"Propelling Us to New Worlds"

Affordable Development and Demonstration of a Small NTR Engine and Stage: A Preliminary NASA, DOE and Industry Assessment

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presented at

Nuclear and Emerging Technologies for Space (NETS-2015)
Albuquerque, NM

Monday, Feb. 23, 2015

Formulation of Affordable and Sustainable NTP Development Strategy is Underway Involving NASA, DOE and Industry

- In FY'11, Nuclear Thermal Propulsion (NTP) was identified as a key propulsion option under the Advanced In-Space Propulsion (AISP) component of NASA's Exploration Technology Development and Demonstration (ETDD) program
- A strategy was outlined by GRC and NASA HQ that included 2 key elements – "Foundational Technology Development" followed by specific "Technology Demonstration" projects
- The "Technology Demonstration" element proposed ground technology demonstration (GTD) testing in the early 2020's, followed by a flight technology demonstration (FTD) mission by ~2025
- In order to reduce development costs, the demonstration projects would focus on developing a small, low thrust (~7.5 – 16.5 klb_f) engine that utilizes a "common" fuel element design scalable to the higher thrust (~25 klb_f) engines used in NASA's Mars DRA 5.0 study (NASA-SP-2009-566)
- Besides reducing development costs and allowing utilization of existing, flight proven engine hardware (e.g., hydrogen pumps and nozzles), small, lower thrust ground and flight demonstration engines can validate the technology and offer improved capability – increased payloads and decreased transit times – valued for robotic science missions identified in NASA's Decadal Study
- NASA, NE-75, ORNL, INL, NNSA, & industry (NSTech, Aerojet Rocketdyne) are working together on formulating a strategy leading to the development of a small GTD engine in the early 2020's followed by a FTD "lunar flyby" mission using a small NTP stage (SNTPS) around 2025
- The preliminary assessment provided here along with similar information provided by DOE/NNSA provides a strawman for continued refinement allowing an informed cost estimate to be made

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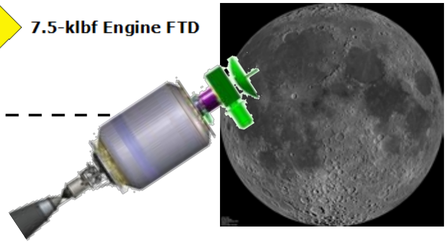
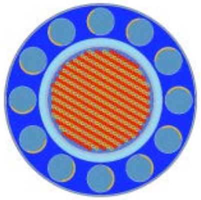
Fiscal Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Key Milestones		Fuels Selection	ATP						Start GTD Engine Tests		End	7.5-klbf Engine FTD		

Notional



Small NTP Stage for Lunar Flyby Mission

Foundational Technology Development



SOTA Reactor Core & Engine Modeling

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

In-House & Contractor System Concept Definition, Design, and Analysis

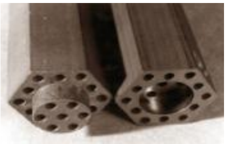
Reference Concept & Initial Requirements

Initial GTD Design

Initial FTD Design

Initial 25-klbf GTD / FTD Designs

NTP Technology Development and Demonstrations



NERVA "Composite" Fuel

Fuel Element Fab, Testing, Validation and Production; Irradiation Testing / PIE; Other Tech Development

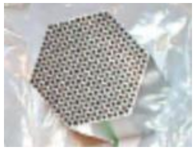
Primary / Secondary Fuels Selection

Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts

Hot H2 Testing in NTREES & DOE Reactor Irradiation Tests

Fuel Element Irradiation Testing in ATR at INL

NTP Test Facilities Development



"Cermet" Fuel

"Fuel-Rich" Engine

Borehole Demo Testing

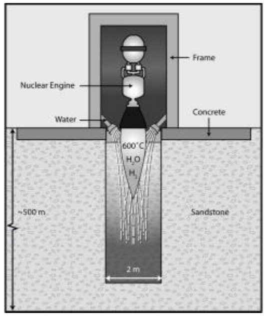
GTF Plan'g/Prel Des

Potential Demos / Mars Flights
2029-30 - Lunar/EM-L2 Flights
2031-33 - Mars Cargo Flights
2033-35 - Mars Crewed Flights

Ground & Flight Technology Demonstrators

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

Ground Test Facility (GTF)



Affordable SAFE Ground Testing at the Nevada Test Site (NTS)

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

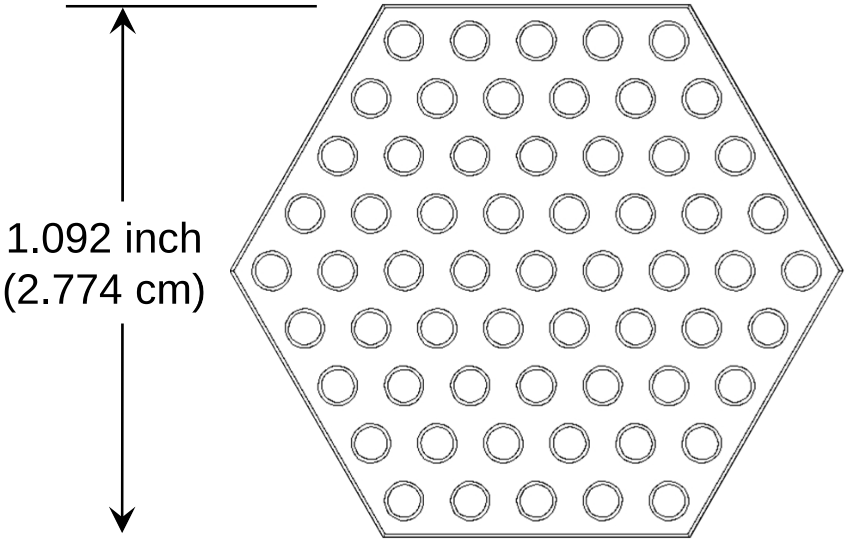
NTR Element Environmental Simulator (NTREES)

Glenn Research Center

at Lewis Field

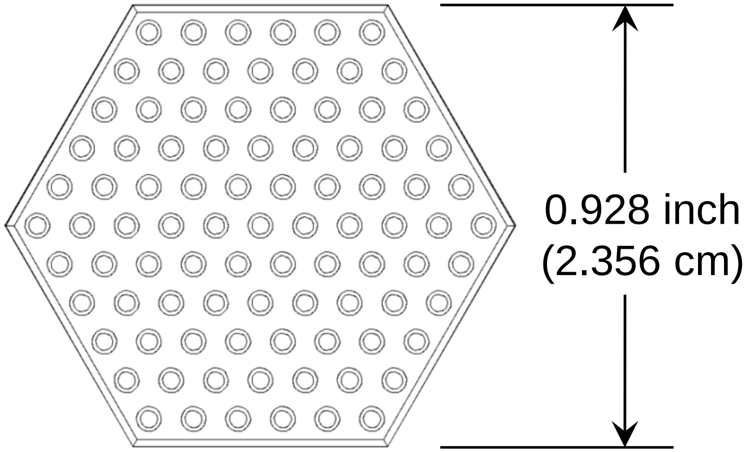
"Heritage" Fuel Element Size Comparisons (Shown to Relative Scale)

