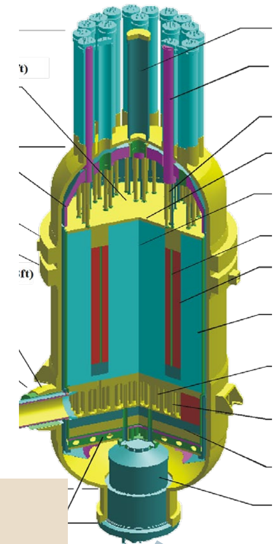


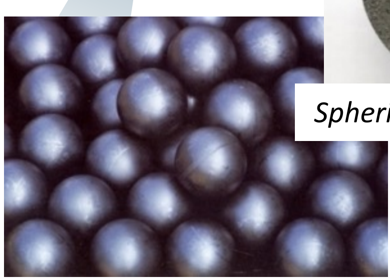
Pebble bed reactor

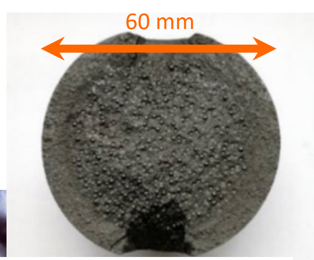


TRISO particle

Prismatic reactor

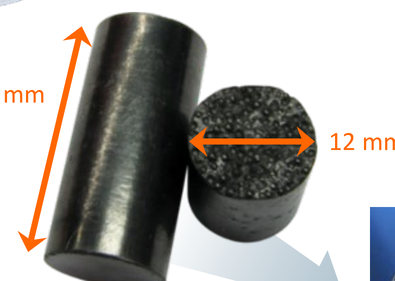






Spherical fuel pebbles

Particle design provides excellent fission product retention in the fuel and is at the heart of the safety basis for high temperature gas reactors



