National Aeronautics and Space Administration

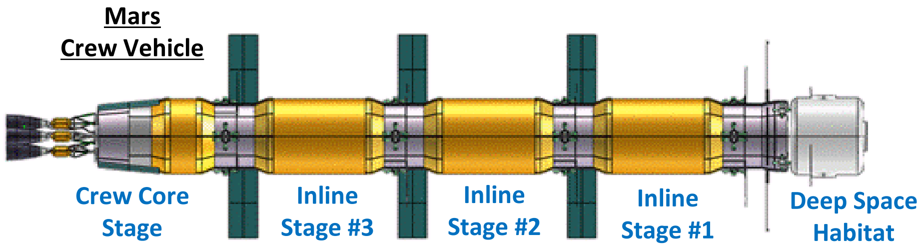
Space Technology Mission Directorate

Game Changing Development Program — Nuclear Thermal Propulsion (NTP)

Sonny Mitchell, PM | FY19 Annual Review | 09.24.19

Technology Overview

- Technology Goal
  - Nuclear Thermal Propulsion (NTP) technology enables development of a high-energy density propulsion system with an I_{sp} nearly double that of the highest performing traditional chemical systems
  - NTP capability offers a viable technology that will significantly reduce transit time to Mars and extend exploration missions beyond solar powered systems
- Technical Capabilities
  - Low enriched uranium cermet fuel kernel
  - Fuel element design meeting 2200-2800K requirements
  - Propulsion compatible fission reactor design
- Exploration & Science Impact
  - NTP technology enables missions where solar powered and chemical systems are limited
  - NTP provides a high-thrust, high-impulse capability that increases mission flexibility in cis-lunar space
  - Highly advanced nuclear propulsion systems will decrease in-space transit time and improve crew safety



Mission Infusion & Partnerships

- Contributing partners and/or stakeholders
  - MSFC: PM, SE & Engine Analysis Lead, Cryogenic ConOps Lead, Compact Element Environmental Test (CFEET) System, Nuclear Thermal Rocket Element Environmental System (NTREES)
  - GRC: Cryocooler Testing, Cryogenic ConOps Support, System Analysis Support
  - SSC: Engine Ground Test 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
  - Department of Energy (DOE): FE / Reactor Design and Fabrication Support
- Infusion/transition plan
  - NTP can provide primary crew transport beyond cis-lunar while Cryogenic Fluid Management (CFM) work has potential commercial applications
    - Estimated date: mid 2030s
  - Developed options to transition to Technology Maturation Plan Phase 1
    - Provides sufficient technical and programmatic data for NASA leadership to make a decision whether or not to commit to a full scale development effort
    - Adds validity to the current cost/schedule estimates of the GCD NTP project and reduces technical risks for flight systems development by maturing the critical engine system components technology base

NTP Technology Goals & Project Objectives

Technology Goals	
Goal #1	Establish a conceptual design for an NTP LEU engine in the thrust range of interest for a human Mars mission
Goal #2	Establish robust production manufacturing methods and sources for a nuclear fuel element/reactor core
Goal #3	Provide trade studies demonstrating impact of NTP technology to cis-lunar and interplanetary missions

Project Objectives	
Objective #1	Determine the feasibility and affordability of a Low Enriched Uranium (LEU)-based NTP engine with solid cost and schedule confidence
Objective #2	Design, build, and test, prototypic fuel element segments through ground based facilities
Objective #3	Demonstrate the feasibility, through analysis, of real-time exhaust processing or exhaust capture as a method of nuclear rocket engine testing

NTP Performance

Key Performance Parameters				
Performance Parameter	State of the Art	Threshold Value	Project Goal	Estimated Current Value
Fuel Loading Fraction (%)	N/A	40	>50	N/A
Specific Impulse, I_{sp} (sec)	450	850	900	875
Fuel Operating Temperature (K)	N/A	2000-2650	2200-2850	N/A
Notes: Values based on current reactor conceptual design and mission architectural analysis.				

Technical Assessment

Technical Elements	TRL			AD[2]	
	Entry	Current[1]	Exit	Entry	Current
NTP Project Cermet FE[2] (MRL)	3	2	4	7	7
NTP Project LEU Cermet Engine	2	2	3	6	6

