"Propelling Us to New Worlds"

Affordable Development and Demonstration of a Small NTR Engine and Stage: How Small is Big Enough?

(AIAA-2015-4524)

EXPL-06 Nuclear Propulsion

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Overview of NTP Development Activities by NASA and DOE

- In FY11, NASA formulated a plan for Nuclear Thermal Propulsion (NTP) development that included "Foundational Technology Development" followed by system-level "Technology Demonstrations"
- The ongoing NTP project, funded by NASA's Advanced Exploration Systems (AES) program, is focused on Foundational Technology Development and includes 5 key task activities:
  (1) Fuel element fabrication and non-nuclear validation testing of "heritage" fuel options;
  (2) Engine conceptual design;
  (3) Mission analysis and engine requirements definition;
  (4) Identification of affordable options for ground testing; and
  (5) Formulation of an affordable and sustainable NTP development program
- Performance parameters for "Point of Departure" designs for a small "criticality-limited" and full size 25 klb_f-class engine were developed during FY's 13-14 using heritage fuel element designs for both Rover/NERVA Graphite Composite (GC) and Ceramic Metal (Cermet) fuel forms
- To focus the fuel development effort and maximize use of its resources, the AES program decided, in FY14, that a "leader-follower" down selection between GC and cermet fuel was required
- An Independent Review Panel (IRP) was convened by NASA and tasked with reviewing the available fuel data and making a recommendation to NASA. In February 2015, the IRP recommended and the AES program endorsed GC as the leader fuel
- In FY'14, a preliminary development schedule / DDT&E plan was produced by GRC, DOE & industry for the AES program. Assumptions, considerations and key task activities are presented here
- *Two small (~7.5 and 16.5 klb_f) engine sizes were considered for ground and flight technology demonstration within a 10-year timeframe; their ability to support future human exploration missions was also examined and a recommendation on a preferred size is provided*

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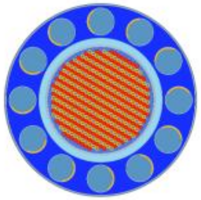
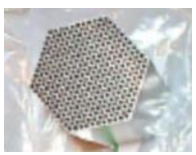


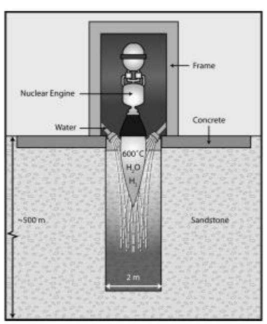
SOTA Reactor Core & Engine Modeling

NERVA "Composite" Fuel ✓



"Cermet" Fuel

"Fuel-Rich" Engine

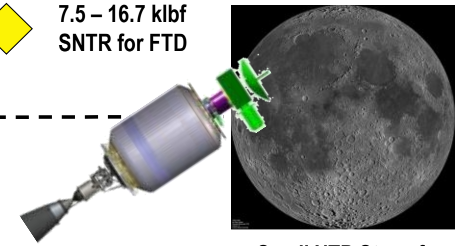


SAFE Ground Test Option at the Nevada National Security Site

Notional

Fiscal Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

Key Milestones
- ◆ Fuels Selection
- ◆ ATP
- ◆ Start — ◆ End: GTD Engine Tests
- ◆ 7.5 – 16.7 klbf SNTR for FTD



Small NTP Stage for Lunar Flyby Mission

Foundational Technology Development

System Concepts & Requirements Definition / Planning / Engine Modeling & Analysis

- In-House & Contractor System Concept Definition, Design, and Analysis
- ◆ Reference Concept & Initial Requirements
- ◆ Initial GTD Design
- ◆ Initial FTD Design
- ◆ Initial 25-klbf GTD / FTD Designs

NTP Technology Development and Demonstrations

- Fuel Element Fab, Testing, Validation and Production; Irradiation Testing / PIE; Other Tech Development
- ◆ Primary / Secondary Fuels Selection
- ◆—◆ Hot H2 Testing in NTREES & DOE Reactor Irradiation Tests
- Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts

NTP Test Facilities Development

- Borehole Demo Testing
- GTF Plan'g/Prel Des

Fuel Element Irradiation Testing in ATR at INL

Ground & Flight Technology Demonstrators

Ground Test Facility (GTF)

Prel. & Final Design	Construction & Asset Installation	Check -out

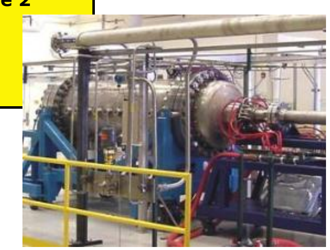
Test Articles for Ground & Flight

◆ CDR GTA ◆ CDR FTA

Detailed Design	Fabrication & Subsys. Assembly	Subsys. Test / Engine Assem.	GTA1	GTA2

