



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

EXPL-01 Advanced Propulsion for Exploration

**S. K. Borowski and R. J. Sefcik (NASA GRC)
A. L. Qualls and B. G. Schnitzler (ORNL)
C. R. Joyner (Aerojet Rocketdyne)
216-977-7091, Stanley.K.Borowski@nasa.gov**

presented at the

**AIAA Space & Astronautics Forum & Exposition (*Space 2014*)
San Diego, CA**

Tuesday, August 5, 2014

Glenn Research Center

at Lewis Field





Contributors

W.M. Marshall¹, T.J. Parkey¹, M. G. Houts², J. W. Warren³, J. E. Fittje⁴, D. R. McCurdy⁴
A.L. Qualls⁵, B. G. Schnitzler⁵, A. D. Belvin⁶, S. D Howe⁷ and C. R. Joyner⁸

¹NASA Glenn Research Center, Cleveland, OH 44135

²NASA Marshall Space Flight Center, MSFC, AL 35812

³NASA Headquarters, Washington, DC 20546

⁴Vantage Partners, LLC at Glenn Research Center, Brook Park, OH 44142

⁵Oak Ridge National Laboratory, Oak Ridge, TN 37831

⁶US Department of Energy, Washington, DC 20585

⁷Center for Space Nuclear Research, Idaho National Laboratory, Idaho Falls, ID 83402

⁸Aerojet Rocketdyne, West Palm Beach, FL 33410

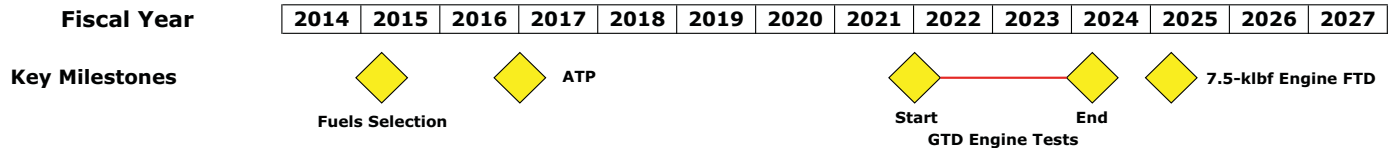




Formulation of Affordable and Sustainable NTP Development Strategy is Underway Involving NASA, DOE and Industry

- 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 smaller, lower thrust (~7.5 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, DOE (NE-75, ORNL, INL) and industry (Aerojet Rocketdyne) are working together on formulating a strategy leading to the development of a small GTD (~7.5 klb_f) 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 proposed by DOE/NE-75 provides a strawman for continued refinement allowing an informed cost estimate to be made

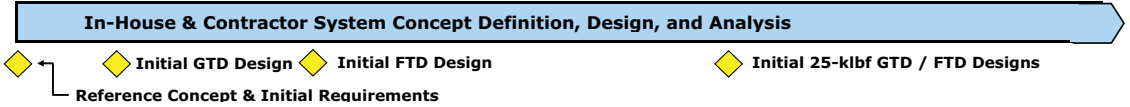




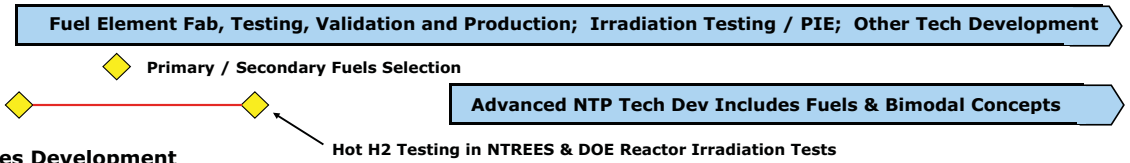
Foundational Technology Development

Notional

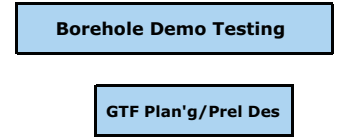
System Concepts & Requirements Definition / Planning / Engine Modeling & Analysis



NTP Technology Development and Demonstrations



NTP Test Facilities Development



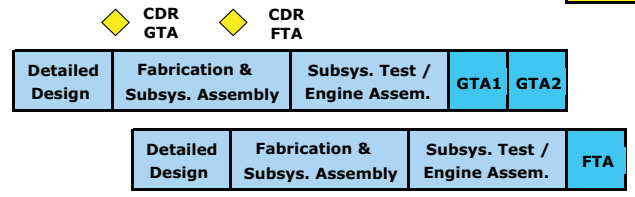
- Potential Demos / Mars Flights**
- 2029-30 - Lunar/EM-L2 Flights
 - 2031-33 - Mars Cargo Flights
 - 2033-35 - Mars Crewed Flight!

Ground & Flight Technology Demonstrators

Ground Test Facility (GTF)



Test Articles for Ground & Flight



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



Fiscal Year

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

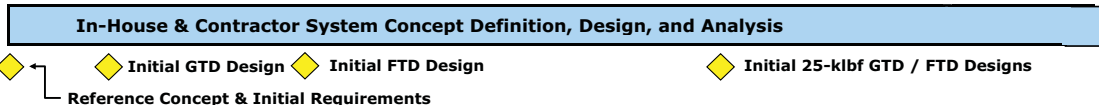
Key Milestones



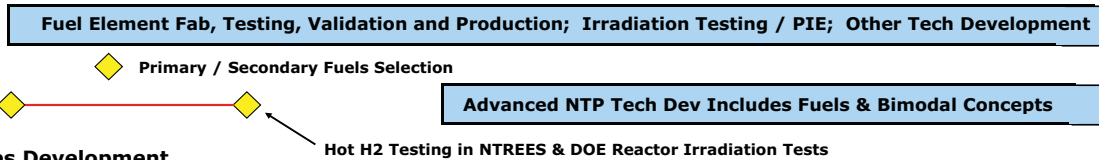
Notional

Foundational Technology Development

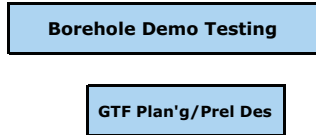
System Concepts & Requirements Definition / Planning / Engine Modeling & Analysis



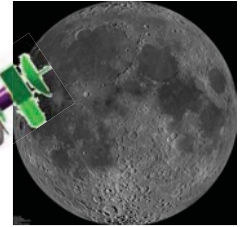
NTP Technology Development and Demonstrations



NTP Test Facilities Development



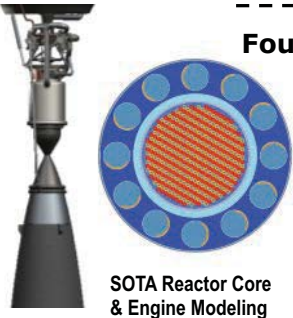
Potential Demos / Mars Flights
 2029-30 - Lunar/EM-L2 Flights
 2031-33 - Mars Cargo Flights
 2033-35 - Mars Crewed Flight!