[1]Date of last TA: 10/18/18

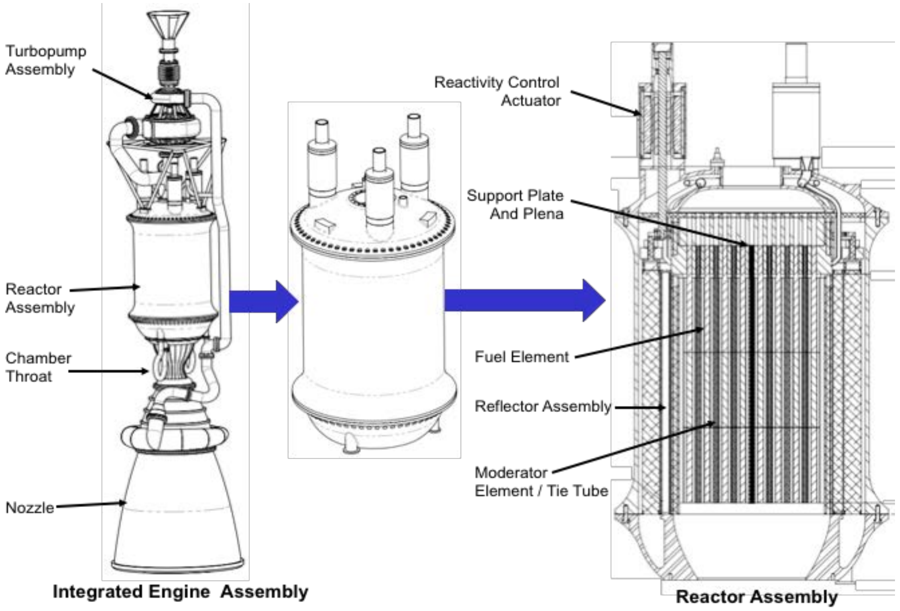
[2]Multiple tests are utilized to determine MRL advancement of fuel elements

NTP Technical Approach

➢ Project plans to accomplish objectives

- Determine NTP feasibility: Defines a key set of criteria against which the engine/reactor/fuel and exhaust capture system will be judged as feasible
- Developed reactor and engine conceptual designs
- Performed a detailed cost analysis and schedule for developing an NTP flight system
- Mature technologies associated with fuel production, fuel element manufacturing, and engine exhaust capture
- Developed a technology maturation plan to TRL 6 that is designed to gather and analyze the necessary data to address the two primary concerns regarding NTP systems:
    - The overall affordability of NTP compared to other systems
    - Ability to develop, test and fly nuclear systems in the current regulatory environment

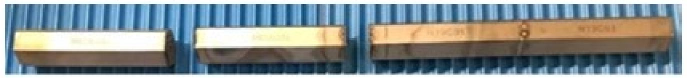
System / Subsystem	Title	Criteria (Capable of being done, carried out, or dealt with successfully)	Objective Evidence of Compliance	Current Status Assessment	
				RYG Assessment	Comments
Engine Systems - Integrated System					
1	Integrated Engine Interactions	Design a NTP engine concept that is matured to a level such that key pulls (gaps or enablers) and critical inputs/dependencies specific to the integrated system are identified.	Report	Green	
2	NTPE Vacuum Thrust	Design a NTP engine concept that will provide a nominal vacuum thrust of 25,000 <TBR> pounds-force (lbf), representing 100% rated power level thrust, while operating at the design nominal propellant inlet conditions and engine-to-tank pressurization flowrates.	Analysis	Green	
3	NTPE Vacuum Specific Impulse (Isp)	Design a NTP engine concept that will provide a minimum nominal vacuum specific impulse (Isp) of 850 seconds while operating at the design nominal propellant inlet conditions and engine-to-tank pressurization flowrates.	Analysis	Green	KPP 2: Specific Impulse (analysis): Threshold Value Isp = 850 sec. Project Goal Isp > 900 sec.
4	NTPE thrust/weight (T/W)	Design a NTP engine concept, (including internal reactor shielding) that will provide a minimum T/W of 3.5 <TBR>	Analysis	Green	Does not include shielding external to the engine. External shielding is mission specific and should be part of an integrated stage/habitat trade study.
5	NTPE Start	Design a NTP engine concept that will perform a controlled engine start to the 100% rated power level thrust upon command.	Analysis	Green	
6	NTPE Shutdown	Design a NTP engine concept that will perform a controlled engine shut-down upon command from any power level.	Analysis	Green	



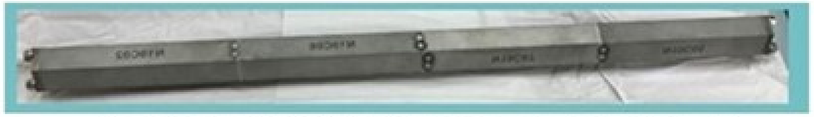
Technical Status

➢ Packed Powder Cartridge Development

- Completed “cold end” Molybdenum (Mo)/depleted Uranium Nitride (dUN) fuel element (FE) fabrication and test in the MSFC Nuclear Thermal Rocket Element Environmental Simulator (NTREES) Facility (API Milestone)
  - At a planned hold at 1850K the NTREES facility experienced a power system fault resulting in a rapid FE cool down reaching a temperature 150K less than planned
  - FE separated into two pieces along a butt weld; no dUN was present in the chamber
  - Rapid transients were the result of a NTREES malfunction, the resulting rate of cooling (≈ 80-90 K/sec) was not greater than expected for a nuclear fuel rod in service
  - Cooling rate was more severe than intended for the CE test but should have been insufficient to induce breakage of a properly designed FE that should have survived
- Recommendations from a Design Independent Review Team: Discontinue approach 1 packed powder cartridge development and focus resources on alternate FE development activities
- Canceled: “Hot end” Mo/tungsten (W)/dUN fuel element NTREES test in January, 2020
  - Will submit a change request to GCD to cancel PPC development deliverables/milestones