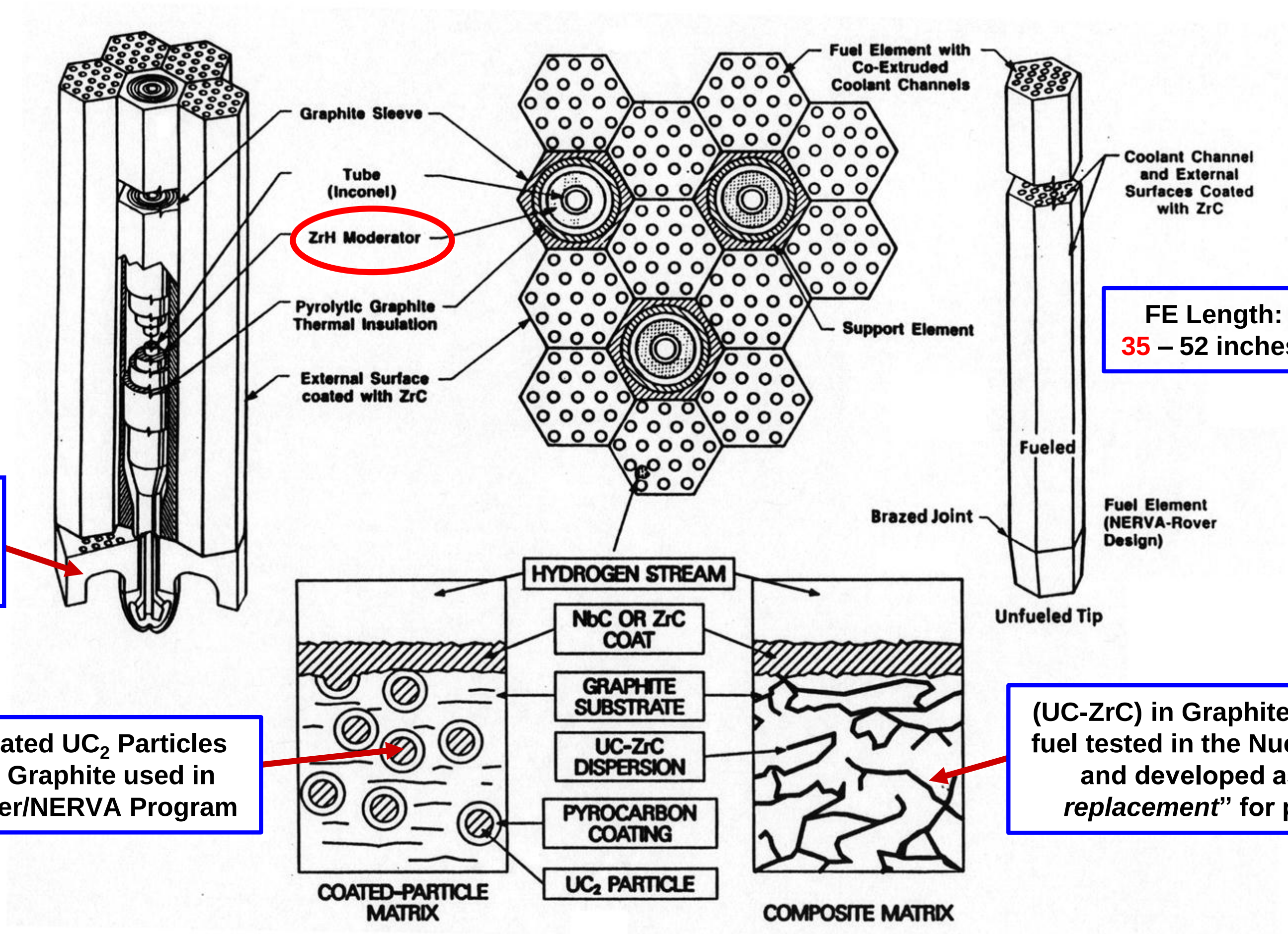
Detailed Design	Fabrication & Subsys. Assembly	Subsys. Test / Engine Assem.	FTA

GTD	Ground Tech Demo
GTA1	Ground Test Article 1
GTA2	Ground Test Article 2
FTA	Flight Test Article
FTD	Flight Tech Demo



NTR Element Environmental Simulator (NTREES)

Rover / NERVA Reactor Core Configuration: SNRE Fuel Element / Tie Tube Bundle Arrangement



NOTE: Tie Tube pedestal supports 6 surrounding FEs

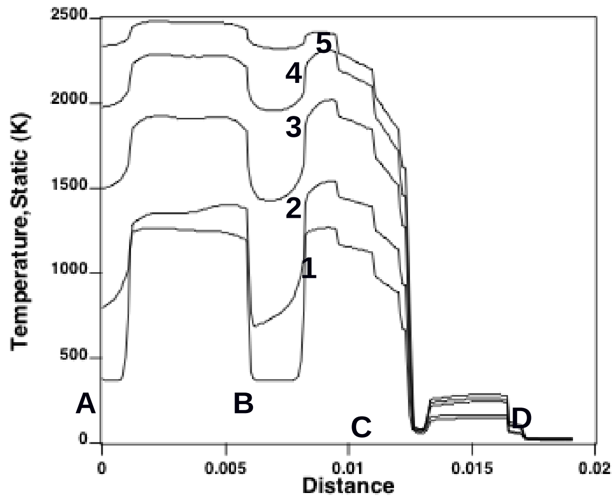
FE Length: 35 – 52 inches

Coated UC_2 Particles in Graphite used in Rover/NERVA Program

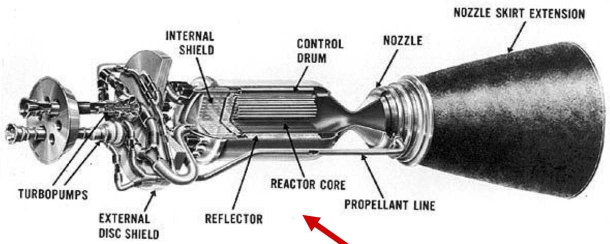
(UC-ZrC) in Graphite "Composite" fuel tested in the Nuclear Furnace, and developed as "*drop-in replacement*" for particle fuel ✓

GRC/DOE Integrated Neutronics, Multi-Physics & Engine Modeling Approach

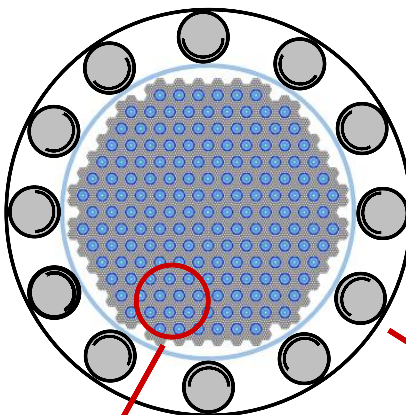
Temperature Distribution Across FE and TT

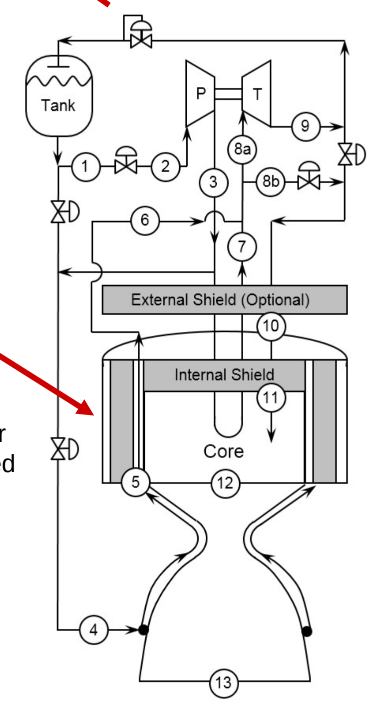


Temperature Distributions at Five Axial Stations
(Numbers Indicate Cold to Hot End Stations)

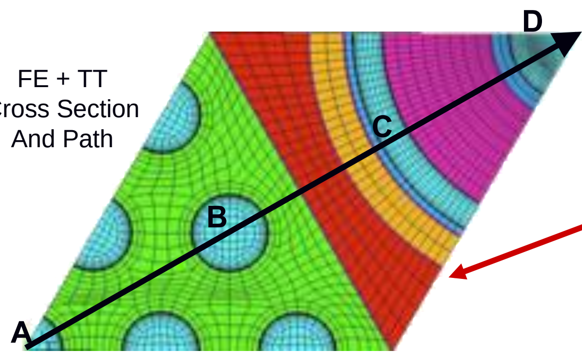


Performance, Size & Mass estimation



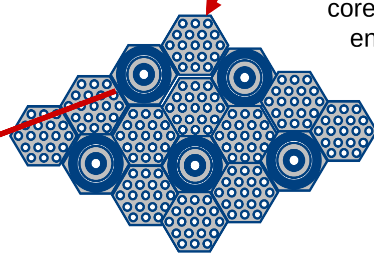


FE + TT Cross Section And Path



ANSYS Model

MCNP neutronics for core criticality, detailed energy deposition, and control worth