ANL-200



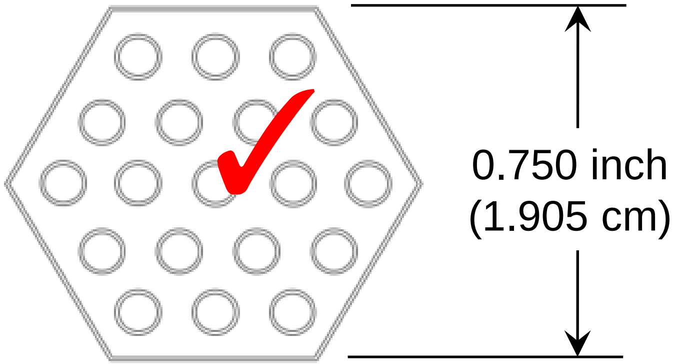
61 Coolant Channels per element

GE-710



91 Coolant Channels per element

Rover / NERVA



19 Coolant Channels per element

S. K. Borowski et al., "Point of Departure" Designs for Small & Full Size (25 klb_f) Composite & Cermet Fuel NTR Engines (March 20, 2013)

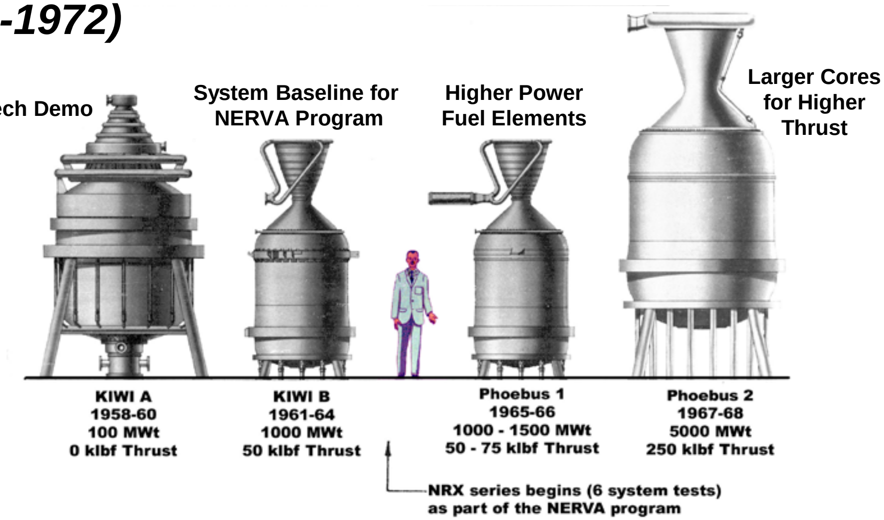
Rover / NERVA* Program Summary

(1959-1972)

The smallest engine tested, the 25 klb$_f$ "Pewee" engine, is sufficient for human Mars missions when used in a clustered arrangement of 3 – 4 engines

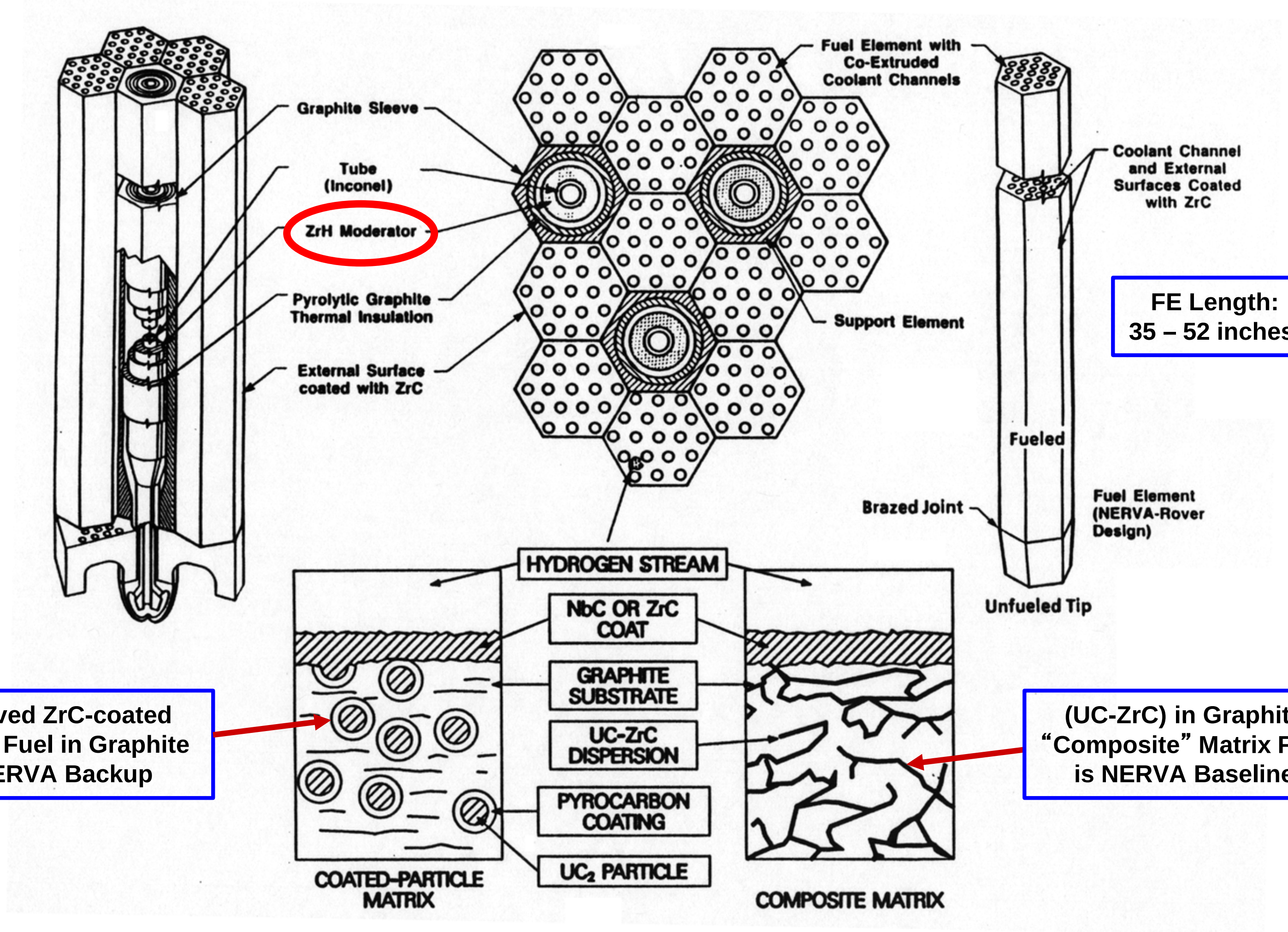
- **20 NTR / reactors designed, built and tested at the Nevada Test Site – "All the requirements for a human mission to Mars were demonstrated"**
- **Engine sizes tested**
  - 25, 50, 75 and 250 klb$_f$
- **H_2 exit temperatures achieved**
  - 2,350-2,550 K (in 25 klb$_f$ Pewee)
- **I_{sp} capability**
  - 825-850 sec ("hot bleed cycle" tested on NERVA-XE)
  - 850-875 sec ("expander cycle" chosen for NERVA flight engine)
- **Burn duration**
  - ~ 62 min (50 klb$_f$ NRX-A6 - single burn)
  - ~ 2 hrs (50 klb$_f$ NRX-XE: 27 restarts / accumulated burn time)