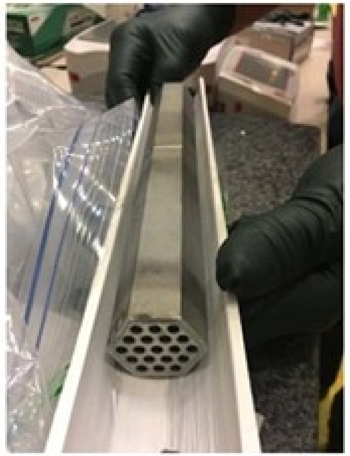
All surrogate FE: Post test showing failure at butt welds



NTP Cold End FE: Mo/dUN 19 hole PPC prior to NTREES testing

Left: Cold end of middle butt weld appears smooth with no cracks

Hotter end of butt weld showed some tubes with circumferential cracks

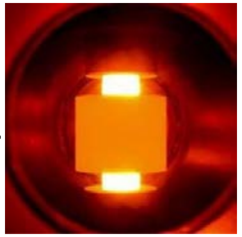


Above and left: Post test FE at the hotter end of the butt weld

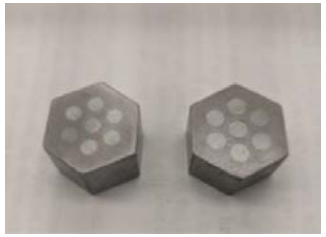
Pursuing multiple manufacturing options for fuel element development
Option 1: Packed Powder Cartridge (Canceled)

Technical Status, continued

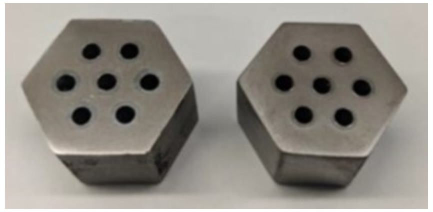
- Spark Plasma Sintering (SPS) FE development at MSFC: SPS process rapidly (~5 min.) consolidates powder material into solid components
  - Successfully fabricated and tested 2 hex Mo/W/dUN fuel wafers for testing in the Compact Fuel Element Environmental Test (CFEET) system (GCD milestone)
    - Included novel process to add 7 cooling channels
    - Integrity and density met standards (>95% TD)
  - Performed CFEET test at 2250K for 20 minutes under hot hydrogen
    - Mass loss: ~0.13%
    - Loss rate: 2.47x10-6 g/cm2 s
    - No noticeable dissociation of UN occurred during testing
    - Experienced migration at Mo/UN interface - confirms that hydrogen is detrimental to fuel performance
  - Cladding is crucial to mitigate hydrogen attack
  - Goal:
    - Fabricate a surrogate fuel test article and test in NTREES by 11/30/19
    - Fabricate a Mo/W/dUN test article and test in NTREES by 3/31/20 (API Milestone)