Fuel Element-to-Tie Tube ratio varies with engine thrust level

Nuclear Engine System Simulation (NESS) code has been upgraded to use MCNP-generated data

Fuel Element (FE) – Tie Tube (TT) Arrangements for SNRE-derived Graphite Composite Engines

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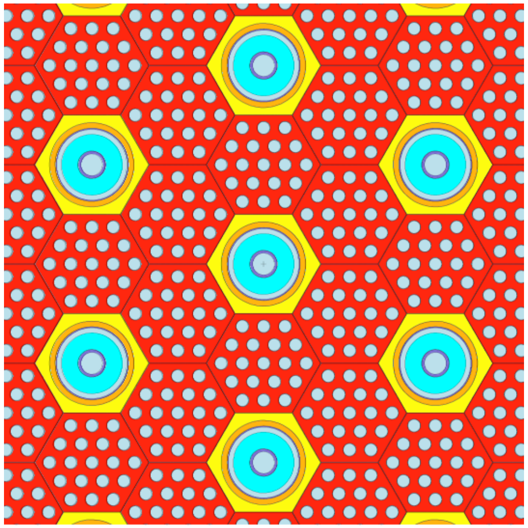
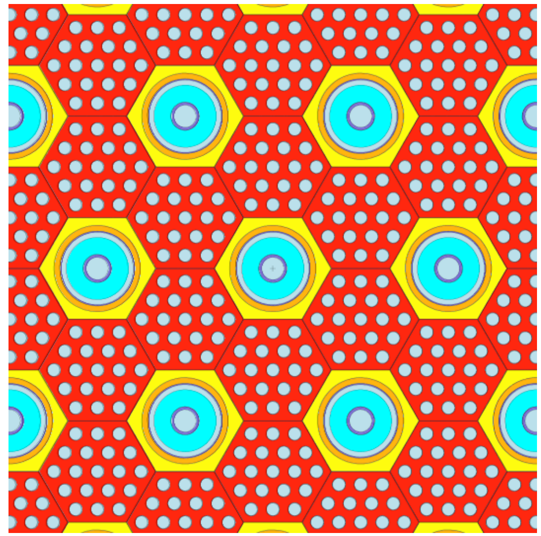
"Sparse" FE – TT Pattern used for Large Engines



Each FE has 4 adjacent FEs and 2 adjacent TTs with a FE to TT ratio of ~3 to 1

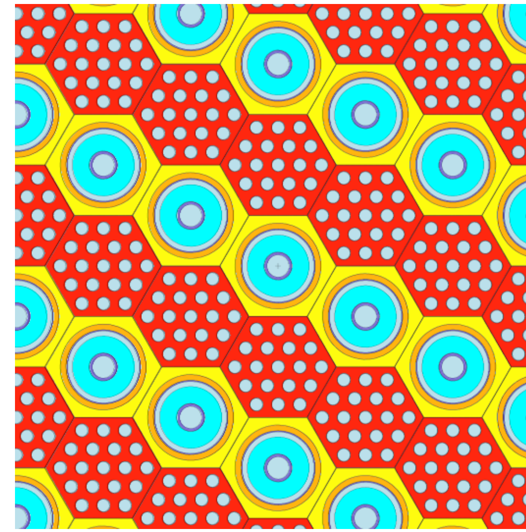
"SNRE" FE – TT Pattern used in Small Nuclear Rocket Engine



Each FE has 3 adjacent FEs and 3 adjacent TTs with a FE to TT ratio of ~2 to 1

Used in full-size 25 klb_f Composite Engine Design

"Dense" FE – Tie Tube Pattern used in Lower Thrust Engines



Each FE has 2 adjacent FEs and 4 adjacent TTs with a FE to TT ratio of ~1 to 1

Used in Small Criticality-Limited Composite Engine Design

NOTE: An important feature common to both the Sparse and SNRE FE – TT patterns is that each tie tube is surrounded by and provides mechanical support for 6 fuel elements

Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846

Performance Characteristics for "Small-to-Full Size" GC SNRE-derived Engines

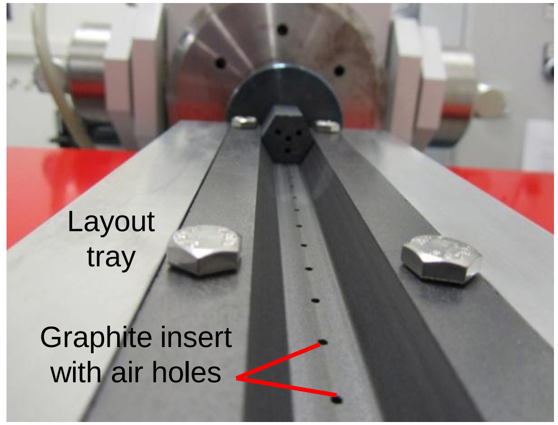
Performance Characteristic	Small Criticality Limited Engine ★	SNRE Baseline	SNRE Baseline +	25 klb$_f$ Axial Growth Option Nominal ★	25 klb$_f$ Axial Growth Option Enhanced
Engine System					
Thrust (klb$_f$)	7.52	16.4	16.7	25.2	25.1
Chamber Inlet Temperature (K)	2739	2695	2733	2790	2940
Chamber Pressure (psia)	565	450	450	1000	1000
Nozzle Area Ratio (NAR)	300:1	100:1	300:1	300:1	300:1
Specific Impulse (s)	894	875	900	909	945
Engine Thrust-to-Weight	1.91	2.92	3.06	3.42	3.41
Approx. Engine Length* (m)	6.19	4.46	6.81	8.69	8.69
Length w/ Retracted Nozzle (m)	4.93	N/A	3.65	6.53	6.53
Reactor					
Active Fuel Length (cm)	89	89	89	132	132
Reflector Thickness (cm)	14.7	14.7	14.7	14.7	14.7
Pressure Vessel Diameter (cm)	87.7	98.5	98.5	98.5	98.5
Element Fuel/Tie Tube Pattern Type	Dense	SNRE	SNRE	SNRE	SNRE
Number of Fuel Elements	260	564	564	564	564
Number of Tie-Tube Elements	251	241	241	241	241
Fuel Fissile Loading (g U per cm^3)	0.60	0.60	0.60	0.25	0.25
Maximum Enrichment (wt% U-235)	93	93	93	93	93
Maximum Fuel Temperature (K)	2860	2860	2860	2860	3010
Margin to Fuel Melt (K)	40	40	40	190	40
U-235 Mass (kg)	27.5	59.6	59.6	36.8	36.8

? ?