**** NERVA: Nuclear Engine for Rocket Vehicle Applications***



The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

“Heritage” Rover / NERVA Reactor Core Fuel Element and Tie Tube Bundle Arrangement



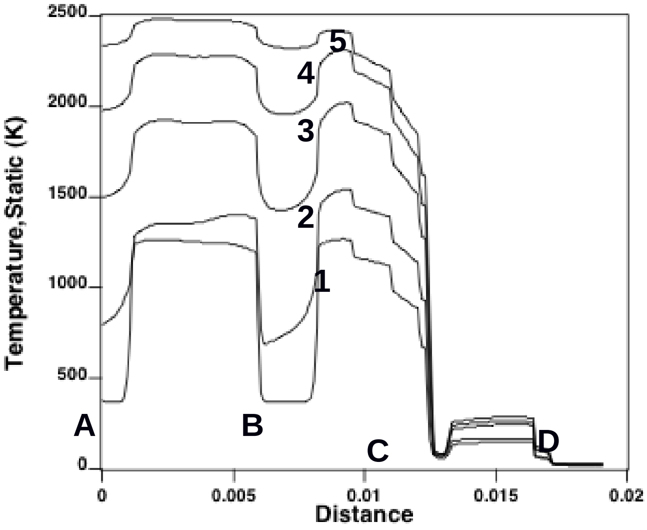
FE Length: 35 – 52 inches

Improved ZrC-coated Particle Fuel in Graphite is NERVA Backup

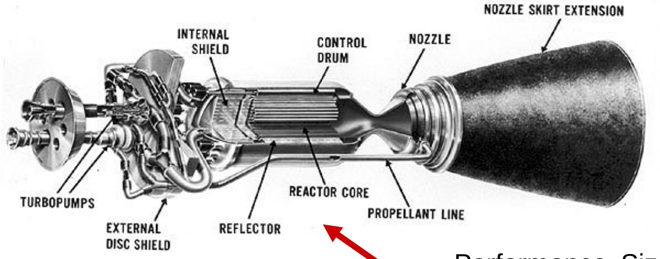
(UC-ZrC) in Graphite “Composite” Matrix Fuel is NERVA Baseline ✓

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

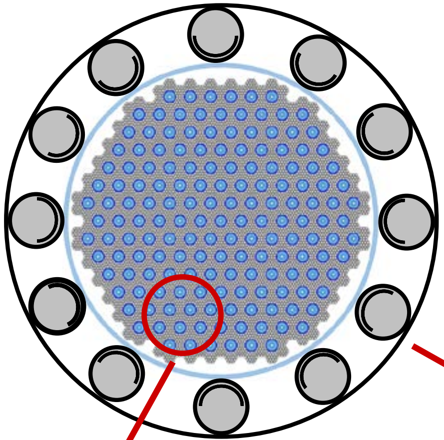
Temperature Distribution Across FE and TT



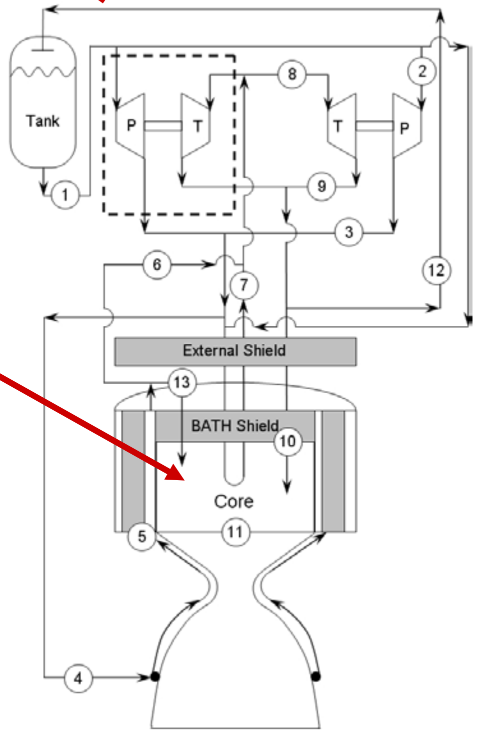
Temperature Distributions at Five Axial Stations
(Numbers Indicate Cold to Hot End Stations)



Performance, Size & Mass estimation

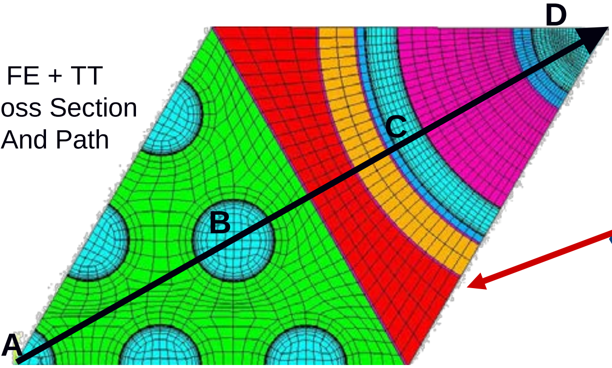


MCNP neutronics for core criticality, detailed energy deposition, and control worth

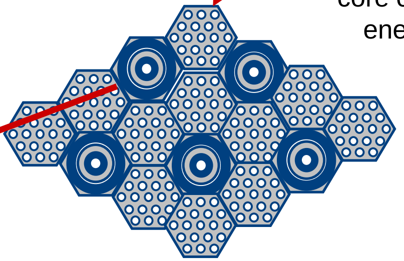


Nuclear Engine System Simulation (NESS) code has been upgraded to use MCNP-generated data