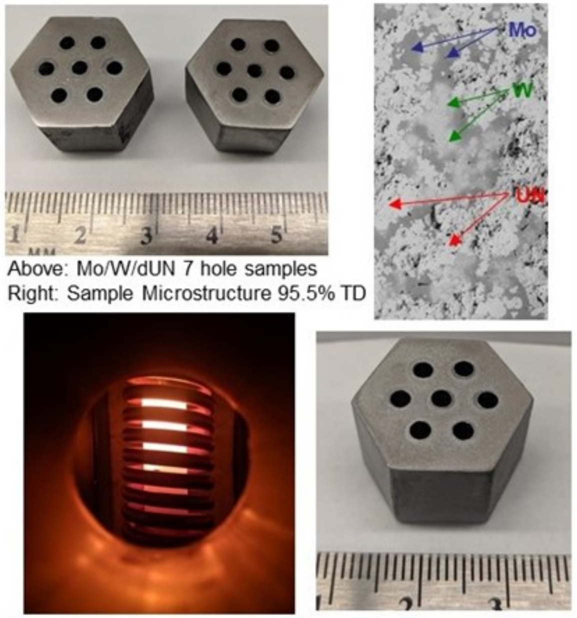
Spark Plasma Sintering



As fabricated samples Mo/W/dUN



Mo/W/dUN samples after cooling channel drilling



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

Mo/W/dUN hot hydrogen CFEET

Sample post test

A NASA Proprietary Process via SPS

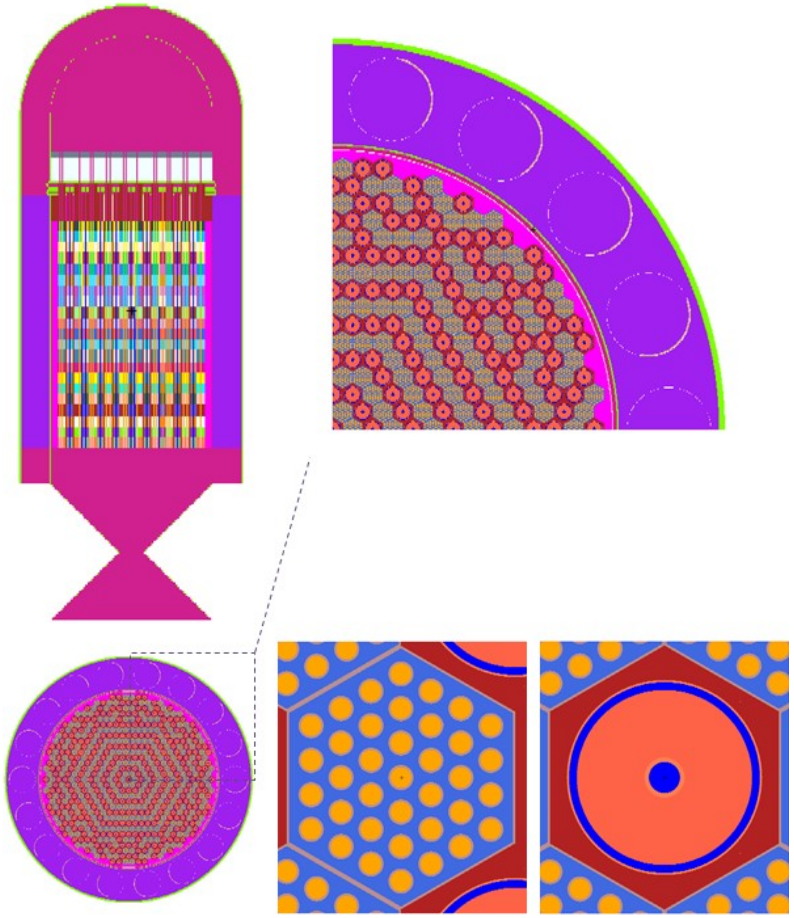
- Allows for sintering built in cooling channels
- Provides close contact between fuel and cooling channel
- Optimizes heat transfer from fuel

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

Technical Status, continued

- Completed optimized core designs as a result of the design analysis cycle iterations
- Carried two fuel element conceptual designs for core arrangements
  - CERMET fuel element
  - Packed-particle in cartridges
- Fully characterized performance of each core design during final design analysis cycle
- Final versions of each core represent designs that satisfy the feasibility matrix criteria at the current level of maturity of the project
- Feedback from structural analysis and NTREES testing should be incorporated for potentially more optimal conceptual designs
- Created a full set of tools to continue to advance the design and develop an optimum core to ensure mission success

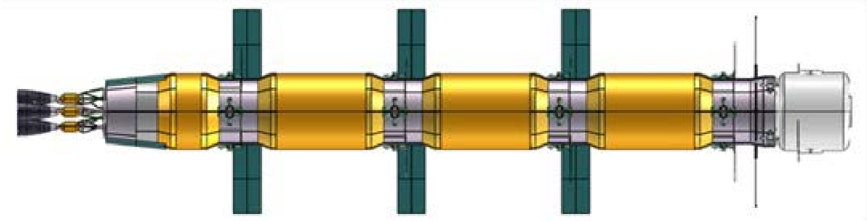
CERMET-Based Core Design Concept

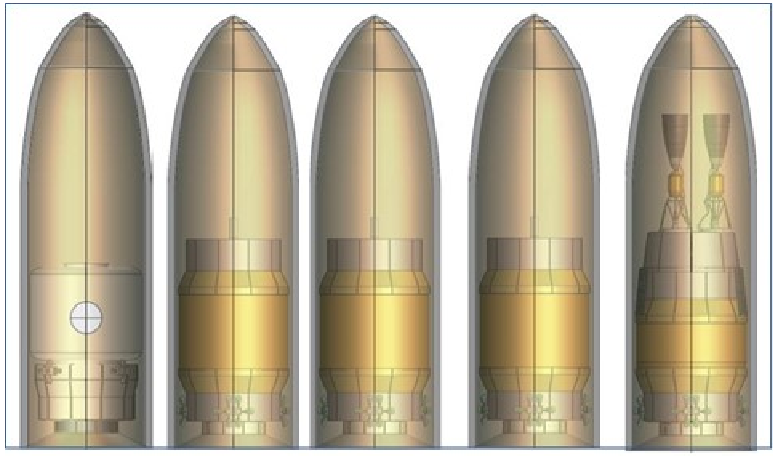


Designs satisfy the feasibility criteria as minimum requirements and exceed the minimum project requirements for mission success