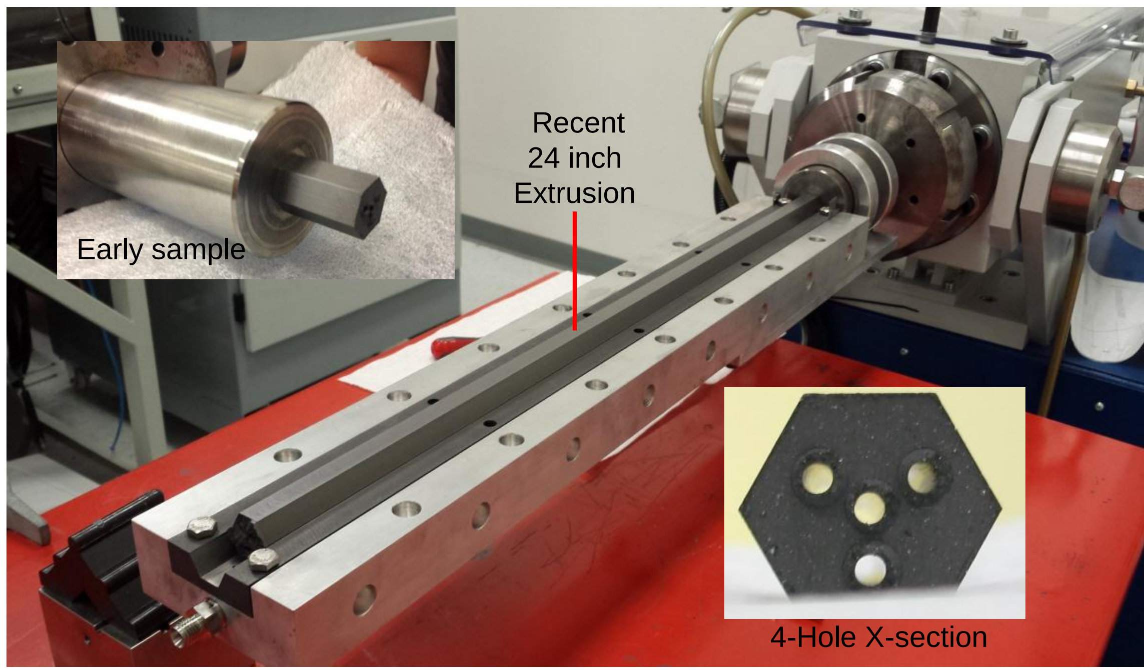
*Varies with thrust level, chamber pressure, NAR and TPA/TVC layout

Equipment Assembled at ORNL for Fabrication of Graphite Composite (GC) Fuel Elements

Graphite FE extruder with installed vent lines for DU capability



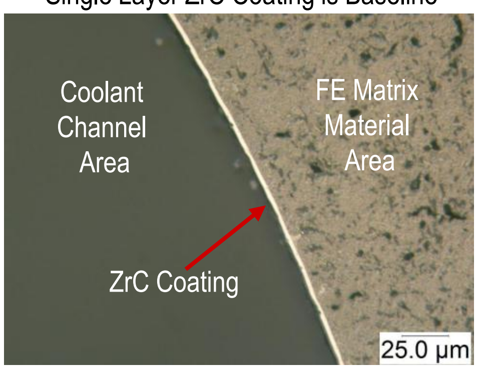
Extruder with 4-Hole Die



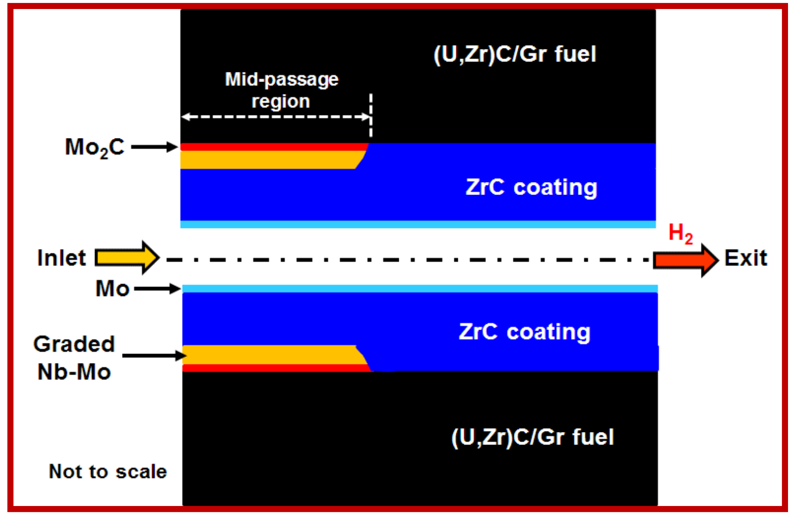
ORNL CVD Furnace for Applying Baseline ZrC Coating along with Alternative Coating Concepts

ORNL 6-zone CVD Coating Furnace

Single Layer ZrC Coating is Baseline



Multilayer Metallic Coating Concept



Advantages of Multilayer Coating Approach:

- Minimizes ZrC/(U,Zr)C-graphite matrix CTE differences.
- Ductile compliant metallic layers will accommodate residual stresses.
- Mo overlay seals cracks in the ZrC coating and reduces H_2 permeation.
- Mo-Nb layers expected to reduce H_2 permeation.
- Mo_2C expected to be a diffusion barrier for carbon.

Maximize Use of the NNSS, DAF and Existing Bore Holes / Tunnels

- Testing should be conducted at the Nevada National Security Site (NNSS) using SAFE (Subsurface Active Filtration of Exhaust) approach in existing boreholes or in long, large diameter horizontal tunnels.

- NNSS provides a large secure, safety zone (~1375 sq. miles) for conducting NTR testing.

- The Device Assembly Facility (DAF) is located within the NNSS and is available for pre-test staging (assembly and "0-power" critical testing) of engine's reactor system prior to transfer to the borehole or tunnel test location.

- DAF is a collection of interconnected steel-reinforced concrete test cells. The entire complex is covered by compacted earth.

- DAF has multiple assembly / test cells; high bays have multi-ton crane capability. The assembly cells are designed to handle SNM.

- Options to use horizontal tunnels exist at the underground U1a complex or the P-tunnel complex located inside the Rainier Mesa.