FE + TT Cross Section And Path



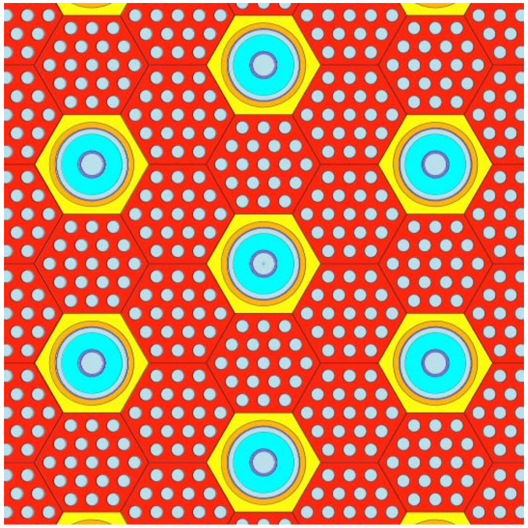
ANSYS Model



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

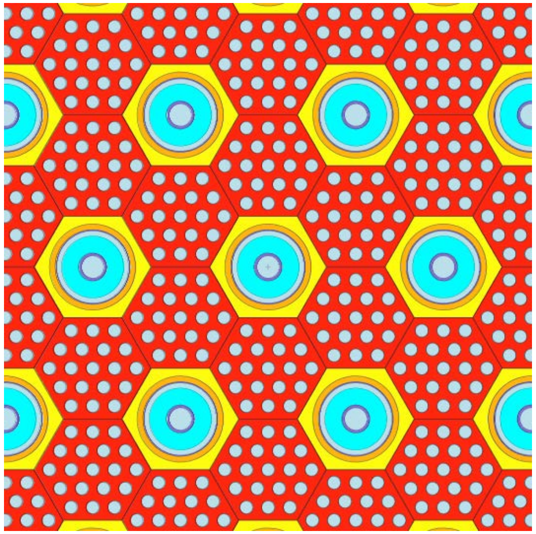
Fuel Element (FE) – Tie Tube (TT) Arrangements for NERVA-derived NTR Engines

"Sparse" FE – TT Pattern used for Large Engines



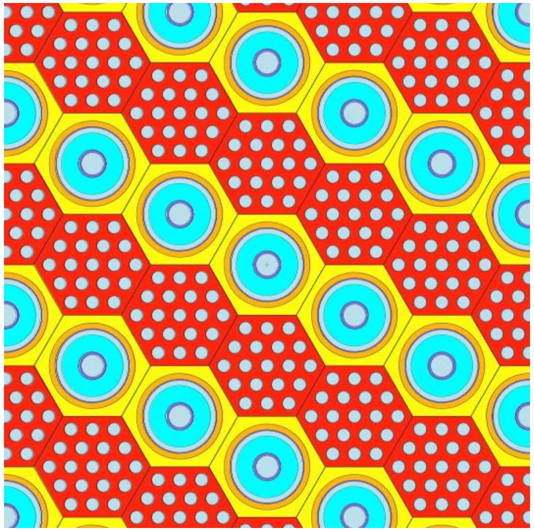
Each FE has 4 adjacent FEs and 2 adjacent TTs with a FE to TT ratio of ~3 to 1

"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

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

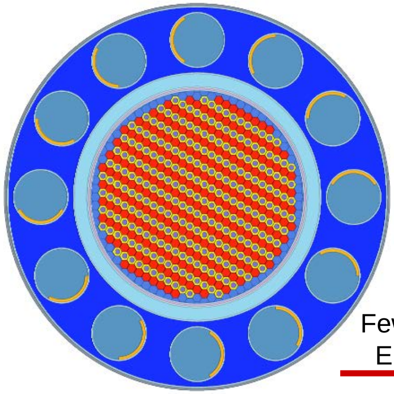


Each FE has 2 adjacent FEs and 4 adjacent TTs with a FE to TT ratio of ~1 to 1

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

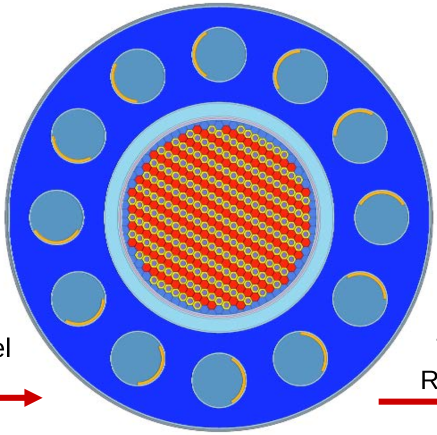
Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846

Cross Sections for Low to High Thrust Engines using Various Fuel Element – Tie Tube Patterns



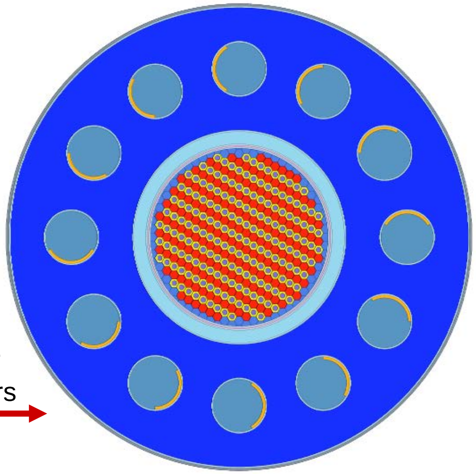
7.5-klb$_f$ thrust engine
(F/W$_{eng}$ ~1.91)

Fewer Fuel Elements →

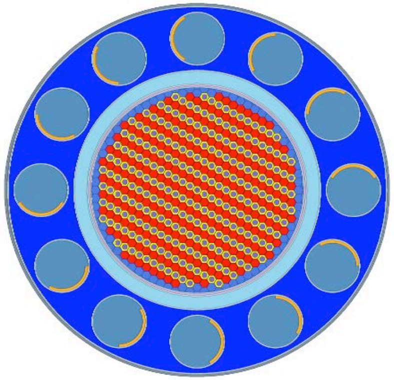


6.0-klb$_f$ thrust engine
(F/W$_{eng}$ ~1.43)

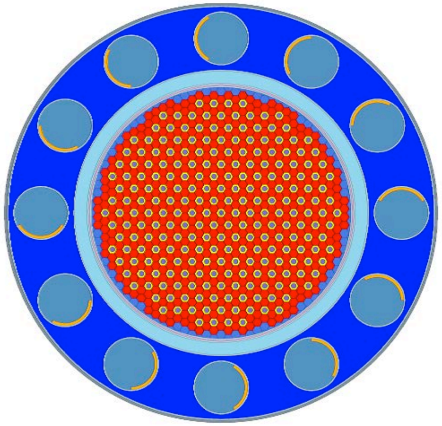
Thicker Reflectors →



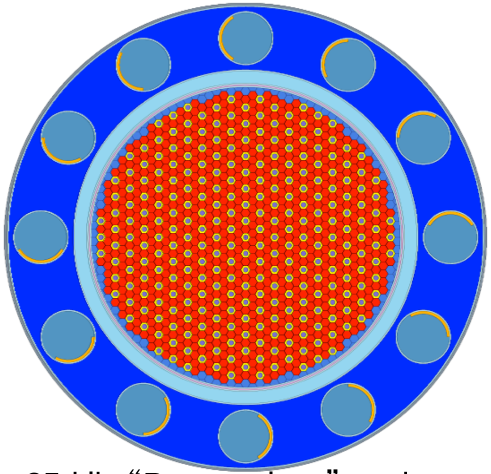
5.3-klb$_f$ thrust engine (F/W$_{eng}$ ~1.10)



