"Propelling Us to New Worlds"

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

**(AIAA-2015-3774)**

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# Overview of NTP Development Activities by NASA and DOE

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- 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
- At the direction of NASA HQ (3/25/15), NASA and DOE are to work together to formulate a detailed development plan and schedule allowing the affordable development of a small (~7.5 – 16.5 $klb_f$) GC engine for possible flight technology demonstration (FTD) mission within a 10-year timeframe

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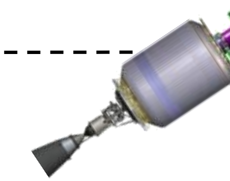
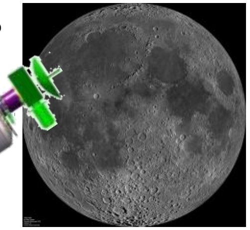
**Notional**

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

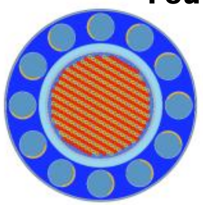
**Key Milestones**
- Fuels Selection
- ATP
- GTD Engine Tests: Start – End
- 7.5-klbf Engine FTD





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

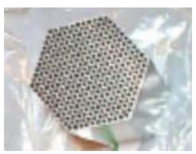
### NTP Technology Development and Demonstrations

NERVA “Composite” Fuel ✓

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

Fuel Element Irradiation Testing in ATR at INL

### NTP Test Facilities Development



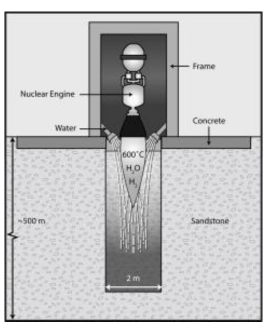
“Cermet” Fuel

“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 Flight:

## Ground & Flight Technology Demonstrators




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

### Ground Test Facility (GTF)

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

### Test Articles for Ground & Flight

- CDR GTA
- CDR FTA

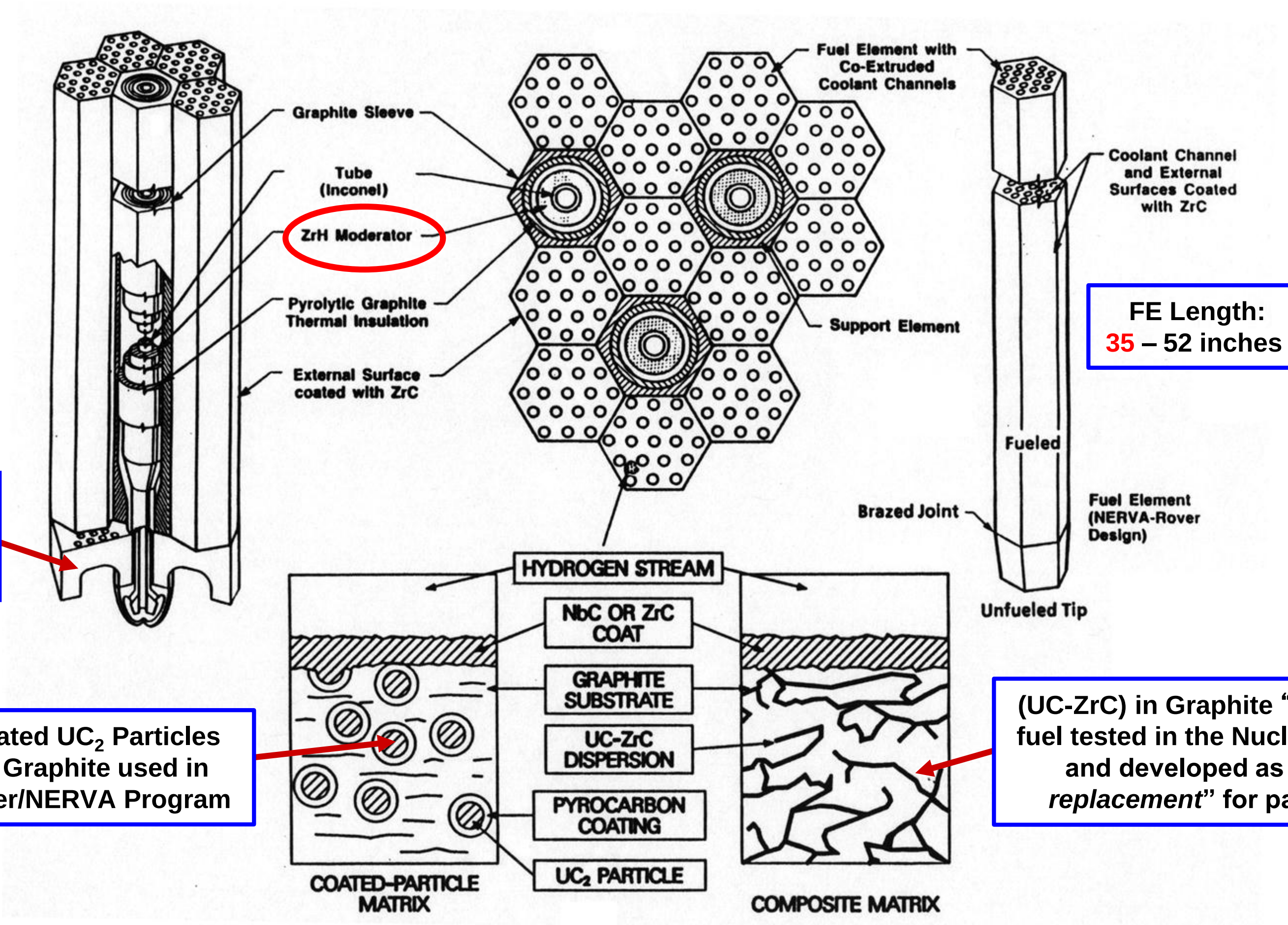
Detailed Design | Fabrication & Subsys. Assembly | Subsys. Test / Engine Assem. | GTA1 | GTA2