Aerial View of the DAF at the NNSS

Possible Concepts of Operation for NTP Ground Testing

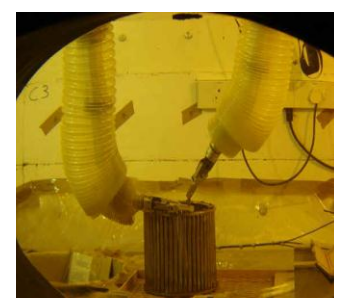
Fuel Element Fabrication	Core Assembly	Reactor Assembly	Engine Assembly	Engine Ground Testing	Disassembly and PIE	Disposal / HEU Recovery
ORNL / Y-12	DAF @NNSS	DAF @NNSS	DAF @NNSS	Borehole	FE, components extraction at test site using Portable Hot Cell	@NNSS entomb in tunnel
Industry		Pressure Vessel, Reactor Control	Nozzle, Pump, H2 Feed Lines	U1a Tunnel	Limited FE and components shipment to INL for PIE	@INL following PIE
				P Tunnel		
				Control / Data Acquisition, H2 Supply		

DAF - Device Assembly Facility
PIE - Post Irradiation Examination
NNSS – Nevada National Security Site

Non-nuclear Components

SHARS* "mobile hot cell" unit – funding for development provided by the IAEA

*Spent High Activity Radioactive Sources (SHARS)



Small 7.5 klb$_f$ NTP Engine and Stage for 2025 Lunar Flyby FTD Mission

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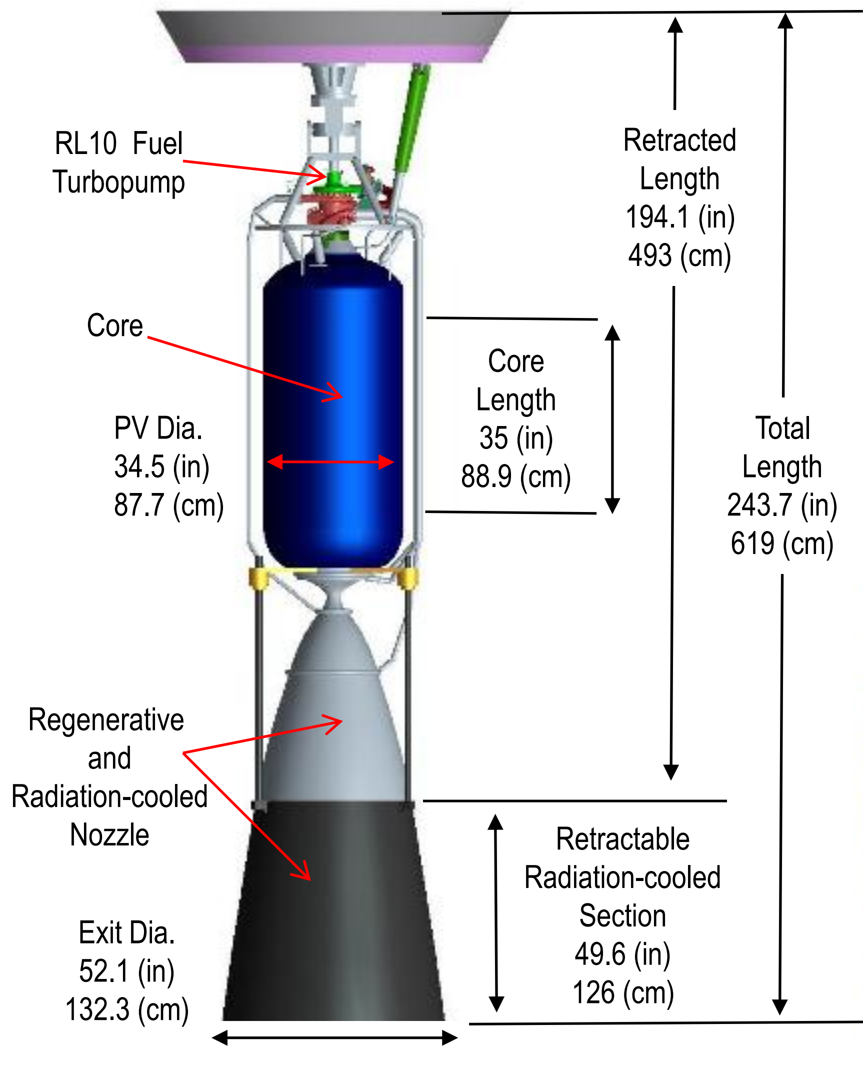
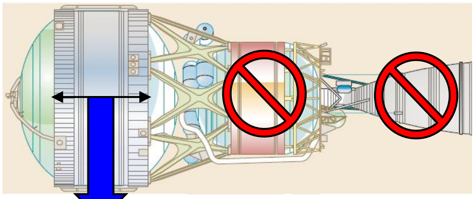
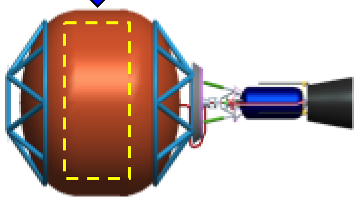


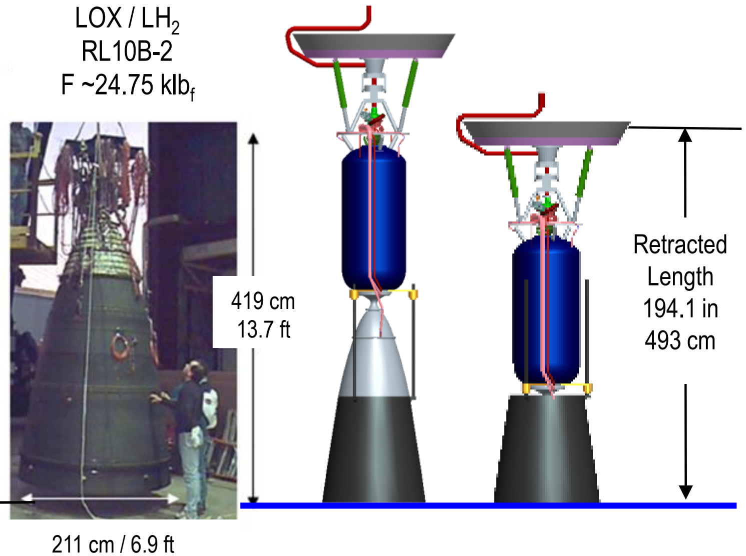
SNTPS has same diameter as the DCSS but has shorter overall length



- Remove LOX Tank, Lines, Valves
- Remove RL10B-2



- Add small NTR engine with retractable nozzle
- SNTPS uses the same LH_2 tank used on the DCSS
- Uses the same LH2 lines
- Use similar thrust structure