7.5-klb$_f$ low thrust engine - Dense



16.4-klb$_f$ SNRE pattern



25-klb$_f$ "Pewee-class" engine
(Radial growth / Sparse pattern)

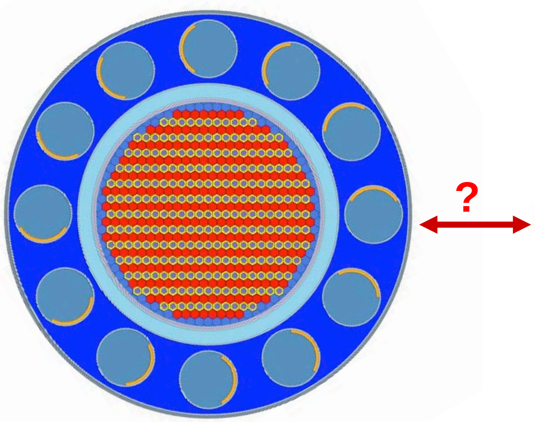
Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846

(Same Scale for all Concepts)

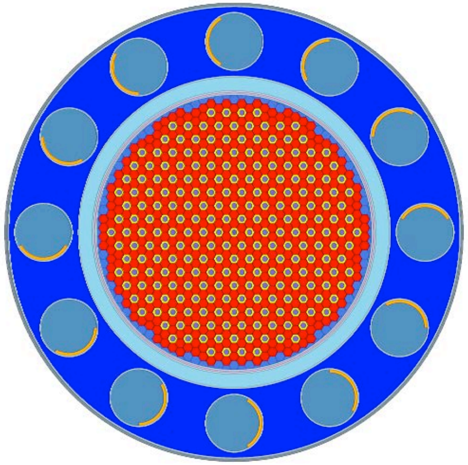
Development of a Common Scalable Fuel Element for Ground Testing and Flight Validation

- During the Rover program, a common fuel element / tie tube design was developed and used in the design of the 50 klbf Kiwi-B4E (1964), 75 klbf Phoebus-1B (1967), 250 klbf Phoebus-2A (June 1968), then back down to the 25 klbf Pewee engine (Nov-Dec 1968)

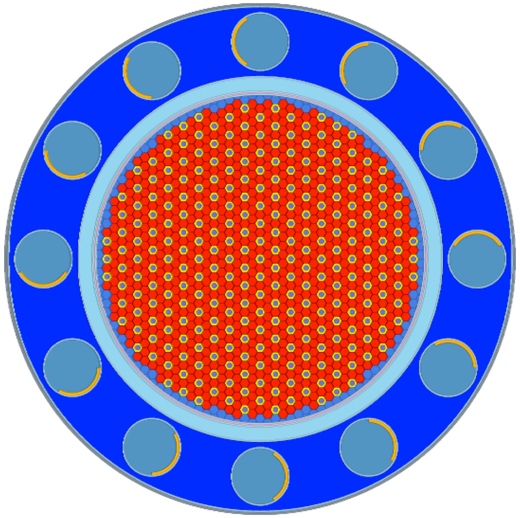
- NASA and DOE are evaluating a similar approach: design, build, ground then flight test a small engine using a common fuel element that is scalable to a larger 25 klbf thrust engine needed for human missions



7.5-klb$_f$ low thrust engine



16.4-klb$_f$ SNRE



25-klb$_f$ “Pewee-class” engine
(Radial growth option / sparse pattern)

Ref: B. Schnitzler, et al., “Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design”, AIAA-2011-5846 paper presented at the 47th Joint Propulsion Conference, San Diego, CA

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Performance Characteristics for Small & Full Size NERVA-derived Engine Designs – Composite Fuel

Performance Characteristic	Small Citicality Limited Engine	SNRE		25 klb$_f$ Axial Growth Option	
		Baseline	Baseline +	Nominal	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

SOTA “Pewee-class” Engine Parameters

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

NTP Fuels and Engine Development Sequence
Nuclear & Non-Nuclear Testing

Fuel Specimens

- Fabrication and characterization
- High temperature testing including hot H_2 exposure and flow rates
- Irradiation testing at high temperature

Fuel Elements (Prototypic Cross-Section, Segments or Full Length)

- Fabrication and characterization
- High temperature testing including H_2 exposure and prototypic flow rates (e.g., NTREES)
- Irradiation testing

Reactor Design

- Neutronics and Physics
- Heat Transfer
- Dynamics
- Structures
- I&C

Engine Ground Test

- Prototypic fuel temperatures, hot H_2 flow rates, and operating times
- Engine test also serves as fuel qualification test

Addressing Ground Test Challenges

- Utilize the SAFE borehole concept
- Use temporary facilities & services at the ground test site
- Minimize engine size & number of tests to qualify for launch
- Maximize existing facilities (e.g., DAF) and capabilities for testing and PIE

Ref: J. Werner, 47th AIAA JPC, INL, 2011

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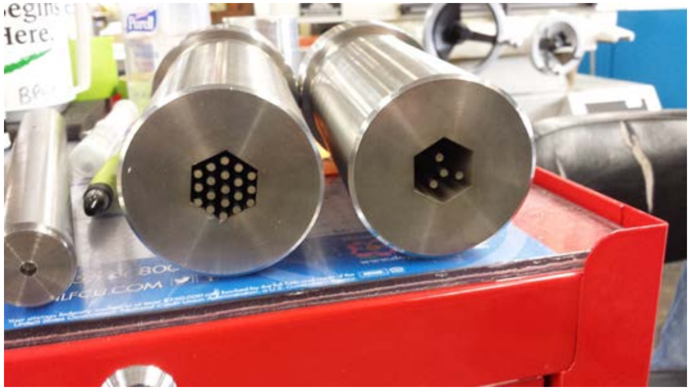
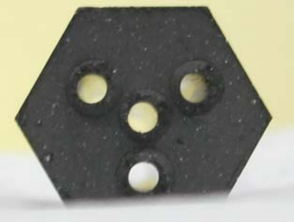
NERVA Graphite - Composite Fuel Elements with Protective ZrC Coating are Being Produced Now at ORNL for NCPS Project

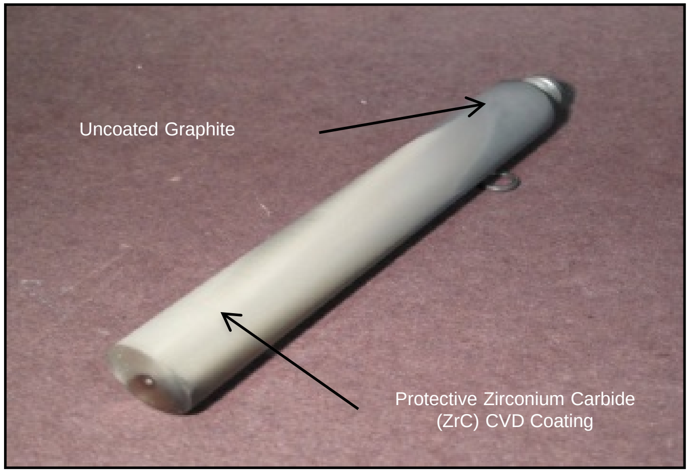
OAK RIDGE National Laboratory



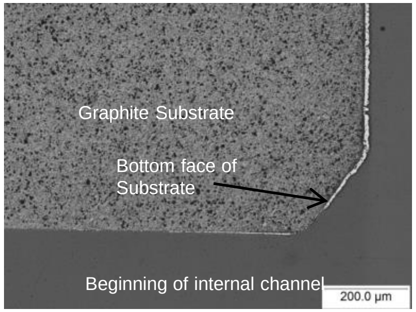
Above: 19 and 4-hole NERVA fuel element extrusion extrusion dies; Left: Graphite extruder with vent lines installed for DU capability