Small NTP Stage for Lunar Flyby Mission



Fuel Element Irradiation Testing in ATR at INL



SOTA Reactor Core & Engine Modeling



NERVA "Composite" Fuel



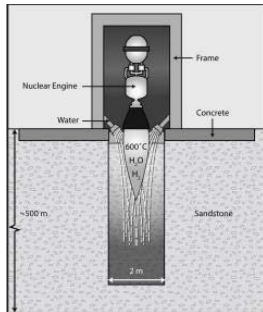
"Cermet" Fuel



"Fuel-Rich" Engine

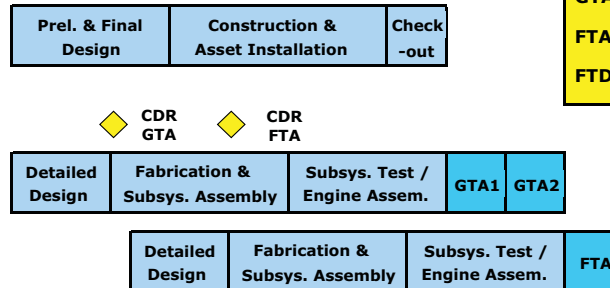
Ground & Flight Technology Demonstrators

Ground Test Facility (GTF)



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

Test Articles for Ground & Flight



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 (NTRRES)

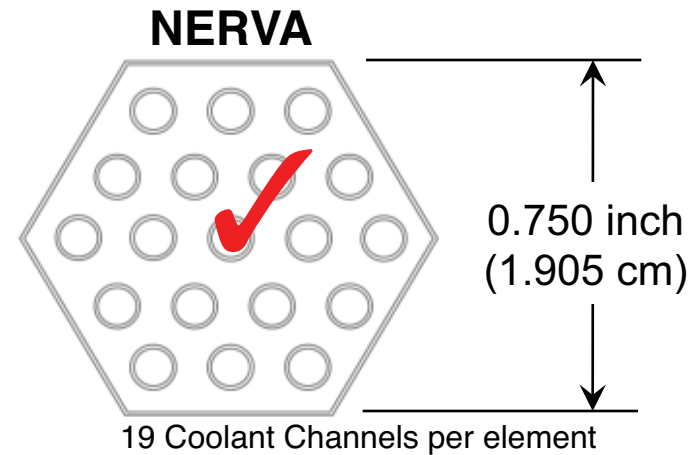
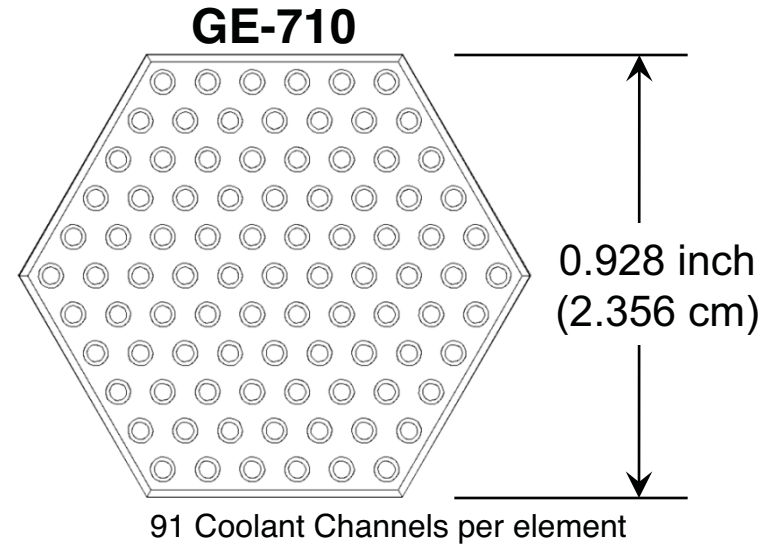
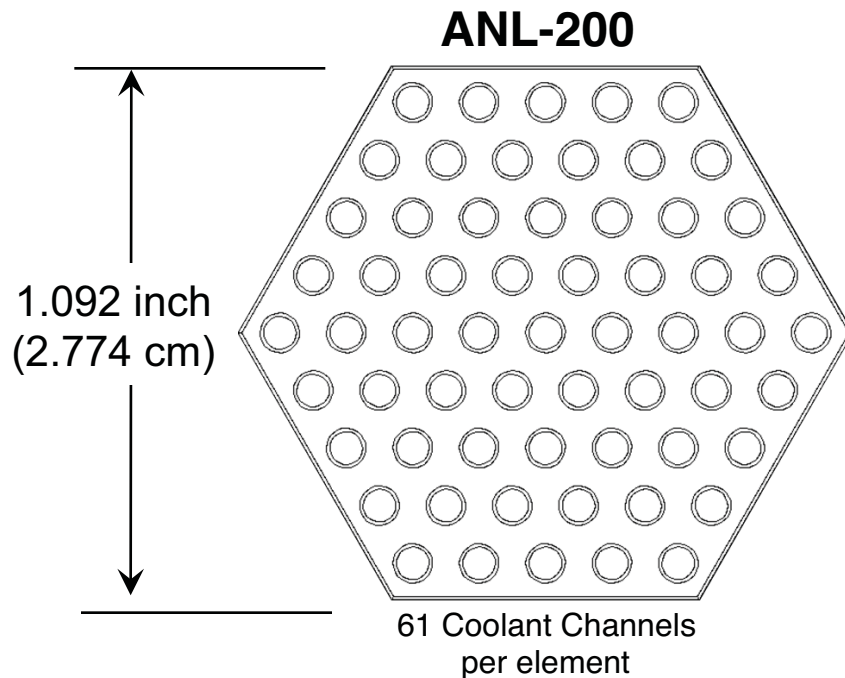
Glenn Research Center

at Lewis Field





“Heritage” Fuel Element Size Comparisons (Shown to Relative Scale)



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



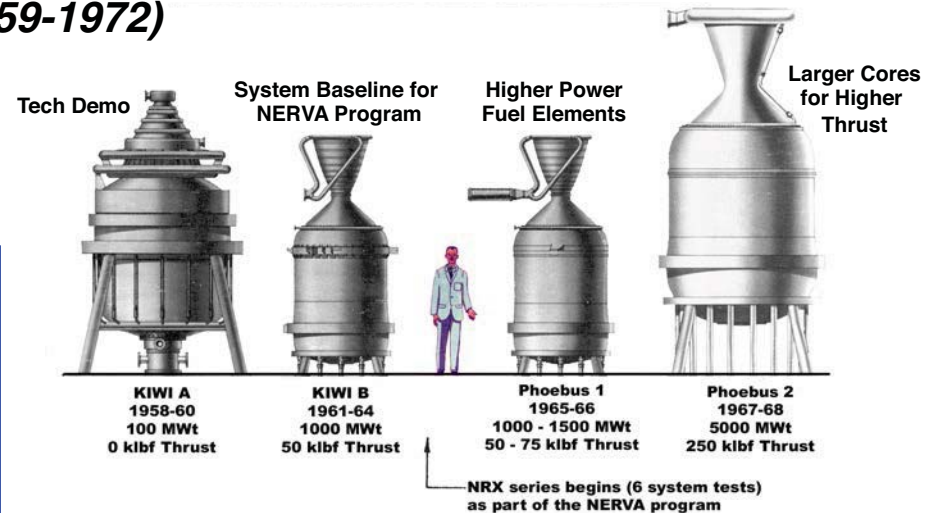
"Propelling Us to New Worlds"

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
- H₂ 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