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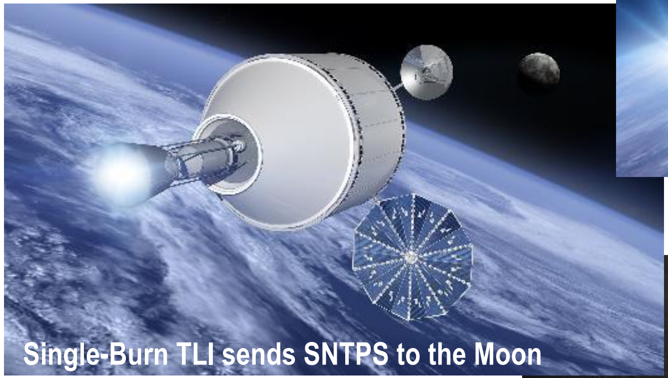
2025 Small NTPS FTD Mission: "Single-Burn Lunar Flyby"

- IMLEO ~9.90 t
- F ~7.52 klb_f, Isp ~894 s, F/W_{eng} ~1.91
- Dry Stage / LH_2 / PL mass ~ 6.42 t 3.23 t / 0.25 t
- ΔV_{TLI} / Burn time ~3.16 km/s / 12.97 mins


SNTPS FTD Launch on Delta 4 M (5,4)


DCSS delivers SNTPS to LEO


Earthrise Final Farewell Pictures


Single-Burn TLI sends SNTPS to the Moon

- ELV launches Small NTPS (SNTPS) to LEO (407 km)
- 3 – Day LEO to Moon Transit
- Lunar Gravity Assist & Disposal


Lunar Gravity Assist sends SNTPS into Deep Space

Reusable NTP Vehicles for NEA, Lunar Cargo and Crewed Landing Missions use Clustered SNREs

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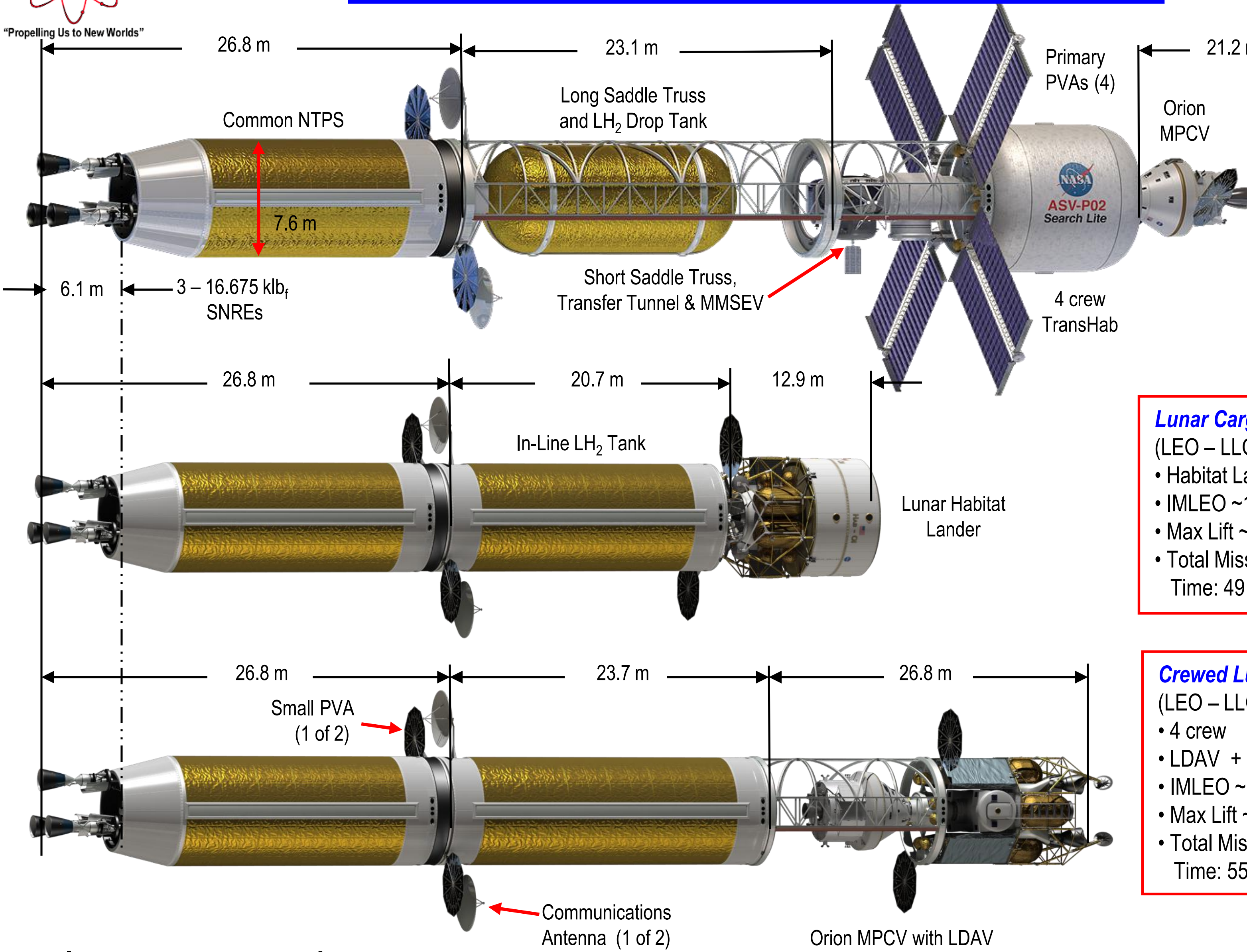

ASV: 2000 SG344 (2028)
(LEO – NEA – 6-hr EEO)
- 4 crew
- PL + MPCV ~55.4 t
- IMLEO ~184.6 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: 50.4 min

Lunar Cargo Delivery:
(LEO – LLO – 24-hr EEO)
- Habitat Lander ~61.1 t
- IMLEO ~186.7 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: 49.2 min

Crewed Lunar Landing:
(LEO – LLO – 24-hr EEO)
- 4 crew
- LDAV + MPCV ~48.9 t
- IMLEO ~188.6 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: 55 min