Above and Left: Extrusion samples using carbon-matrix/Ha blend 0.75” across flats, 0.125” coolant channels



Above: Test Piece highlighting ZrC Coating
Right: Coating primarily on external surface



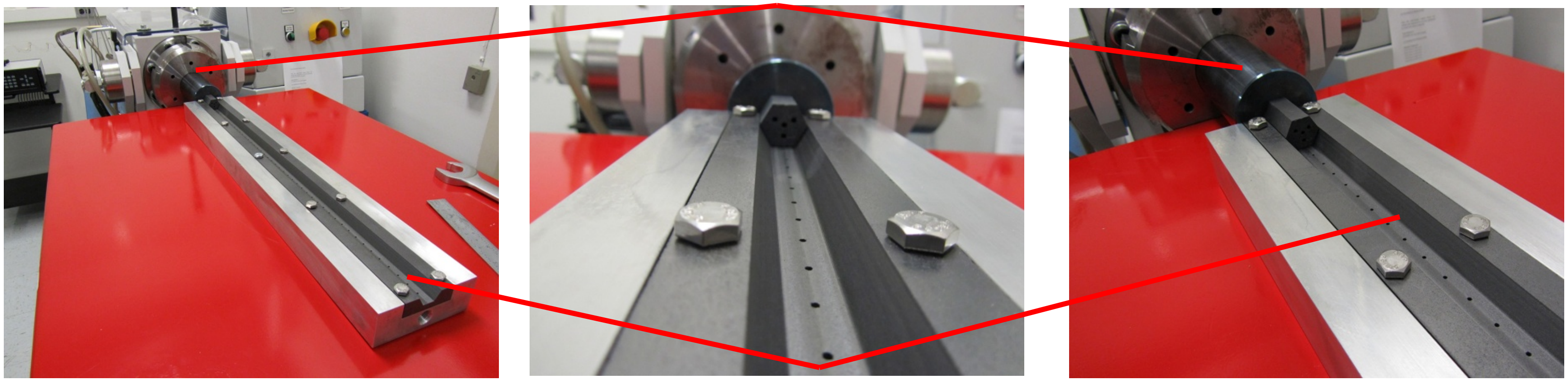
Right: Layoff base / Graphite insert

NERVA Graphite - Composite Fuel Elements with Protective ZrC Coating are Being Produced Now at ORNL for NCPS Project

OAK RIDGE National Laboratory

- Fuel Fabrication
  - Layoff base/graphite insert has been fabricated and installed.
  - New feed materials (graphite, resin, and ZrC) have been ordered.
  - A new 19-hole extrusion die has been designed and fabricated.
  - Modifications have been made to the 4-hole hexagonal die design to reduce friction during extrusion.
  - 4-hole fuel elements will be used first to establish ZrC coating specs, then will transition to prototypic NERVA-type 19-hole element.
  - Elements with depleted uranium (DU) will undergo rf-heating tests first before enriched uranium elements are tested in DOE reactor.

Extruder



Layoff Table

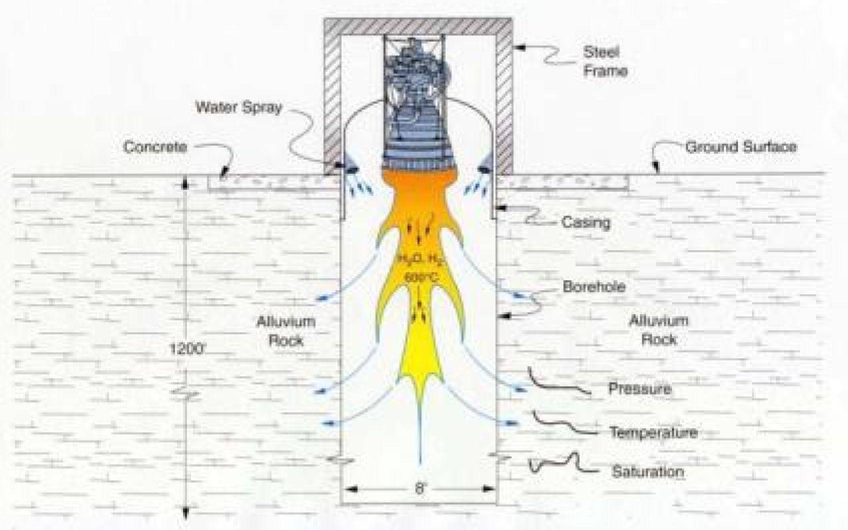
Maximize Use of NTS, DAF and Existing Bore Holes / Tunnels

- Testing should be conducted at the Nevada Test Site (NTS) using SAFE (Subsurface Active Filtration of Exhaust) approach in existing boreholes or tunnels.
- NTS provides a large secure, safety zone for conducting NTR testing.
- The Device Assembly Facility (DAF) is located within the NTS 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 within the NTS.
- 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 exist at NTS/NNSS to test in vertical boreholes or in tunnels.

Aerial View of the DAF at the Nevada Test Site

Non-Nuclear Subscale SAFE Bore Hole Feasibility Test

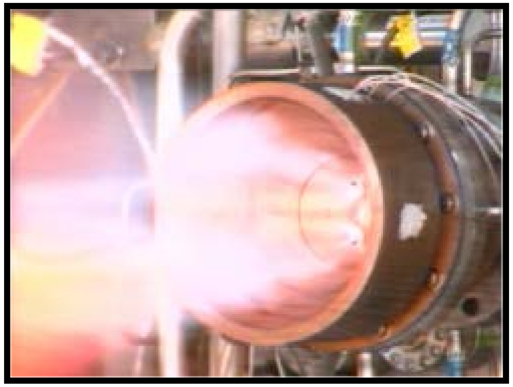
Source: Dr. Steve Howe, CSNR



Schematic at left shows the idealized configuration of the testing concept including the mounting pad, containment, water spray, and dispersion profiles