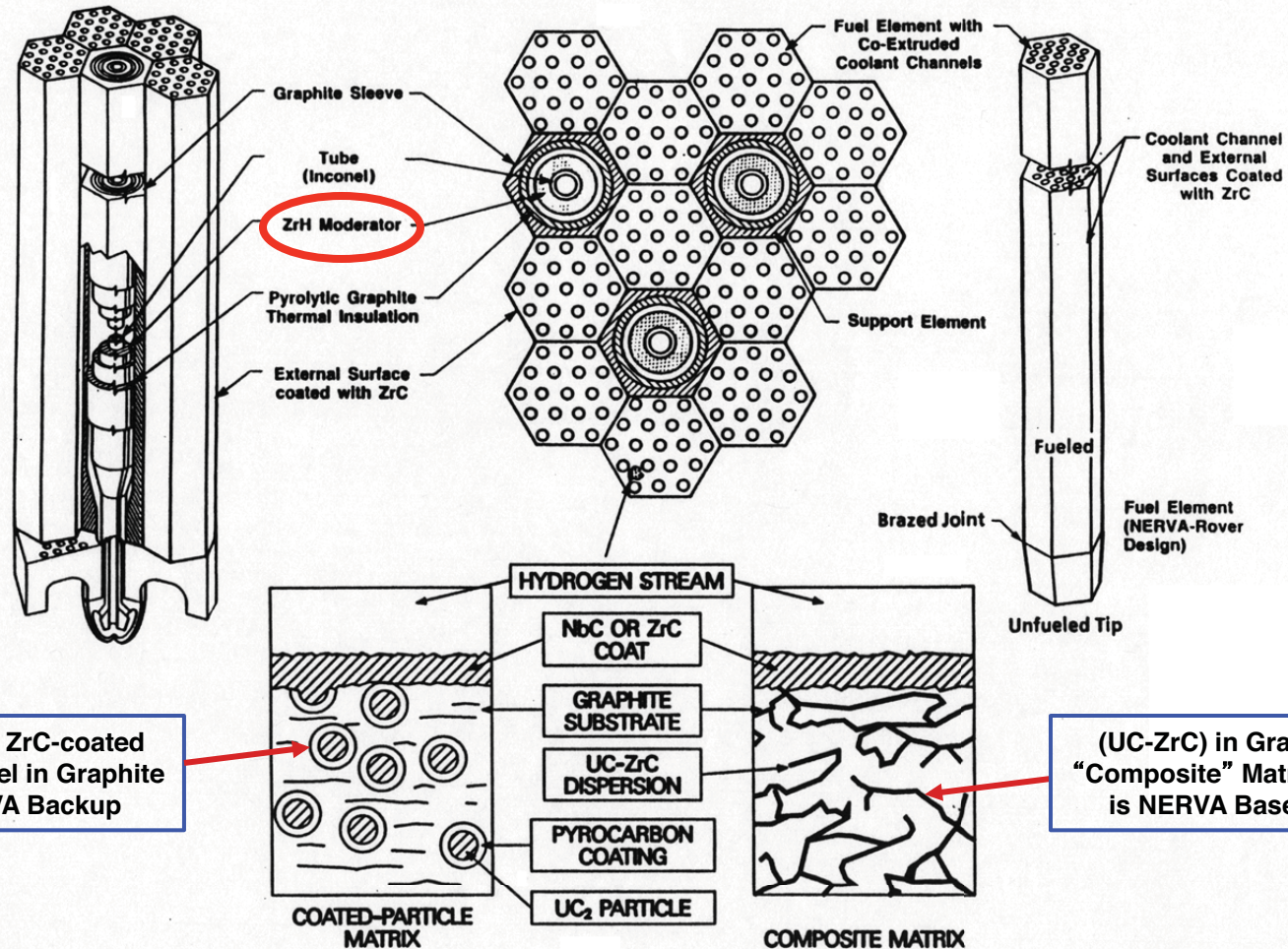
The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

Glenn Research Center

at Lewis Field



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

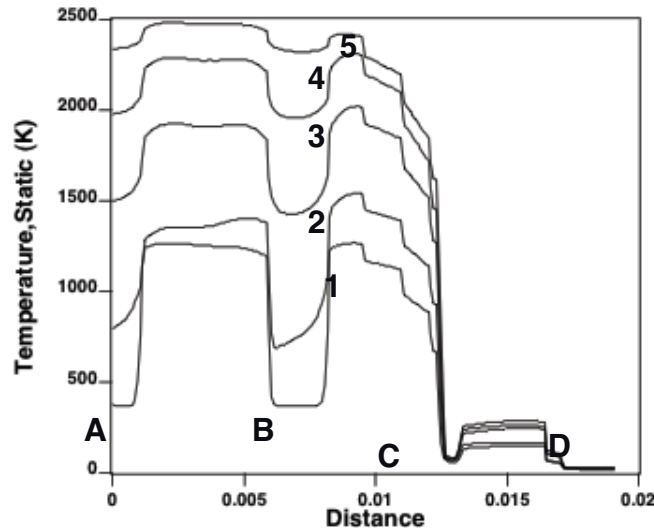




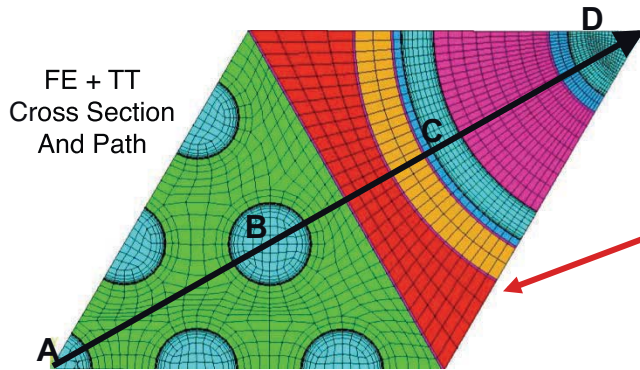
"Propelling Us to New Worlds"

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

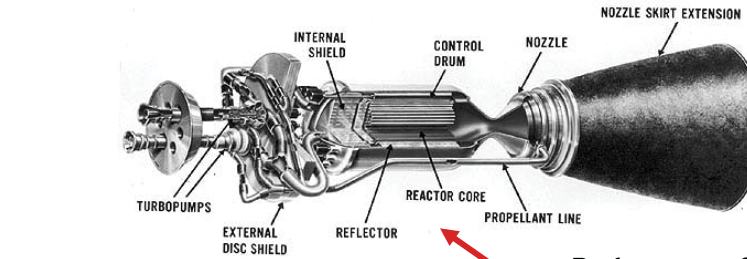
Temperature Distribution Across FE and TT



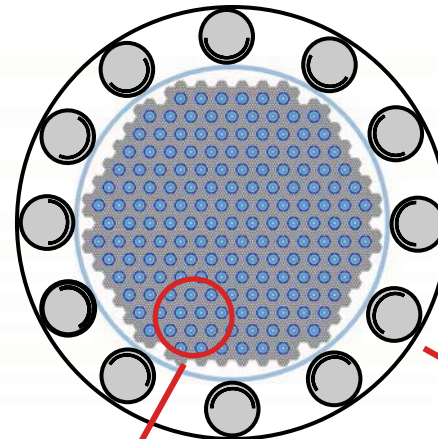
Temperature Distributions at Five Axial Stations (Numbers Indicate Cold to Hot End Stations)