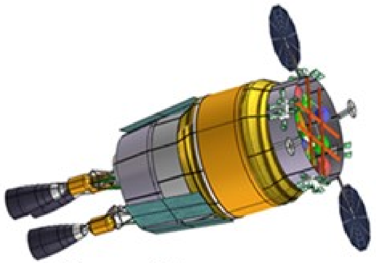
Technical Status, continued

- Completed updates to on NTP Mars Vehicle Architecture

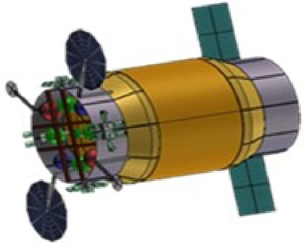




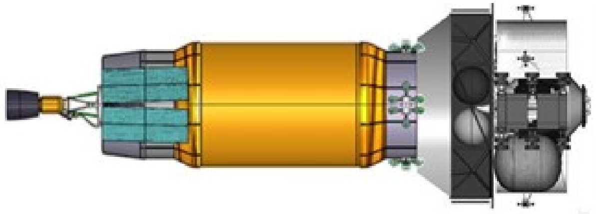
All Elements Fit SLS 8.4m PLF



Core Stage



Inline Stage



Est.*

Cargo Stage Derived From Core

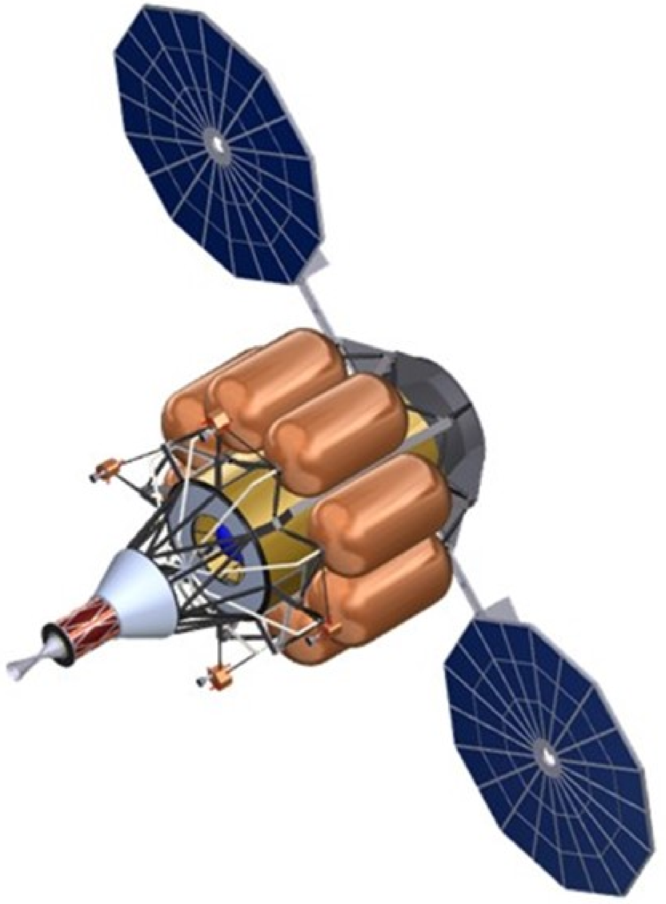
*Estimated Interface Based On:
AIAA Publications, *NASA Transit Habitat Design for Mars Exploration – Polsgrove* (AIAA SPACE 2018), *Human Mars Lander Design for an Evolvable Mars Campaign* – Polsgrove (IEEE 2016)

A High Thrust, High Isp NTP Architecture Developed to Fit in SLS 8.4m PLF

Technical Status, continued

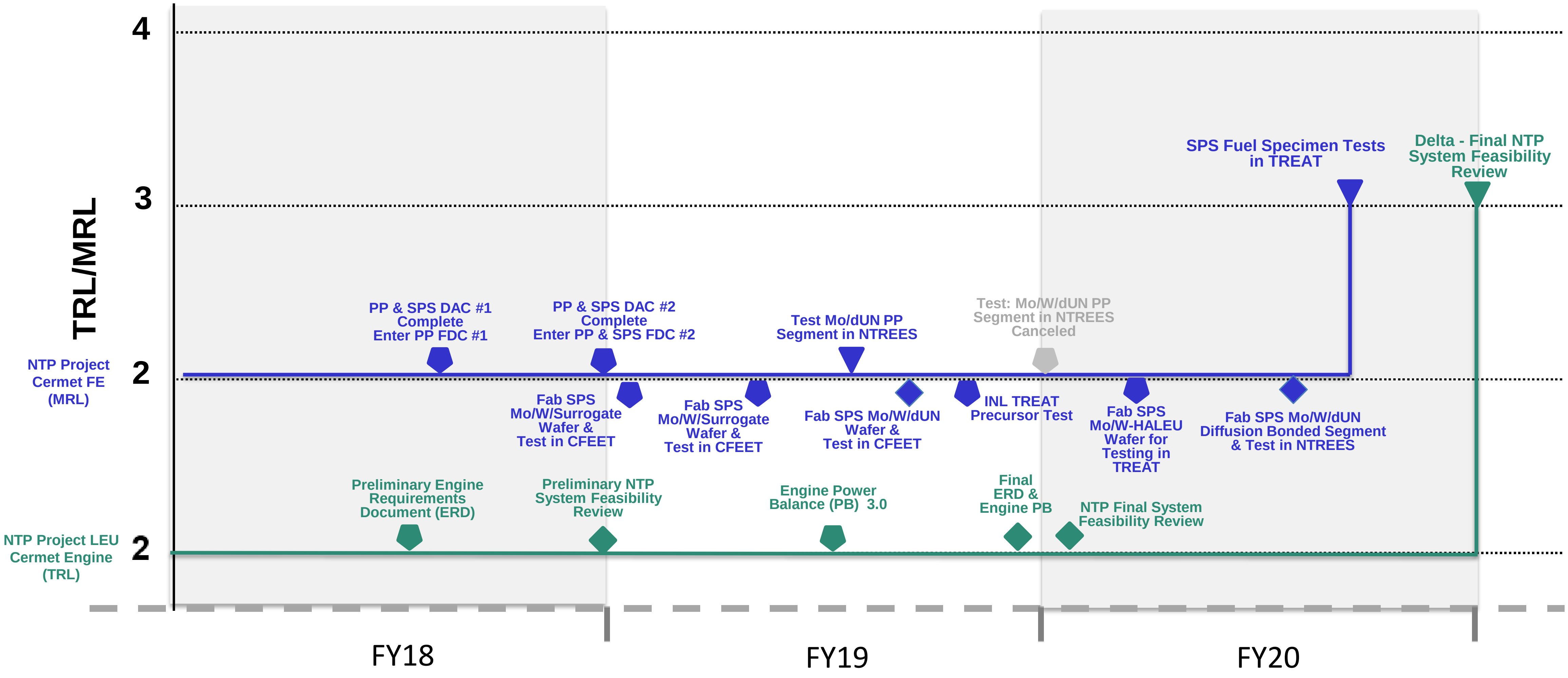
➢ NTPFD Study Schedule/Technical Performance Status