- Driving the hydrogen exhaust into the alluvium soil at the NTS allows capture of gases in a geology proven to contain heavy elements
- Fission products (if any) exhausted into the hole will be trapped into the soil strata at low concentrations ~10^{-9} gms/cm^3
- Use of the bore hole as an "in-situ" exhaust scrubber system potentially offers a low cost testing option for NTR
- Potential option is to have a suitably sized subscale validation test performed in the Phase II NTP project for ~2 – 2.5 M$
- Component inventory and cost breakdown for subscale test being reevaluated by GRC and DOE/NSTech to identify potential savings

SAFE: Subsurface Active Filtration of Exhaust

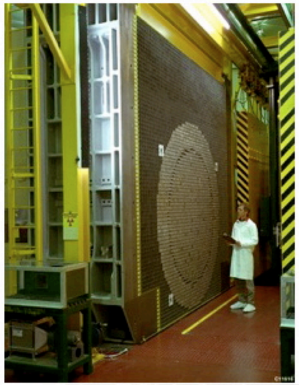


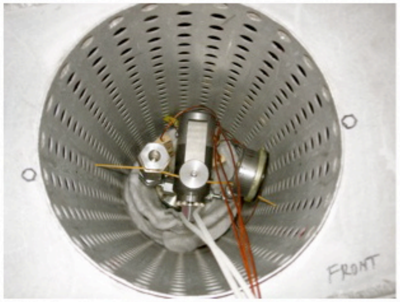
Aerojet-Rocketdyne's ~2.1-klbf "fuel rich" H/O engine is an attractive option for non-nuclear, subscale validation testing

Trailers Configured for Controls and Measurements Readily Moved to Other Test Areas

Other Nuclear Tests

- Cold Critical Experiments
  - Confirmation of critical configuration
  - Excess Reactivity
  - Static physics/safety parameters
- Hot Critical Experiments
  - Kinetics parameters
  - Safety coefficients (feedback)
- Gamma/Neutron Exposures
  - Irradiations to establish tolerance

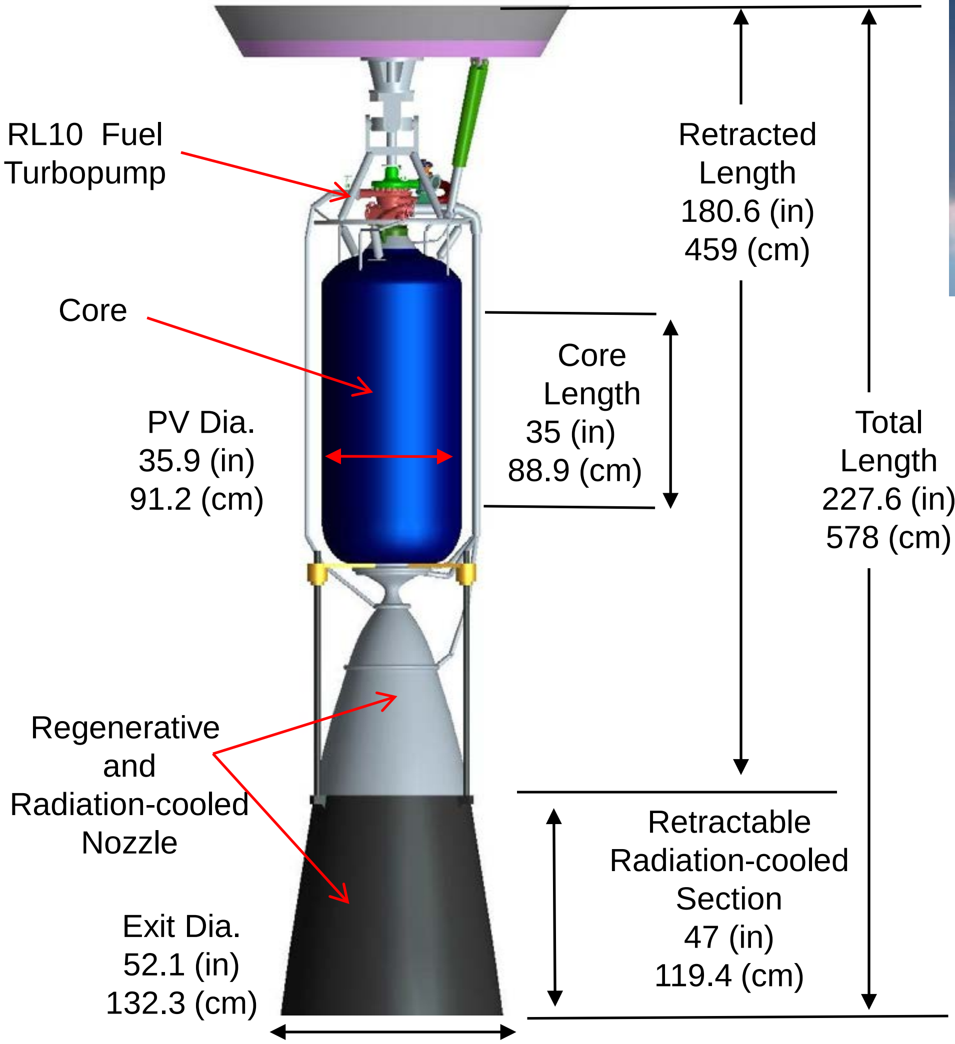




“Propelling Us to New Worlds”

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

- IMLEO ~11.72 t
- F ~7.52 klb$_f$, I_{sp} ~894 s
- LH_2 mass ~4.70 t
- Stage dry mass ~6.77 t
- Burn time ~18.9 mins


RL10 Fuel Turbopump

Core

PV Dia.
35.9 (in)
91.2 (cm)

Regenerative and Radiation-cooled Nozzle

Exit Dia.
52.1 (in)
132.3 (cm)

Retracted Length
180.6 (in)
459 (cm)

Core Length
35 (in)
88.9 (cm)

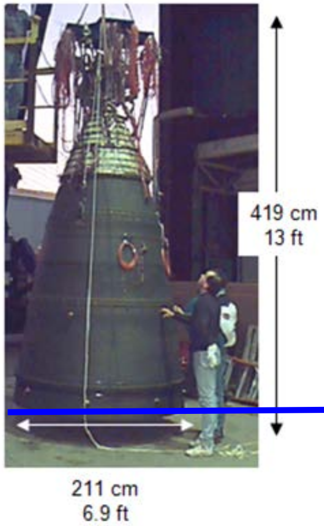
Total Length
227.6 (in)
578 (cm)

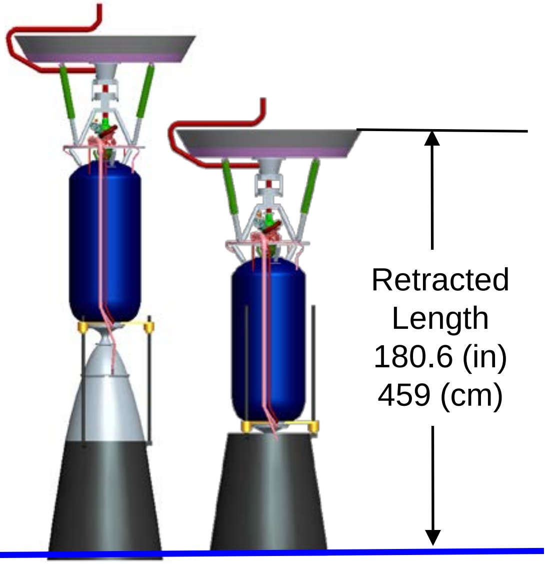
Retractable Radiation-cooled Section
47 (in)
119.4 (cm)


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


DCSS delivers SNTPS to LEO

LO2/LH2
RL10B-2
Tvac 24,750-lbf




Retracted Length
180.6 (in)
459 (cm)

2025 Small NTPS FTD Mission: “Single-Burn Lunar Flyby”

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


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


Lunar Gravity Assist sends SNTPS into Deep Space

- IMLEO ~11.72 t
- F ~7.52 klb_f, I_{sp} ~894s, F/W_{eng} ~1.91
- LH_2 mass ~4.70 t
- Stage dry mass ~6.77 t
- PL ~0.25 t
- Burn time ~18.9 mins

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.