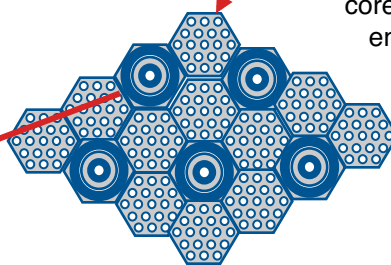
ANSYS Model



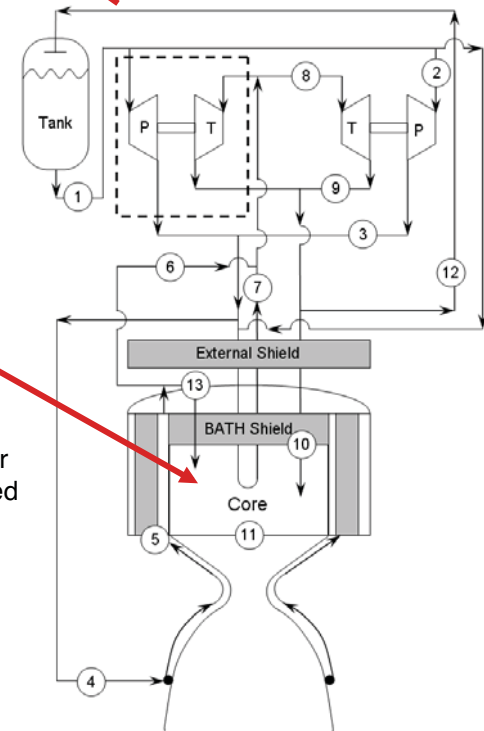
Performance, Size & Mass estimation



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



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

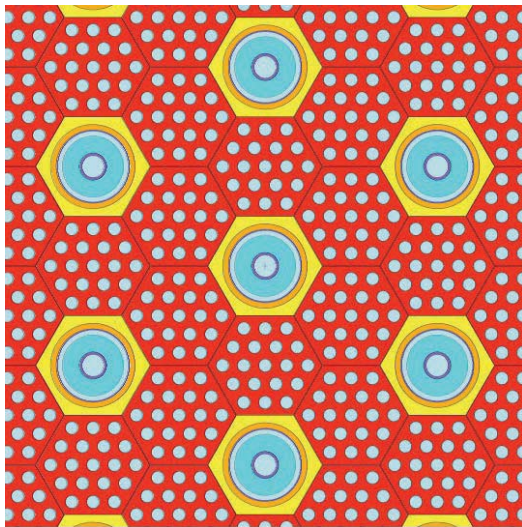


Nuclear Engine System Simulation (NESS) code has been upgraded to use MCNP-generated data



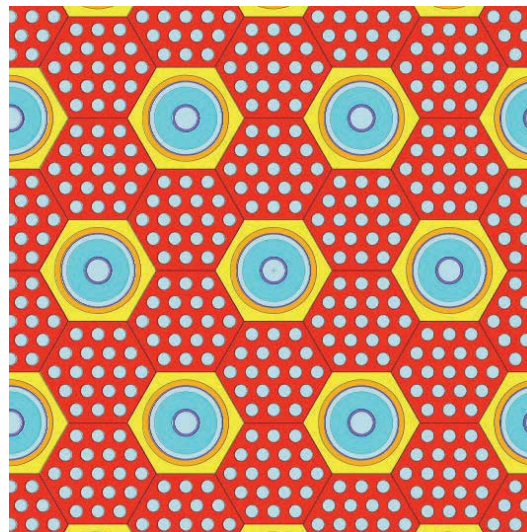
Fuel Element (FE) – Tie Tube (TT) Arrangements for NERVA-derived NTR Engines

“Sparse” FE – TT Pattern used
for Large Engines



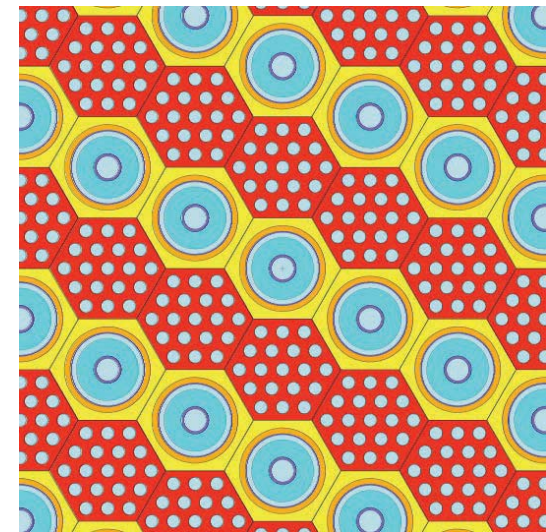
Each FE has 4 adjacent FEs and
2 adjacent TTs with a FE to TT
ratio of ~3 to 1

“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

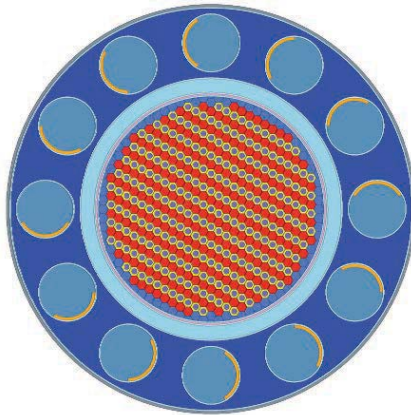
Ref: B. Schnitzler, et al., “Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design”, AIAA-2011-5846



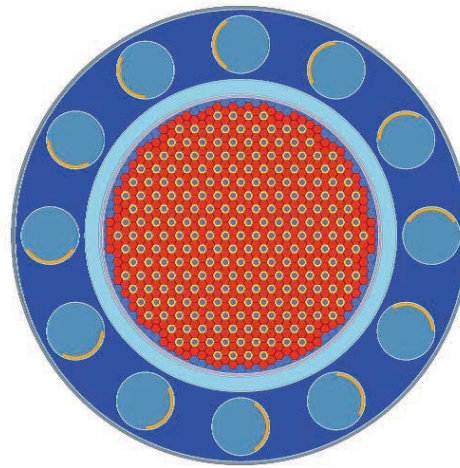
"Propelling Us to New Worlds"

Development of Common Scalable Fuel Elements for Development & Testing

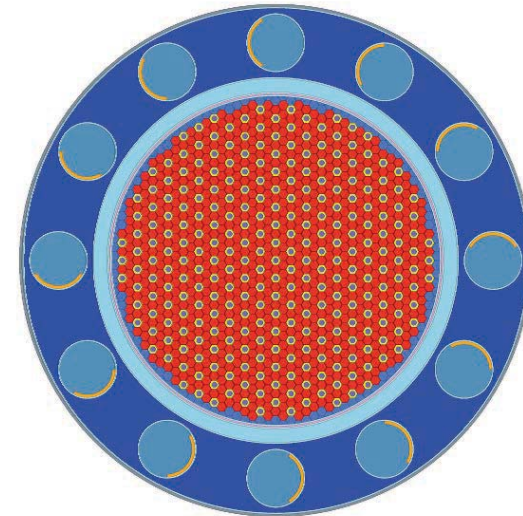
- During the Rover program, a common fuel element / tie tube design was developed and used in the design of the 50 klbf Kiwi-B4E (1964), 75 klbf Phoebus-1B (1967), 250 klbf Phoebus-2A (June 1968), then back down to the 25 klbf Pewee engine (Nov-Dec 1968)
- NASA and DOE are evaluating a similar approach: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