- 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 8/29/19
- AMA is preparing a kickoff of the NTPFD Industry-supported study
- Integrated findings (FD1 and FD2) will be briefed at the Project Formulation Briefing to STMD senior management in mid-November

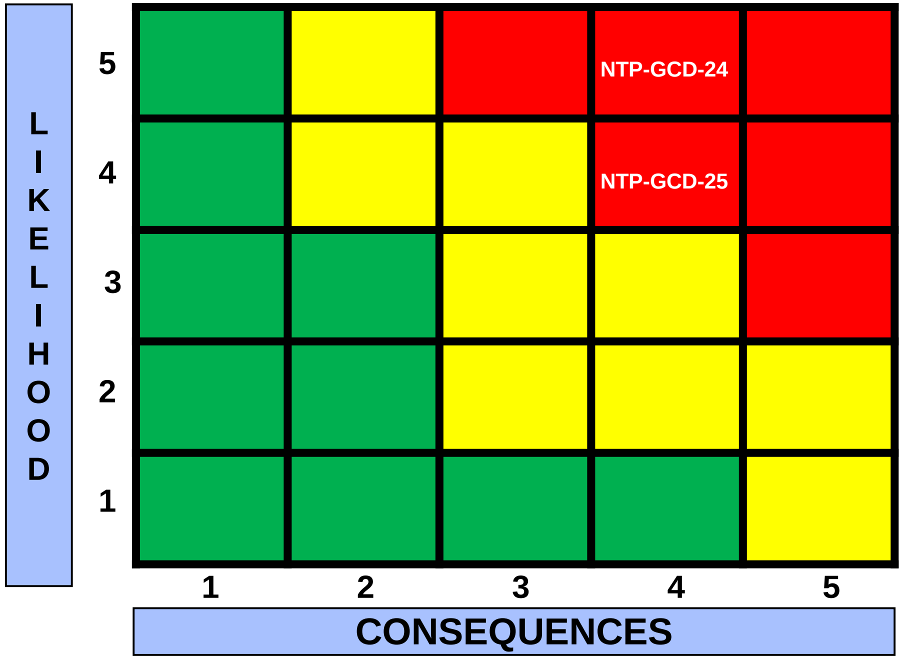


NTP Lifecycle Milestone/Maturity Schedule

Project Milestone · GCD Milestone · Controlled Milestone · TRL Progression · PP- Packed Powder Fuel Element · SPS- Spark Plasma Sintered Fuel Element



Technical Risk Summary



Risk ID	Description/Status	Trend
NTP-GCD-24	NTREES Impacts from Blue Origin (Mitigate)	New
NTP-GCD-25	SPS Mo/W Material Availability (Mitigate)	New

Criticality

- High
- Med
- Low

L x C Trend

- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New Since Last Period

Approach

- M - Mitigate
- W - Watch
- A - Accept
- R - Research

EPO Summary Chart

- Summary of Education and Public Outreach - Upcoming
  - 70th International Astronautical Congress, Washington, DC, Oct. 21-25, 2019
  - American Nuclear Society (ANS) Winter Meeting and Nuclear Technology Expo, Washington, DC, Nov. 17-21, 2019
  - 2020 The Materials Society (TMS) Annual Meeting and Exhibition, San Diego, CA, Feb. 23-27, 2020
  - Nuclear Emerging Technologies for Space (NETS), Knoxville, TN, April, 2020

Annual Summary

- Completed NTP System Feasibility Assessment Report: Details the *feasibility* and *affordability* of a LEU engine, reactor, fuel and engine ground testing system with solid cost and schedule confidence
  - Defines key criteria that is measured by objective evidence: a report, analysis, test, or piece of design data
  - Serves as the main tool for accomplishing the final system feasibility review (GCD Milestone)
- Continuing to work FE Fabrication/Testing
  - Completed packed powder cartridge (PPC) cold end (CE) (molybdenum (Mo)/depleted uranium nitride (dUN) fuel element testing in NTREES on 6/27/19 (API milestone)
  - Successfully fabricated and tested 2 Spark Plasma Sintered (SPS) hex Mo/tungsten (W)/dUN fuel wafers & tested in the CFEET system (GCD milestone)
  - Design Independent Review Team (DIRT) reviewed FE design and fabrication capability for PPC, SPS and TRISO development feasibility and recommended canceling PPC FE development
- Completed and submitted FY19 Project Deliverables
  - Final NTP Cost and Engine Ground Testing Reports
  - Final Engine Requirements Document (ERD): Establishes technical performance metrics for a NTP Engine System
  - Final Engine Technology Maturation Plan (TMP) – system development path to TRL 6
  - Updated Architectural Analysis Summary baselining crew vehicle configuration: core plus 3 Inline stages
    - Configuration exceeds capability for minimum energy Mars missions for all desired mission opportunity years
    - Configuration has additional capability to enable faster crew transit times to and from Mars (times depend on specific mission opportunities)
    - Performed core/stage variation analysis examining NTP robustness for cis-lunar missions