NTR
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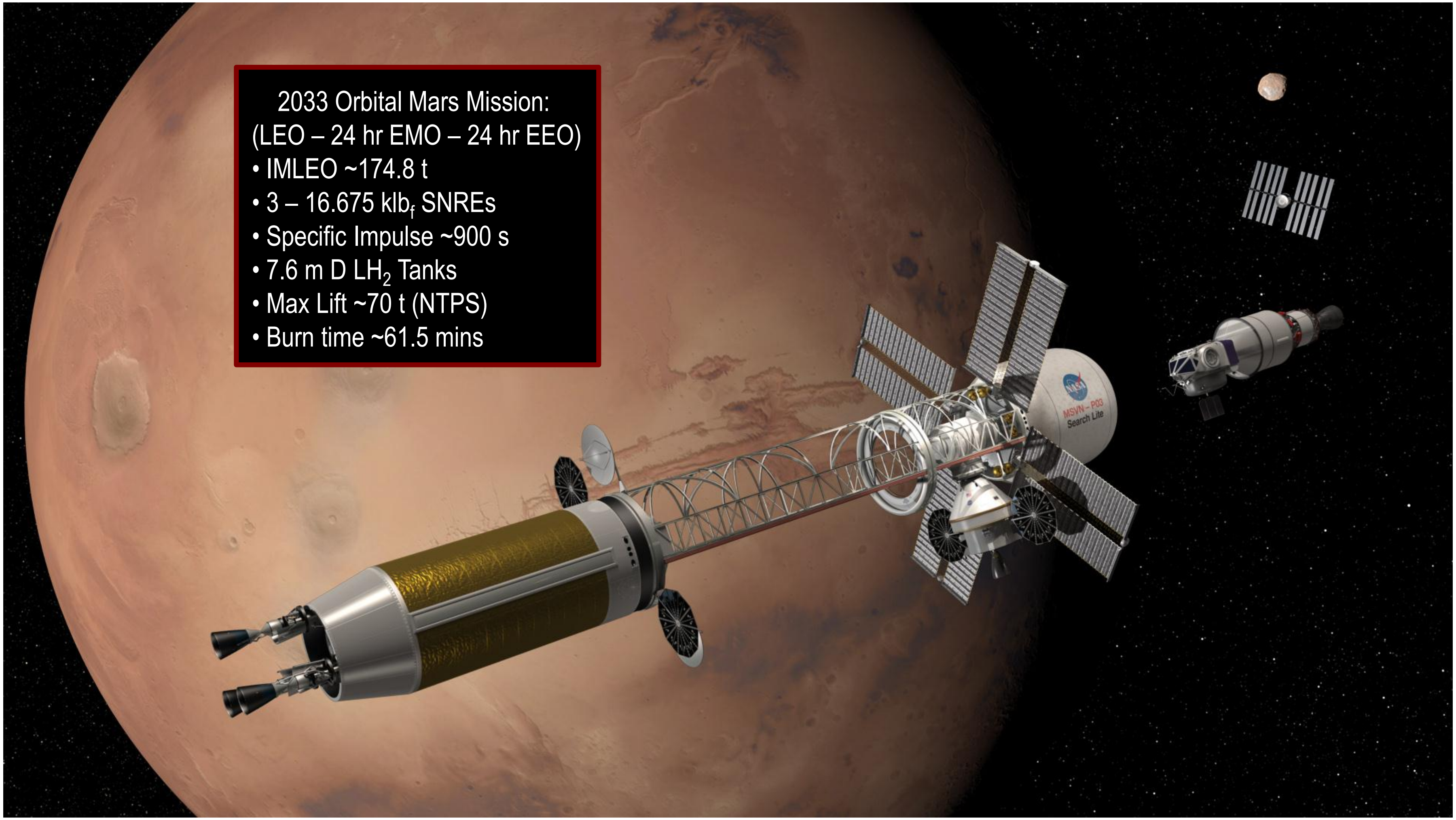
Reusable NTP MSVN for NASA's EMC Carries 4 Crew and Uses SEP-delivered LH_2 Propellant for Earth Return



Performance Requirements for Small GC NTRs for FTD, Lunar, NEA and Mars Exploration Missions

Requirements / Missions	Engine Thrust (klb_f)	T/W_{eng}	T_{ex} (°K)	I_{sp} (s)	No. Engines	U-235 Mass (kg)	No. burns	Longest Single burn (min)	Total burn time (min)	U-235 Burnup (%)
Lunar Flyby FTD Mission	~7.5	~1.9	2739	894	1	27.5	1	~13.0	-	~0.0062
Lunar Flyby FTD Mission	~16.7	~3.1	2733	900	1	59.6	1	~6.7	-	~0.0035
Lunar Cargo Delivery	~16.7	~3.1	2733	900	3	59.6	5	~21.4	~49.2	~0.025
Lunar Landing Crewed	~16.7	~3.1	2733	900	3	59.6	5	~21.0	~55.0	~0.028
NEA *2000 SG344* Crewed	~16.7	~3.1	2733	900	3	59.6	5	~27.4	~50.4	~0.026
EMC Crewed	~16.7	~3.1	2733	900	3	59.6	5	~24.2	~61.5	~0.032

- Both engines assume a peak fuel temperature of 2860 K and have a fuel loading of ~0.6 grams of HEU per cm^3

The $SNRE^+$ option is recommended for development and testing. It can be used for the single engine FTD mission, and with clustered engines can support reusable lunar cargo delivery, crewed landing, and NEA survey missions. Even human missions to Mars are possible with reduced crew size and prepositioning of assets as currently being envisioned in NASA's EMC study.

Assumptions for “Sporty” SNTPS GTD & FTD Mission Schedule

- A 10-year period to a ground tested “qualification engine” by 2024 is conceivable but challenging and many things must line up / flow well.

- By necessity it would be a success-oriented high–risk activity requiring immediate and serious financial commitments to the following areas:
  - Management and acquisition approach is streamlined
  - Composite fuel is the baseline and fuel element (FE) production levels are scaled up prior to complete verification of all processing activities; Testing conducted in bore holes at NTS
  - NEPA and launch safety analyses is initiated along with ID’ed shipping and ATLO facility mods

- A single “portable hot cell unit” would be co-located near the site of the candidate borehole / tunnel. The unit would be a “turnkey” procurement and used to disassemble the reactor after testing to extract a sampling of FEs and reactor components for shipment to INL for PIE. The unit would be similar to that used by the UK at their Sellafield hot cell facility or the mobile SHARS unit developed by the IAEA. Afterwards the unit would be used to disassemble the reactor into smaller groupings of parts that would be shipped off-site for final disposal in “existing” shipping casks.