7.4-klbf_f low thrust engine



16.4-klbf_f SNRE

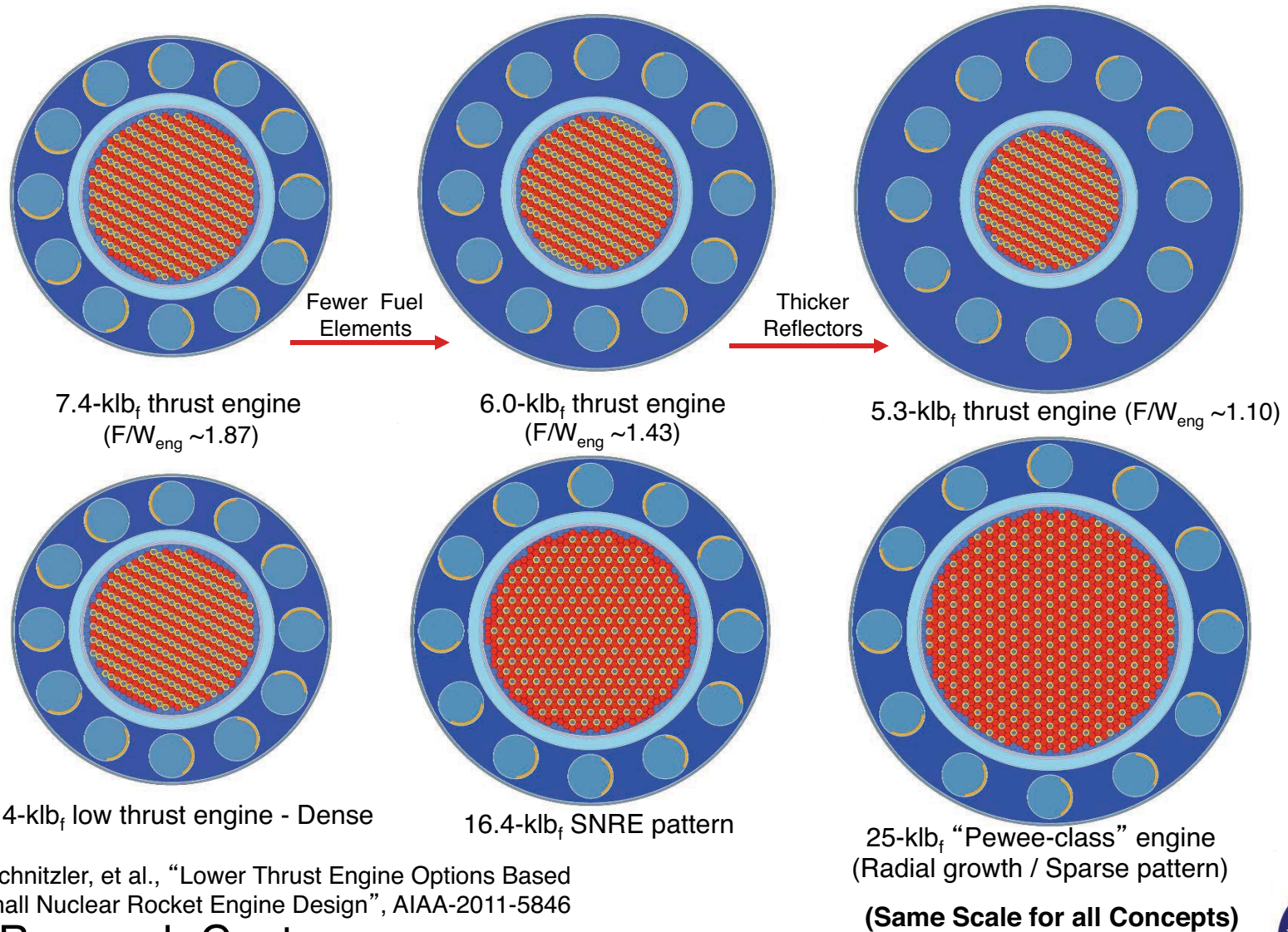


25-klbf_f "Pewee-class" engine
(Radial growth option / sparse pattern)

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



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



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



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

Performance Characteristic	7,420-lbf	SNRE	Axial Growth Option		Radial Growth Option	
	Option	Baseline	Nominal	Enhanced	Nominal	Enhanced
Engine System						
Thrust (klb _f)	7.42	16.4	25.1	25.1	25.1	25.1
Chamber Inlet Temperature (K)	2736	2695	2790	2940	2731	2807
Chamber Pressure (psia)	1000	450	1000	1000	1000	1000
Nozzle Expansion Ratio(NAR)	300:1	100:1	300:1	300:1	300:1	300:1
Specific Impulse (s)	894	875	906	941	894	913
Engine Thrust-to-Weight	1.87	2.92	3.50	3.50	3.60	3.60
Reactor						
Active Fuel Length (cm)	89.0	89.0	132.0	132.0	89.0	89.0
Effective Core Radius (cm)	14.7	29.5	29.5	29.5	35.2	35.2
Engine Radius (cm)	43.9	49.3	49.3	49.3	55.0	55.0
Element Fuel/Tie Tube Pattern Type	Dense	SNRE	SNRE	SNRE	Sparse	Sparse
Number of Fuel Elements	260	564	564	564	864	864
Number of Tie Tube Elements	251	241	241	241	283	283
Fuel Fissile Loading (g U per cm ³)	0.60	0.60	0.25	0.25	0.45	0.45
Maximum Enrichment (wt% U-235)	93	93	93	93	93	93
Maximum Fuel Temperature (K)	2860	2860	2860	3010	2860	2930
Margin to Fuel Melt (K)	40	40	190	40	110	40
U-235 Mass (kg)	27.5	59.6	36.8	36.8	68.5	68.5

NOTE: Fuel Matrix Power Density: 3.437 MW_t / liter

SOTA "Pewee-class" Engine Parameters

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



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

Fuel Specimens

- Fabrication and characterization
- High temperature testing including hot H₂ 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 H₂ 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 H₂ 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

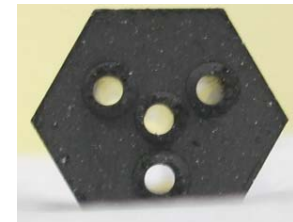




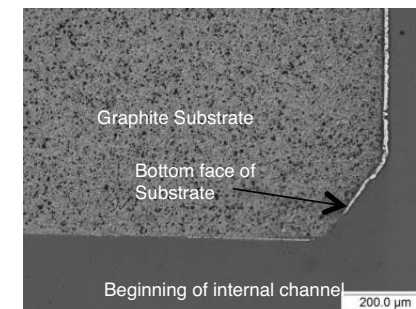
NERVA Graphite - Composite Fuel Elements with Protective ZrC Coating are Being Produced Now at ORNL for NCPS Project



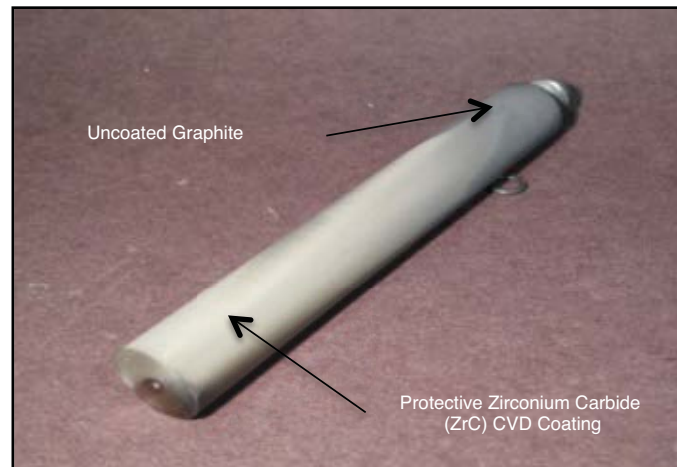
Above: 19 and 4-hole NERVA fuel element extrusion dies; Left: Graphite extruder with vent lines installed for DU capability