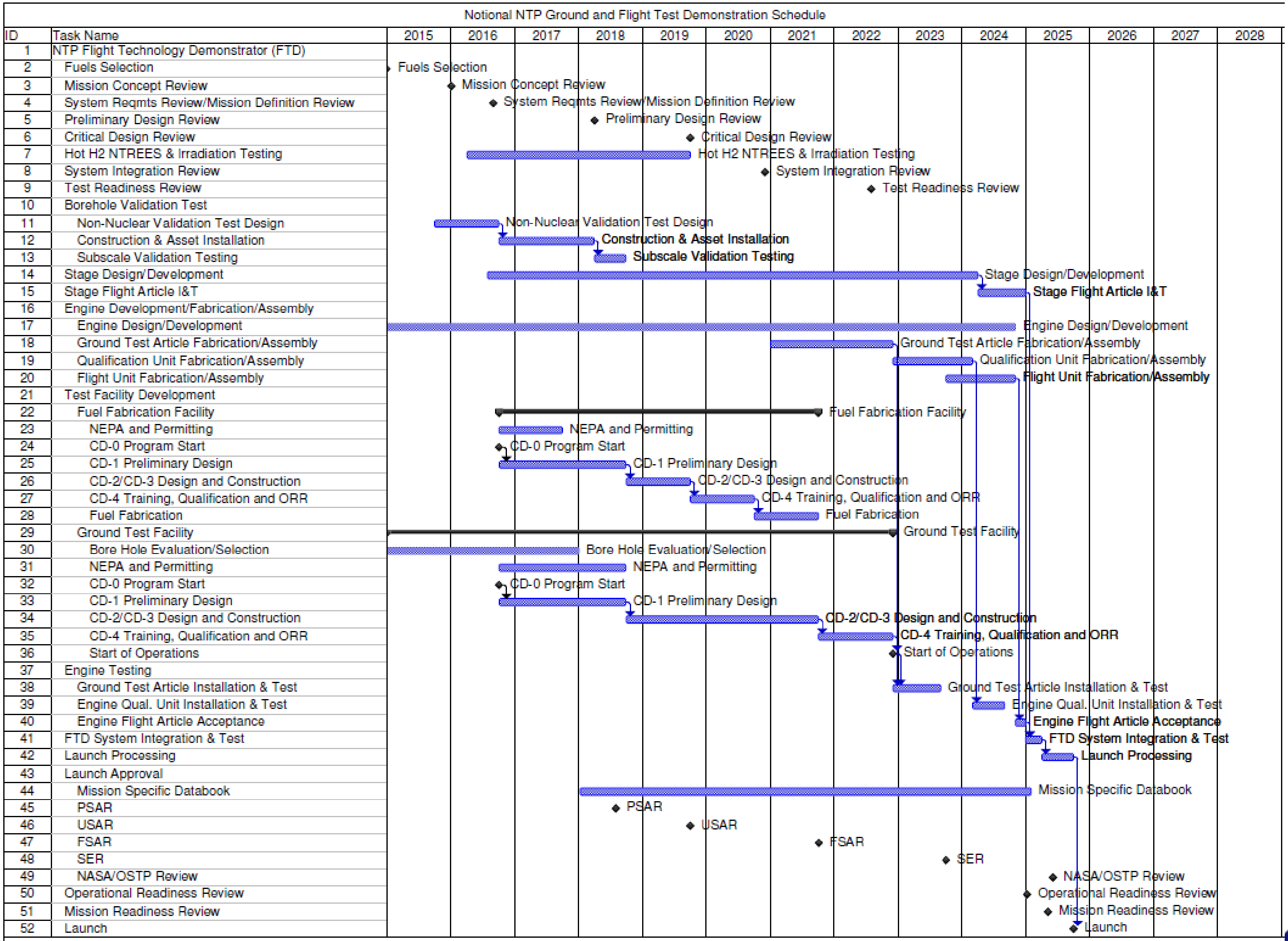
- By necessity it would be a success-oriented high–risk activity requiring immediate and serious financial commitments to the following areas:
  - Management and acquisition approach is streamlined
  - Composite fuel is the baseline and fuel element (FE) production levels are scaled up prior to complete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

- A single co-located nuclear "skunk works" type temporary facility is sited at the NTS near the site of the candidate borehole / tunnel. Its function would be reactor assembly, criticality testing, disassembly and PIE. Required equipment would be procured as "turn-key" for placement in the temporary facility. A single hot cell module (similar to that used by the UK at their Sellafield hot cell facility) would be used to disassemble and inspect the reactor and fuel elements after operation. After inspection, smaller groupings of parts could 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

"Propelling Us to New Worlds"

Notional NTP Ground & Flight Test Demonstration Milestone 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	Bore Hole 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	USAR
47	FSAR
48	SER
49	NASA/OSTP Review
50	Operational Readiness Review
51	Mission Readiness Review
52	Launch

NPR 7120.8 WBS for NASA Research and Technology Development Program utilized

Summary and Conclusions

- NASA, NE-75, ORNL, INL, NNSA and industry (NSTech, Aerojet Rocketdyne) are working together on formulating a strategy leading to the development of a small GTD (~7.5 – 16.5 klb_f) NTR engine in the early 2020's followed by a FTD mission using a small NTP stage (SNTPS) around 2025

- 10-years to a ground tested "qualification engine" by 2024 will require immediate, serious 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 NTS using existing bore holes and/or tunnels; should maximize the use of existing facilities and consider temporary new facilities as required; new nuclear infra-structure is a long lead item – *DOE*

- If graphite-based fuel and borehole testing are not used, years of additional schedule and significant additional dollars will be required – *DOE*

- The FTD mission proposed by GRC is a single-burn "lunar flyby" mission to keep it simple and more affordable; small size engine and stage can also reduce development costs & allowing utilization of existing, flight proven engine hardware (e.g., hydrogen pumps and nozzles) – *Aerojet Rocketdyne*

If NASA wants to go somewhere soon they need to get moving now - DOE