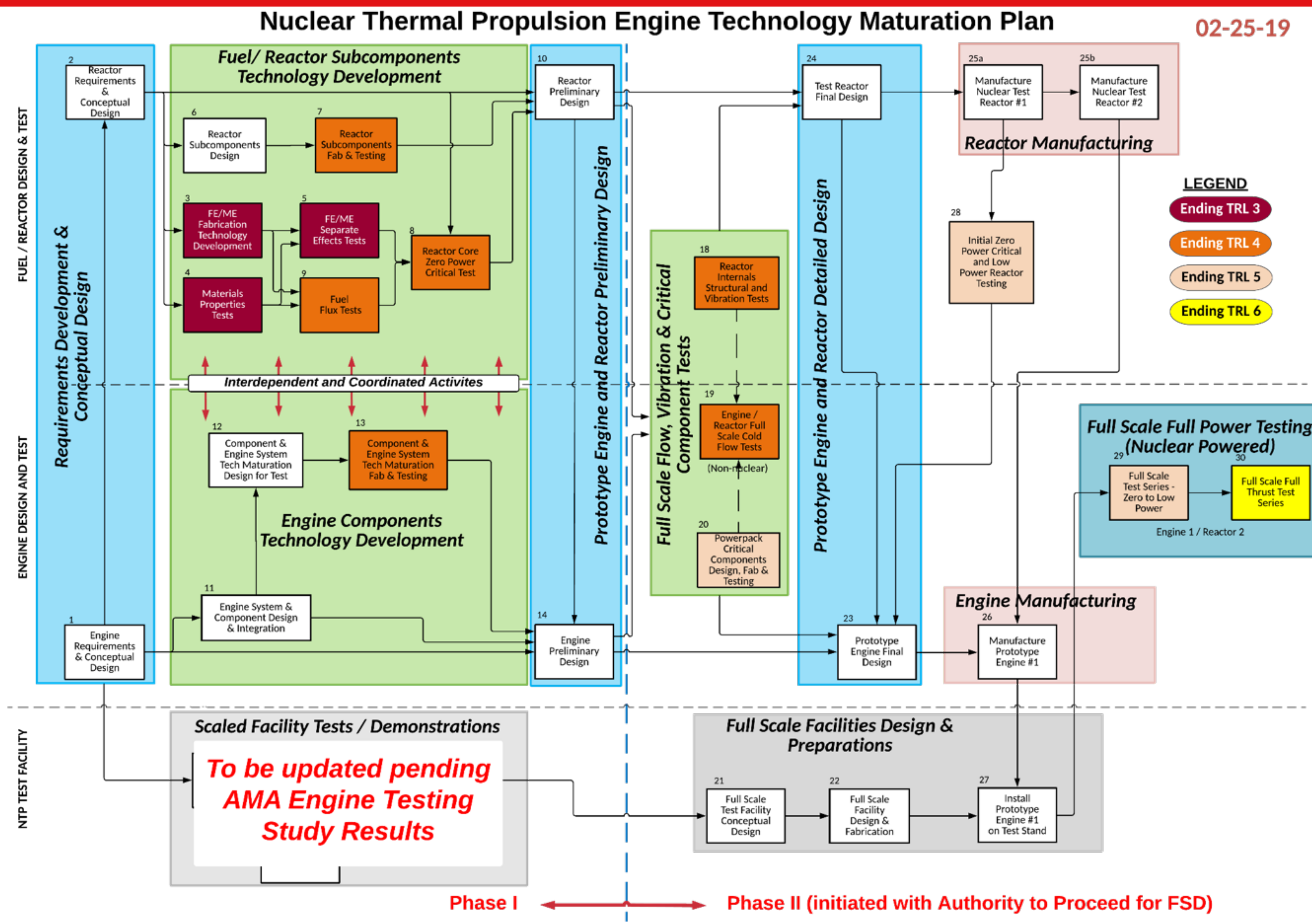
Cylindrical fuel compacts

Prismatic graphite blocks

Benefits of NTP

- **NTP can be used to provide flexible mission planning by trading objectives including:**
  - Offers the most favorable combinations of lowest total mission mass and shortest mission durations compared to chemical or solar electric propulsion
  - Enables significantly shorter trip times than chemical propulsion systems
    - Reductions of 20% or more are achievable depending on mission architecture and vehicle design assumptions
  - Enables opposition-class (short stay) missions with significantly reduced overall trip time compared to conjunction class (long stay) missions
    - Reductions of several months are possible
  - Extends mission abort capability after trans-Mars injection to as much as a few months compared to a hours or a couple of days at most for chemical propulsion
  - Reduces the number of heavy-lift launches required to perform the mission compared to chemical propulsion

Technology Maturation Plan



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

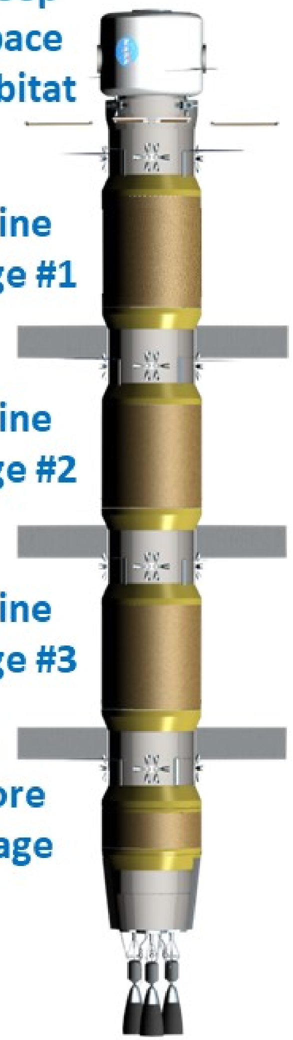
Deep Space Habitat

Inline Stage #1

Inline Stage #2

Inline Stage #3

Core Stage



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.

Acronyms

CFEET	Compact Fuel Element Environmental Test
CMC	Coated Mixed Carbide
COPV	Composite Overwrapped Pressure Vessel
COTS	Commercial Off-The-Shelf
DIRT	Design Independent Review Team
DoD	Department of Defense
DoE	Department of Energy
dUN	Depleted Uranium Nitride
FD	Flight Demonstration
FE	Fuel Element
GCD	Game Changing Development
GH2	Gaseous Hydrogen
GR&A	Ground Rules & Assumptions
GRC	Glenn Research Center (NASA)
HEU	High-Enriched Uranium
INL	Idaho National Laboratory (DoE)
K	Kelvin
LaRC	Langley Research Center (NASA)
LEU	Low-Enriched Uranium
LV	Launch Vehicle
MCR	Mission Concept Review
Mo	Molybdenum
MSFC	Marshall Space Flight Center (NASA)
MWt	MegaWatt thermal
NTP	Nuclear Thermal Propulsion
NTREES	Nuclear Thermal Rocket Element Environmental Simulator
NASA	National Aeronautics and Space Administration
PPC	Packed Powder Cartridge
RCS	Reaction Control Systems
SCO	Strategic Capabilities Office
SiC	Silicon Carbide
SPS	Spark Plasma Sintering
SSC	Stennis Space Center (NASA)
STMD	Space Technology Mission Directorate
TBD	To Be Determined
TRISO	TRi-structural ISOtropic
TREAT	Transient Reactor Test (Facility)
TRL	Technology Readiness Level
W	Tungsten
ZrC	Zirconium Carbide