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



Right: Layoff base / Graphite insert



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

Glenn Research Center

at Lewis Field

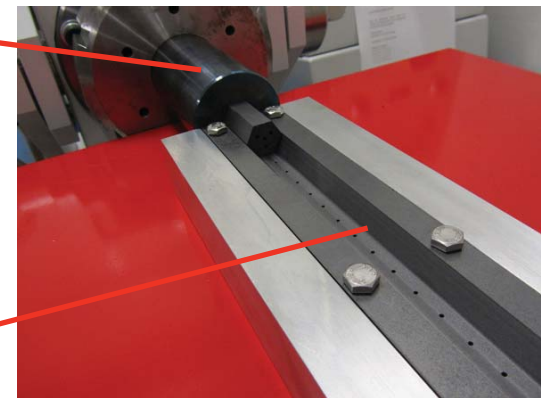
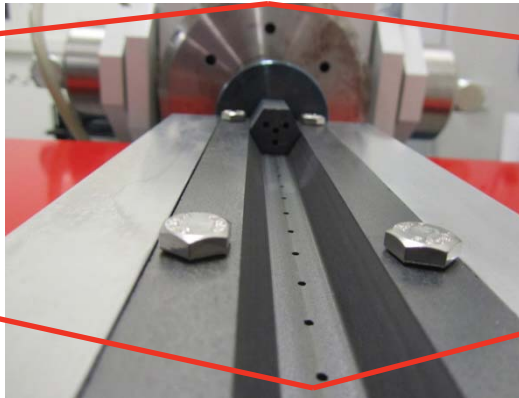


NERVA Graphite - Composite Fuel Elements with Protective ZrC Coating are Being Produced Now at ORNL for NCPS Project

❑ 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 for Testing

- Testing should be conducted at the Nevada Test Site (NTS) using SAFE (Subsurface Active Filtration of Exhaust) approach in existing Boreholes.
- 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 & “0-power” critical testing) of engine’s reactor system prior to transfer to borehole test location also within the NTS.
- DAF is a collection of more than 30 individual steel-reinforced concrete test cells connected by a large rectangular common corridor. Entire complex is covered by compacted earth and spans an area of ~100,000 ft².
- DAF has multiple assembly / test cells; also high bays with multi-ton crane capability. The assembly cells designed to handle weapons grade materials; *cells rated for handling up to ~60 kg of enriched U-235 which is twice the amount found in the small 7.42 klb_f NTRE.*



Aerial View of the DAF at the Nevada Test Site

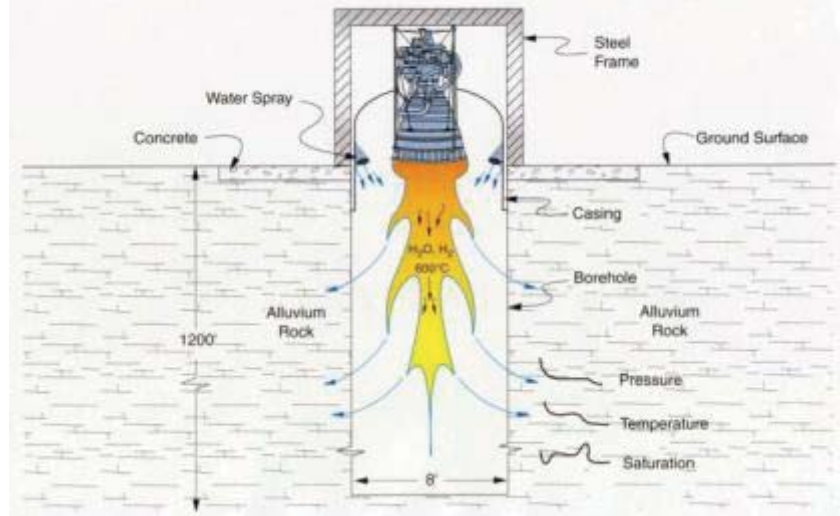




"Propelling Us to New Worlds"

Non-Nuclear Subscale SAFE Bore Hole Feasibility Test

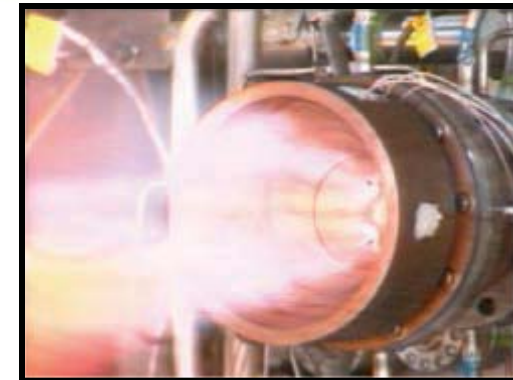
Source: Dr. Steve Howe, CSNR



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 $\sim 10^{-9}$ gms/cm³
- 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 NCPS effort for $\sim \$2M$
- Component inventory and cost breakdown for subscale test being reevaluated by GRC and DOE to identify potential savings



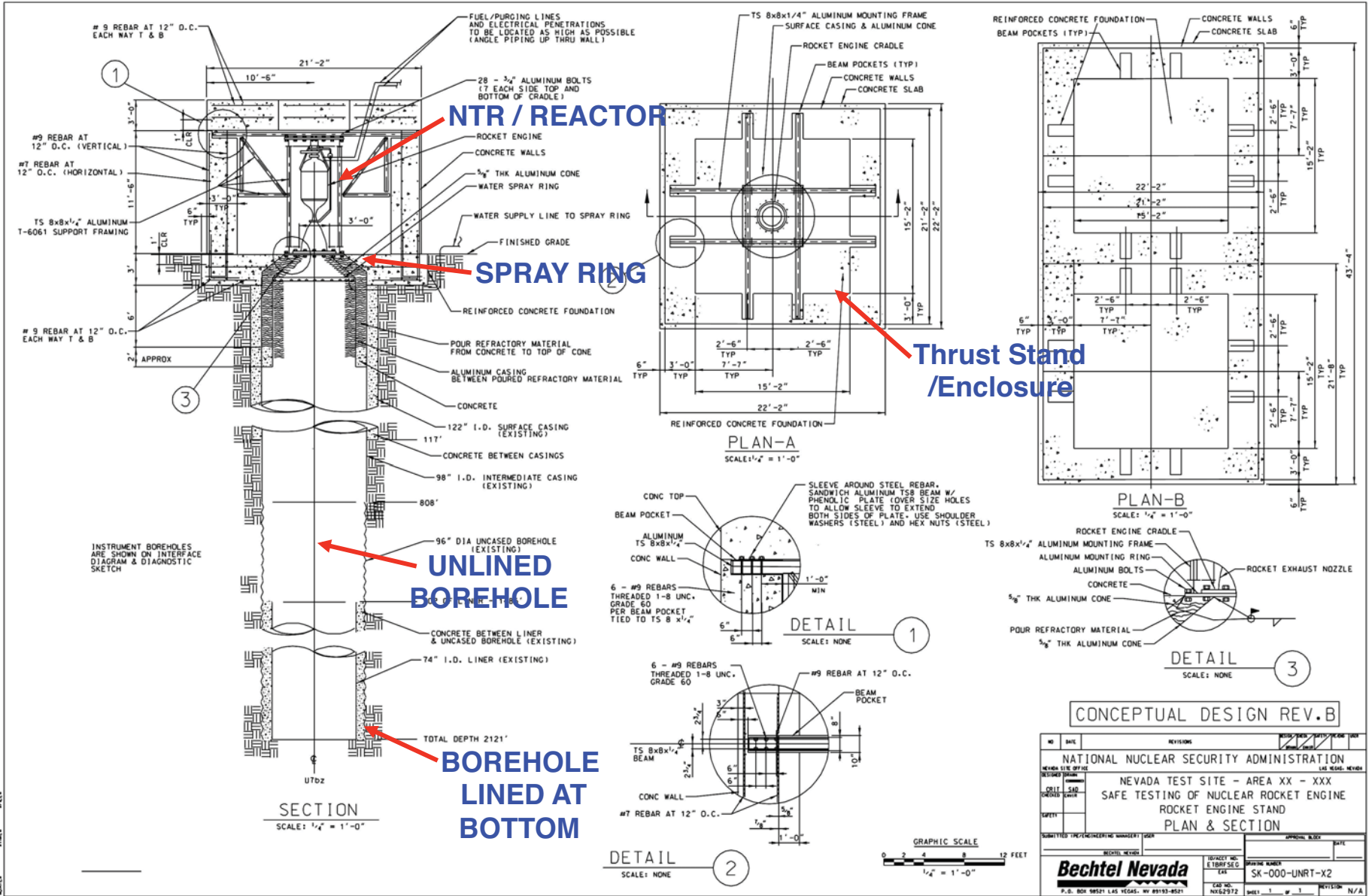
Aerojet-Rocketdyne's ~ 2.1 -klbf "fuel rich" H/O engine is an attractive option for non-nuclear, subscale validation testing