BACKUP

Project Assessment Summary

Project	Performance				Comments
	C	S	T	P	
Mid Year					**Schedule:** • Test date slipped due to fabrication issues for the packed powder cartridge (PPC) 19-hole cold end (CE) fuel element (FE): with molybdenum (Mo)/depleted uranium nitride (dUN) **Technical:** • PPC 19-hole cartridge FE(s): - Performance risks and material availability for threaten fab and test of the hot end Mo/tungsten (W)/dUN FE • Spark Plasma Sintering (SPS) Cermet Fabrication at MSFC - Fabricated the first Mo/dUN wafer at MSFC via SPS - SPS development activity continuing to make good progress
Annual					**Schedule**: Returns to green • Based on recommendations from the Design Independent Review Team approach 1 packed powder cartridge development is discontinued. Resources will be redirected on alternate FE development activities. Will submit change request to GCD removing PPC development and deliverables/milestones including the PPC hot end Mo/tungsten (W)/dUN fuel element NTREES test in January, 2020. SPS development on schedule. **Technical**: • SPS Cermet Fabrication: Making progress - successfully fabricated/tested Mo/W/dUN wafers in CFEET. Integrity and density met standards. Working surrogate Mo/W/HfN 16” uncladded diffusion bonded NTREES test article. Challenges continue with SPS Mo/W materials availability. Mitigations in work.

EPO Summary Chart

➢ Conferences attended

Conference Name	Papers/Posters/Panel Discussions
American Nuclear Society (ANS) Winter Meeting and Nuclear Technology Expo	Radiation Protection and Shielding: Space Fission Systems, Presentation
Nuclear Emerging Technologies for Space (NETS) 2019,	1. "A Versatile Nuclear Thermal Propulsion (NTP) System," Presentation; 2. "Space Nuclear Power and Propulsion," Panel Discussion 3. "Recent FY18/FY19 NTP Materials Development Activities at NASA Marshall Space Flight Center." Presentation 4. "Investigation of Process Parameter Effects on Spark Plasma Sintered Molybdenum Cermets for Nuclear Thermal Propulsion Applications." Presentation and Proceedings. 5. "Microstructural Evolution of High Density W-Cermets Exposed to Flowing Hydrogen at Temperatures Exceeding 2000 K." Presentation and Proceedings. "Hot Hydrogen Testing and Microstructural Characterization. Presentation and Proceedings. 6. "Review of Irradiation Hardening and Embrittlement Effects in Refractory Metals Relevant to Nuclear Thermal Propulsion Applications." Presentation and Proceedings
TMS 2019 Annual Meeting	"Microstructural Evolution of High Density W-Cermets Exposed to Flowing Hydrogen at Temperatures Exceeding 2000 K." Student Poster.

GCD Project Performance Evaluation Criteria

	Technical/Performance
Green	Project is demonstrably making progress on the Learning Trajectory (e.g. milestones met, knowledge advanced) or advancing TRL. Project is on track to meet L1 requirements.
Yellow	Project is making progress on the Learning Trajectory or advancing TRL with issues. Project is on track to meet L1 requirements but issues exist that may threaten achievement.
Red	Project has ceased to make progress on the Learning Trajectory or advance TRL. Project is unable to meet one or more L1 requirements.

	Cost
Green	Project can meet its commitments with its planned/allocated budget.
Yellow	Project cannot meet its commitments within its planned/allocated budget but will not be requesting additional budget from Program. Mitigation plans have been developed.
Red	Project cannot meet its commitments within its planned/allocated budget and will be requesting additional budget from Program.

	Schedule
Green	Project can meet its commitments within its planned/allocated schedule baseline for critical milestones.
Yellow	Project cannot meet its commitments within its planned/allocated schedule baseline but mitigation plans have been developed to pull it back in.
Red	Project cannot meet its commitments within its planned/allocated schedule baseline.

	Programmatic (Institutional, Internal/External Dependencies **)
Green	Relevance of technology to stakeholders and/or technology infusion path is maintained. Mission sponsor still actively interested. No issues exist with workforce, test facilities, etc.
Yellow	Relevance of technology to stakeholders and/or technology infusion path are threatened. Mission sponsor backing off. Issues exist with workforce, test facilities, etc. but plans to mitigate are available.
Red	Relevance of technology to stakeholders and/or technology infusion path are not projected to be met, or has lost relevance to stakeholders. Mission sponsor cancelled interest. Issues pertaining to workforce, test facilities, etc. are preventing progress along the Learning Trajectory.