- The GTD program would focus on borehole testing of two units:
  – Engineering reactor and engine test article (90% fidelity) in 2023
  – Qualification engine (100% fidelity) in 2024 after qual-level testing (e.g., vibration) in 2023;
- The flight unit – identical to the qualification unit – would be launched in 2025

Notional NTP Ground & Flight Test Demonstration Milestone Schedule

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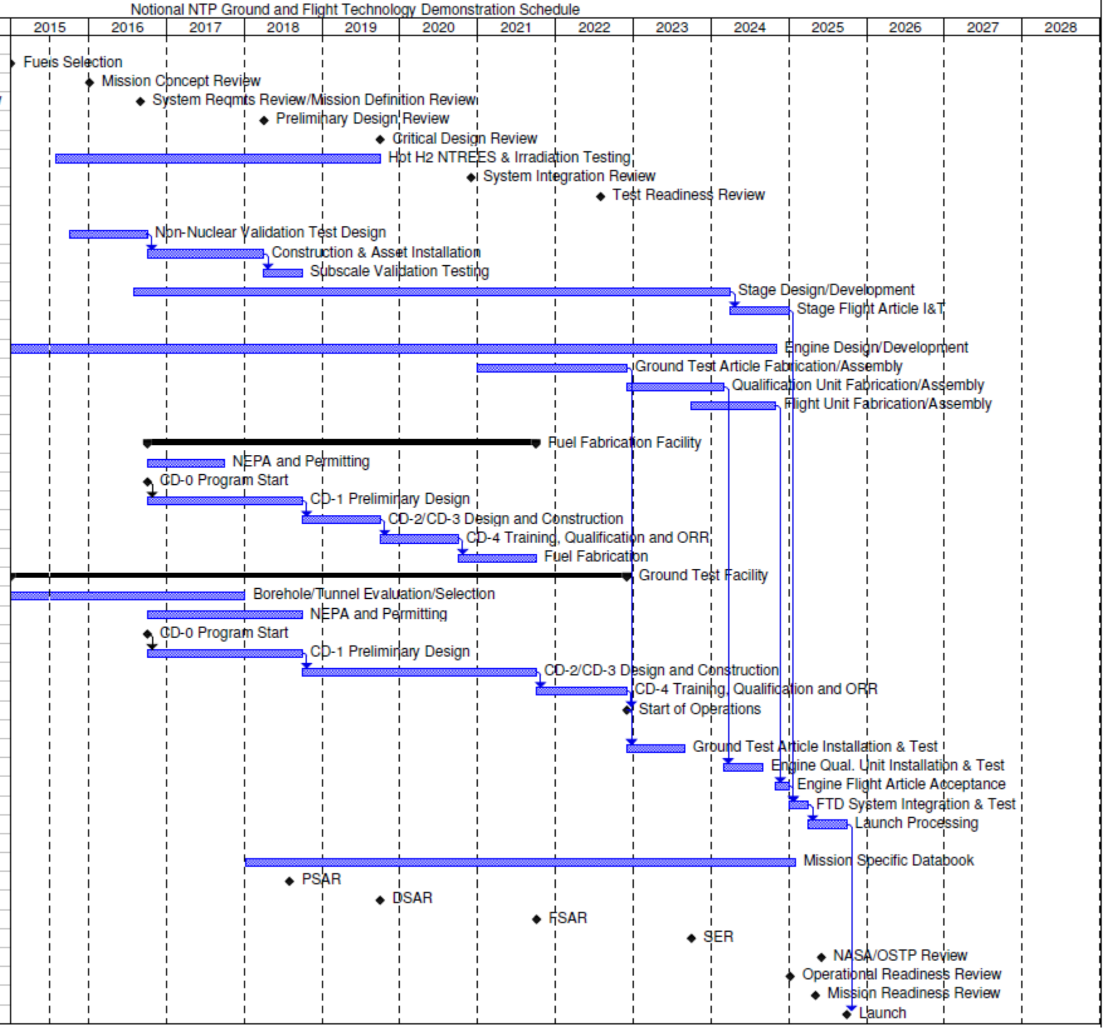
Oak Ridge National Laboratory

Idaho National Laboratory

Notional NTP Ground and Flight Technology Demonstration Schedule

ID	Task Name
1	NTP Flight Technology Demonstrator (FTD)
2	Fuels Selection
3	Mission Concept Review
4	System Reqmts Review/Mission Definition Review
5	Preliminary Design Review
6	Critical Design Review
7	Hot H2 NTREES & Irradiation Testing
8	System Integration Review
9	Test Readiness Review
10	Borehole Validation Test
11	Non-Nuclear Validation Test Design
12	Construction & Asset Installation
13	Subscale Validation Testing
14	Stage Design/Development
15	Stage Flight Article I&T
16	Engine Development/Fabrication/Assembly
17	Engine Design/Development
18	Ground Test Article Fabrication/Assembly
19	Qualification Unit Fabrication/Assembly
20	Flight Unit Fabrication/Assembly
21	Test Facility Development
22	Fuel Fabrication Facility
23	NEPA and Permitting
24	CD-0 Program Start
25	CD-1 Preliminary Design
26	CD-2/CD-3 Design and Construction
27	CD-4 Training, Qualification and ORR
28	Fuel Fabrication
29	Ground Test Facility
30	Borehole/Tunnel Evaluation/Selection
31	NEPA and Permitting
32	CD-0 Program Start
33	CD-1 Preliminary Design
34	CD-2/CD-3 Design and Construction
35	CD-4 Training, Qualification and ORR
36	Start of Operations
37	Engine Testing
38	Ground Test Article Installation & Test
39	Engine Qual. Unit Installation & Test
40	Engine Flight Article Acceptance
41	FTD System Integration & Test
42	Launch Processing
43	Launch Approval
44	Mission Specific Databook
45	PSAR
46	DSAR
47	FSAR
48	SER
49	NASA/OSTP Review
50	Operational Readiness Review
51	Mission Readiness Review
52	Launch



Glenn Research Center

NPR 7120.8 WBS for NASA Research and Technology Development Program utilized

at Lewis Field

Summary and Conclusions

- In FY14, NASA and DOE (NE-75, ORNL, INL), with input from industry, formulated a preliminary development plan for the AES program for testing a small GTD (~7.5 – 16.5 klb_f) engine in the early 2020's followed by a FTD mission of a small NTP stage around 2025

- 10-years to a FTD mission in 2025 will require an immediate start and a serious and sustained financial commitment along with a streamlined management and acquisition approach – *DOE*

- Graphite-based "composite fuel" is the baseline; an engine using this fuel type can be built sooner than one using another less established / less tested fuel at relevant conditions – *DOE*

- Testing should be conducted at the NNSS using existing boreholes or tunnels and should maximize the use of existing facilities; consider new temporary / mobile facilities only as required; new nuclear infrastructure is a long lead item – *DOE*

- The FTD mission proposed is a 1-burn "lunar flyby" using a single $SNRE^+$ engine chosen to keep things simple and more affordable; *clustered SNREs can support a full range of human exploration missions allowing a "one size fits all" approach to NTR development* – *GRC*

- The keys to affordability include using: (1) proven "Graphite Composite" fuel; (2) "separate effects" testing (NTREES and irradiation) to qualify the fuel; (3) SOTA numerical models to design, build and operate the engine; (4) small engine design with a "common" FE that is scalable to larger sizes, when and if required; (5) existing DOE facilities at the NNSS (e.g., DAF, boreholes or tunnels); and (6) flight-proven, non-nuclear engine & stage hardware to maximum extent possible for the FTD mission