SAFE: Subsurface Active Filtration of Exhaust

Glenn Research Center

at Lewis Field





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

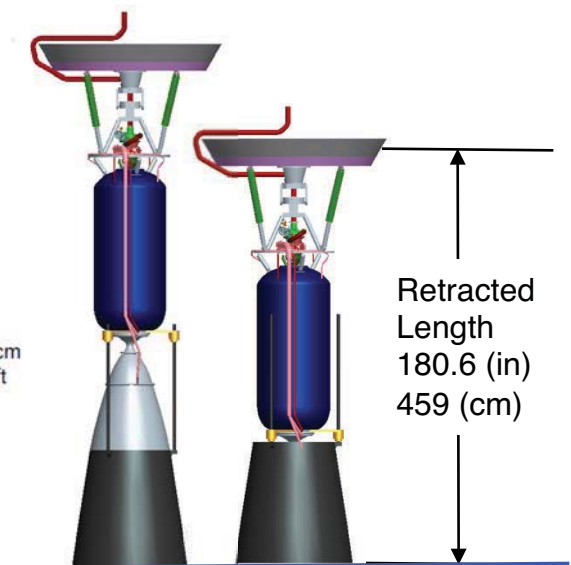
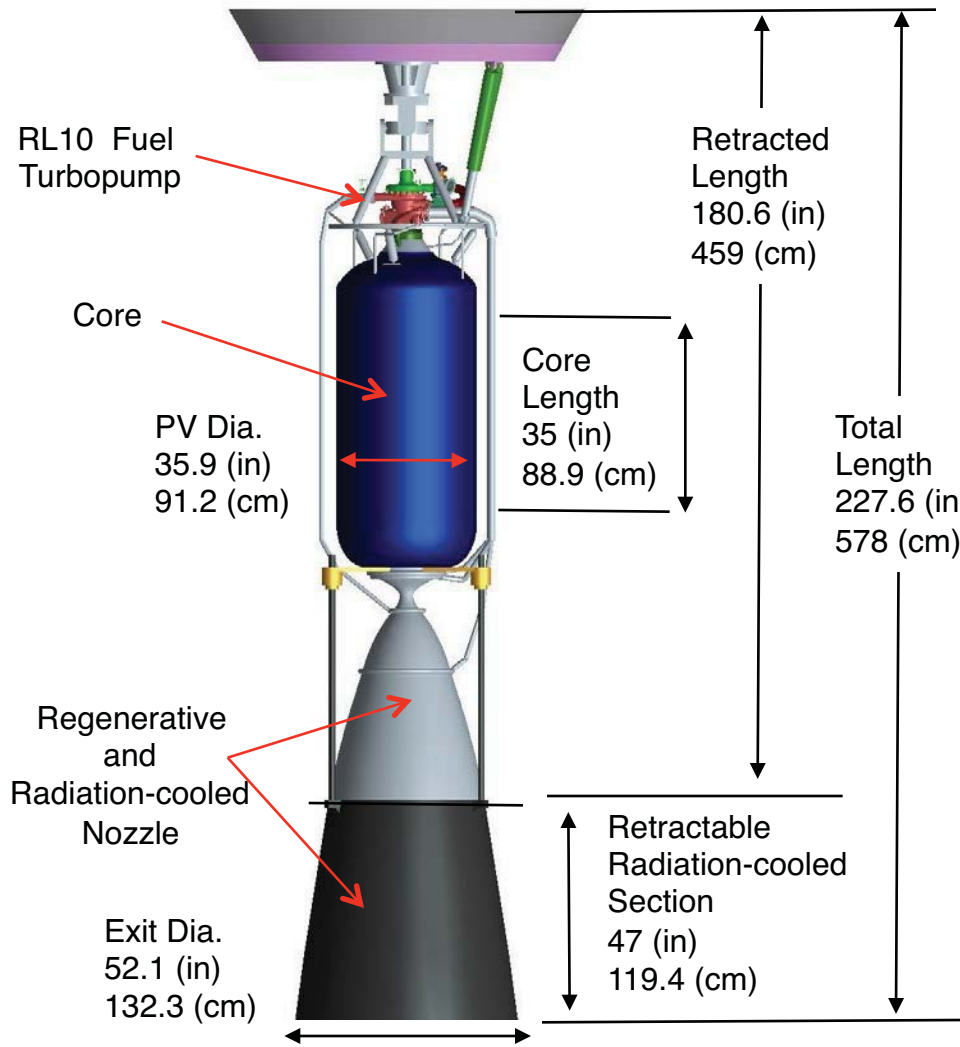




Small NERVA-derived 7.42 klb_f NTR Engine Layout and Dimensions



Aerojet Rocketdyne has been working with GRC to define a small, low thrust NTR scalable to higher thrust engines



Current Liquid Rocket and Stage Technologies are Leveraged to Create Affordable NTP Approach

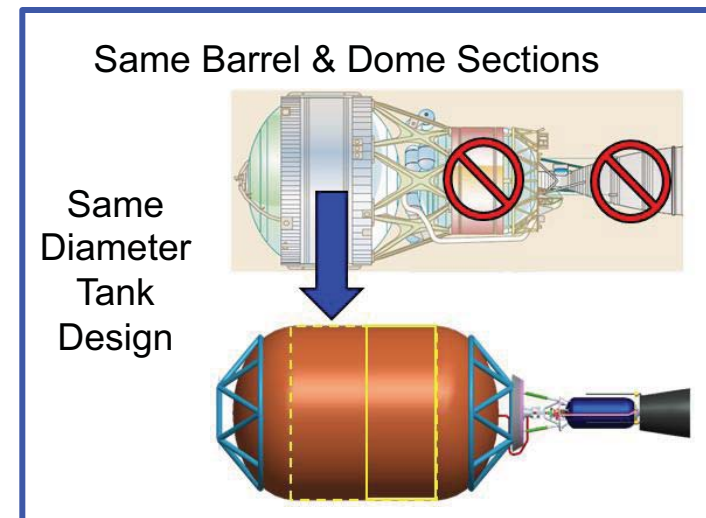
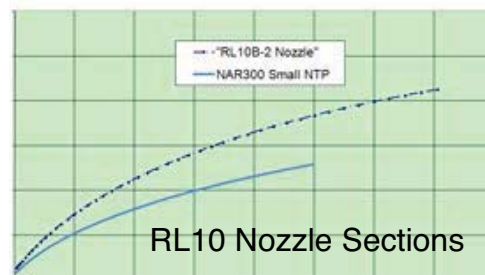
Aerojet Rocketdyne specific chemical liquid rocket engine hardware can be leveraged to reduce the time and cost to develop the small NTP Stage

- The small NTP engine turbo pumps, valves, and nozzles manufactured from same production lines as RL10 and J-2X
 - Small NTP uses RL10 fuel turbopump and nozzle is smaller than current RL10B-2 on Delta 4; could use LOX TP with gas supply to get to Lox-Augmentation of hot hydrogen exhaust
- NTP Stage uses hydrogen tank, avionics, valves from Delta 4 cryogenic stage