Source: BPR Assessment Criteria for NASA R&T Projects, OCE/S. Hirshorn, 09/17/2015

Nuclear Thermal Propulsion (NTP)

NTREES Impacts from Blue Origin – Sonny Mitchell

NTP-GCD-24

Trend

New

Criticality

High

Current L/C

5x4

Planned Closure

12/31/2019

Open Date

08/19/2019

Risk Statement :

Given the MSFC gaseous hydrogen facility is being temporarily converted to methane in order to support in-house testing for a commercial company which needs high pressure Methane, and that the NTREES is recharged from the gaseous Hydrogen supply, there is a possibility that NTREES testing plans for NTP will be impacted, resulting in schedule slips or compromises in the test objectives.

Impact:

The MSFC management team has committed the use of MSFC testing facilities to Blue Origin from September – November 2019. The testing needs high pressure gaseous methane and the Center does not have a another system in place that can provide that. To accommodate the need, the facility office has committed to converting the current high pressure gaseous hydrogen system in NTREES to gaseous methane. Currently, the NTP Project has plans to test a 16” long SPS surrogate fuel element late Oct or early November (internal project milestone) and plans to test a 16" Packed Powder dU FE in mid December (STMD GCD milestone). Current mitigations being reviewed will compromise the test objectives for the SPS FE specimen and, if there are problems switching back over to the gaseous hydrogen, there could be further slips in the testing of the PP FE.

Status:

New risk, opened 08/19/2019

Mitigation:

Mitigation Options:

1. Wait until the MSFC Hydrogen supply is reactivated to do multiple tests at high pressures.
2. Rent a gaseous hydrogen trailer from a local vendor. Run time is limited by trailer pressure ~2200 psig, which can significantly shorten the test durations and operate at lower pressures.
3. Fill current hydrogen trailers before hydrogen facility is converted to Methane and hold any use until test day.

Nuclear Thermal Propulsion (NTP)

SPS Mo/W Material Availability – Sonny Mitchell

NTP-GCD-25

Trend

New

Criticality

High

Current L/C

4x4

Planned Closure

03/31/2020

Open Date

08/19/2019

Risk Statement :

Given that the current SPS milestone is to deliver a hot end FE specimen for testing in NTREES and that there is currently not a supply available for the required Mo/W alloy powder within the needed time frame, there is a possibility that the project goal KPP (2850K) will not be met, resulting in a schedule slip to the test milestone or a compromise in test objectives.

Impact:

The current SPS Mo/W FE design relies on an alloy of Mo and W to achieve the desired operating temperature. Without a supply of the alloy in powder form, the project will either have to use individual powder stock and develop a process that will produce the alloy powder in house, which will cause a schedule delay in making the test specimen, or they will have to use a blended powder form which will not have the higher melting point desired, resulting in a compromise of the KPP test objectives.

Status:

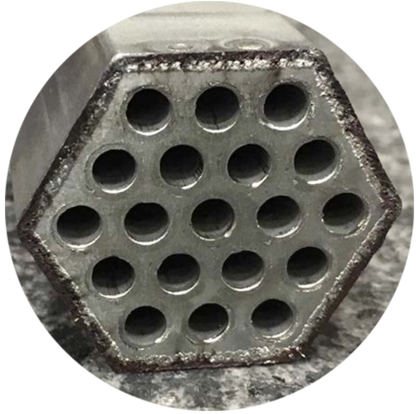
New risk, opened 08/19/2019

Mitigation:

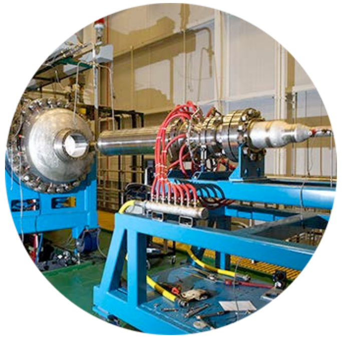
1. Make the first specimens for CFEET and NTREES with blended powder to develop the SPS process parameters, but compromise on the test temperature objectives.
2. Get planetary mill equipment in house to produce alloy powders from blended powder stock to demonstrate a CFEET sample size at temperature.
3. Create NTREES sample with a small section with Mo/W alloy produced with planetary mill, with remainder made from W powder stock to achieve temperature (option).

NTP

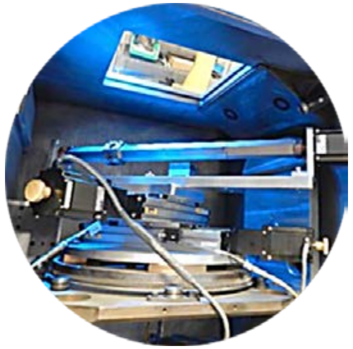
Channel drilling for packed powder cartridge fuel element



End cap – packed powder fuel element cartridge



MSFC Nuclear Thermal Rocket Element Environmental System (NTREES)



Rotisserie for performing butt welds on packed powder cartridge fuel elements

Fuel specimen testing in the MSFC Compact Fuel Element Environmental Test (CFEET) system

Fuel element packed powder cartridges prior to butt weld assembly