RL10 Hydrogen Turbo pump

J-2X Chamber Design





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



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

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



DCSS delivers SNTPS to LEO

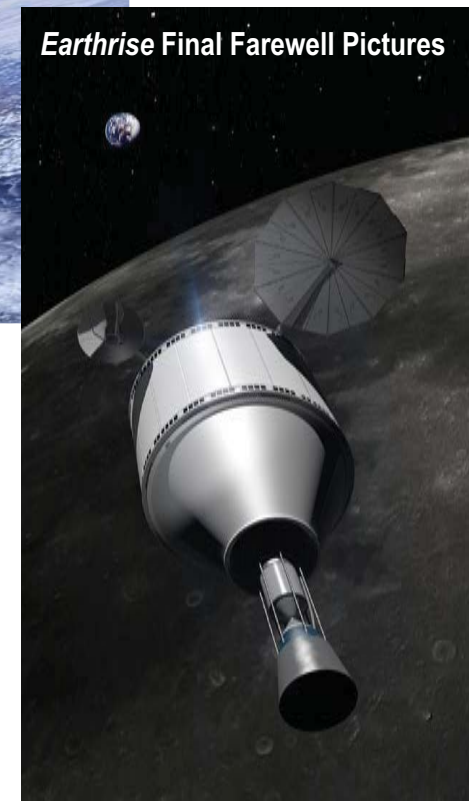


Single-Burn TLI sends SNTPS to the Moon

- IMLEO ~12.72 t
- $F \sim 7.42 \text{ klb}_f$, $I_{sp} \sim 900\text{s}$, $F/W_{eng} \sim 1.87$
- LH_2 mass ~5.07 t
- Stage dry mass ~7.40 t
- PL ~250 kg
- Burn time ~20.9 mins



Lunar Gravity Assist sends SNTPS into Deep Space



Earthrise Final Farewell Pictures



"Propelling Us to New Worlds"

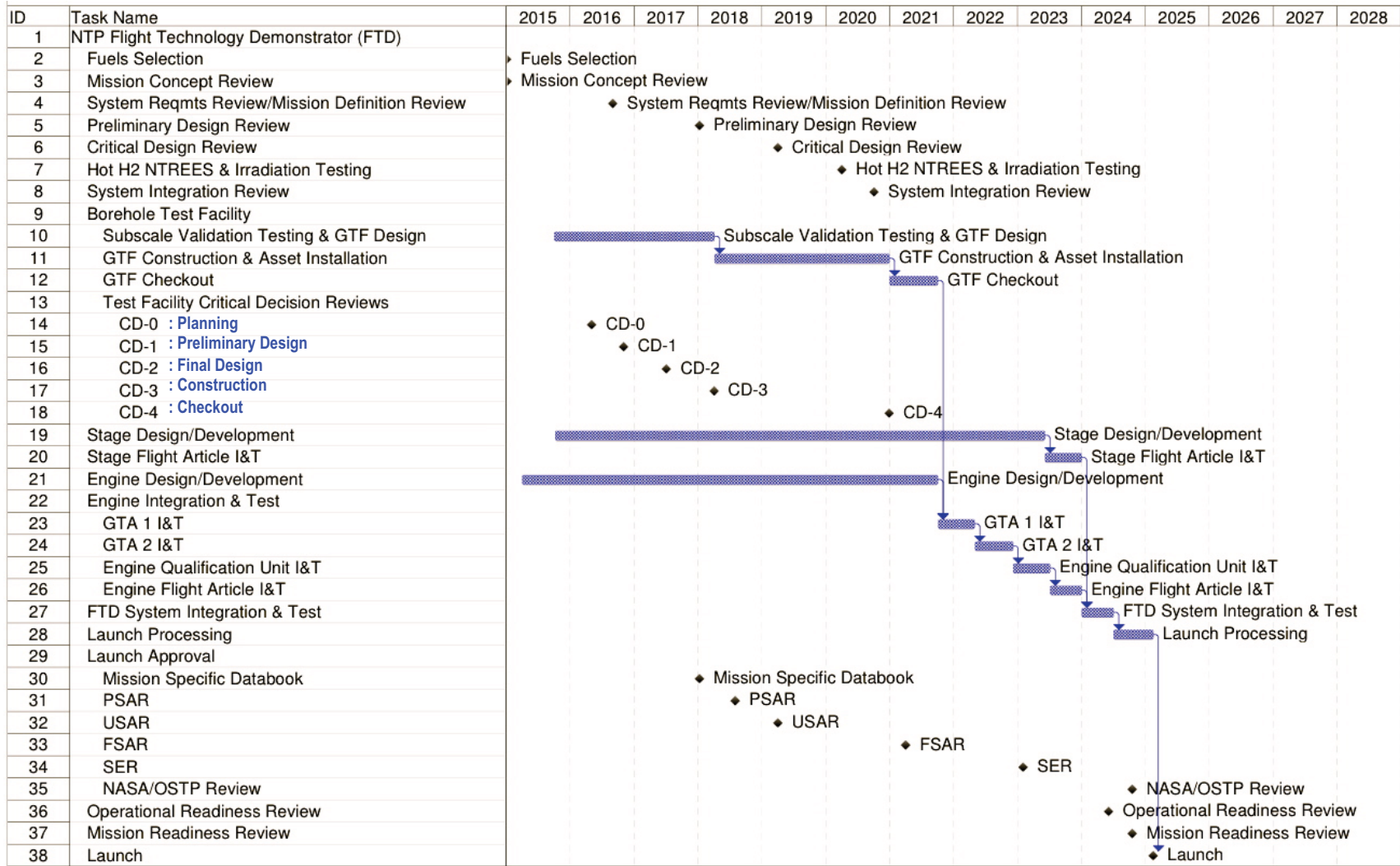
Assumptions for “Sporty” SNTPS GTD & FTD Mission Schedule

- 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 co-located nuclear “skunk works” type temporary facility is sited at the NTS near the site of the candidate bore holes. Its function would be reactor assembly, criticality testing, and subsequent disassembly. Required equipment would be procured as “turn-key” for placement in the building. 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 reactors after operation. After disassembly, small groupings of parts would be shipped off-site for final disposal in existing shipping casks.
- The GTD program would focus on borehole testing of three units:
 - 1) prototype reactor and engine (80% fidelity) in 2022
 - 2) engineering reactor and engine (90% fidelity) in 2023
 - 3) 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





Not Quite So Sporty Schedule

15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Control System Test Facilities
Component Safety Test Facilities
Training and Simulator Test Facilities



fuel development and testing
fuel and material Irradiation test facilities at existing reactor
HEU fuel fabrication facility in existing CAT 1 facility
fuel qualification



ground test facility assuming borehole testing w/o effluent system
reactor assembly facility
Remote Inspection/Post-Irradiation Examination Facilities



fuel element and bundle separate effects testing for qualification
reactor design
shield design and fabrication
stage integration



ground test unit
ground test
ground test unit
ground test
qualification unit
Flight unit



transportation assuming one new shipping cask



CAT 1 Flight Assembly and ATLO facility



Reviews and Approvals from NEPA and facility ORRs through INSRP



Glenn Research Center

launch

at Lewis Field





"Propelling Us to New Worlds"



Summary and Conclusions

- NASA, DOE (NE-75, ORNL, INL) and industry (Aerojet Rocketdyne) are working together on formulating a strategy leading to the development of a small GTD (~7.5 klb_f) 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 infrastructure 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 you want to go somewhere soon you need to get moving now - DOE

Glenn Research Center

at Lewis Field