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




FE Length: 35 – 52 inches

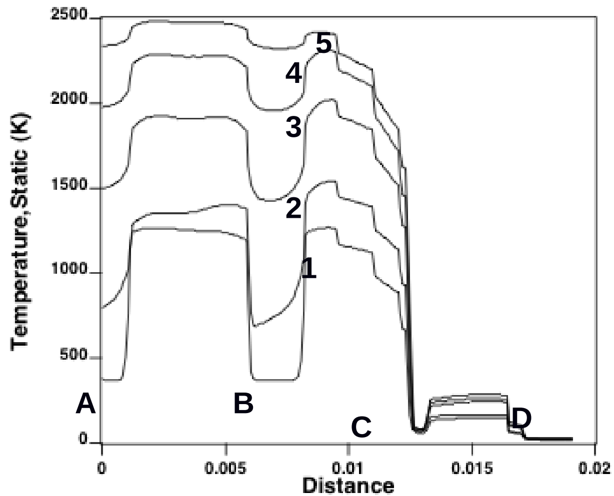
NOTE: Tie Tube pedestal supports 6 surrounding FEs

Coated $UC_2$ Particles in Graphite used in Rover/NERVA Program

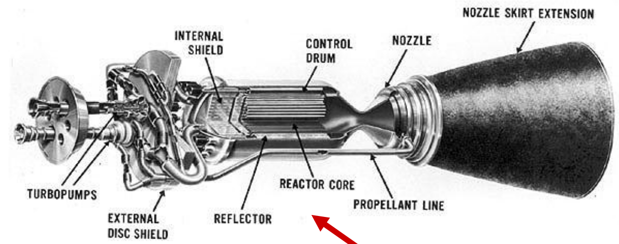
(UC-ZrC) in Graphite "Composite" fuel tested in the Nuclear Furnace, and developed as "*drop-in replacement*" for particle fuel ✓

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

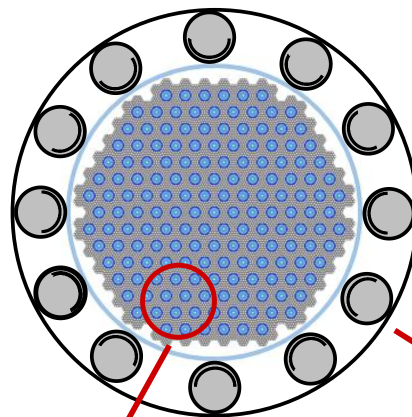
Temperature Distribution Across FE and TT



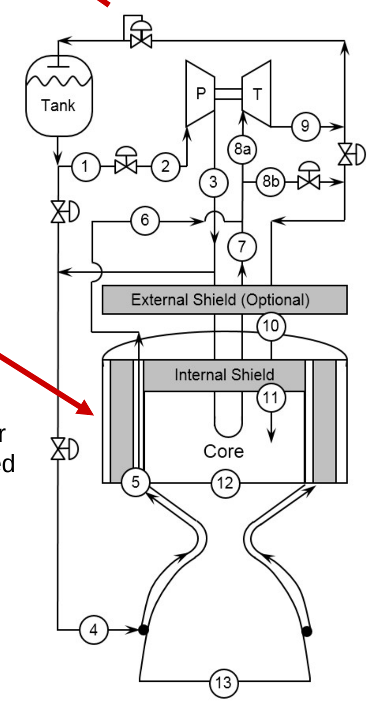

Temperature Distributions at Five Axial Stations
(Numbers Indicate Cold to Hot End Stations)




Performance, Size & Mass estimation

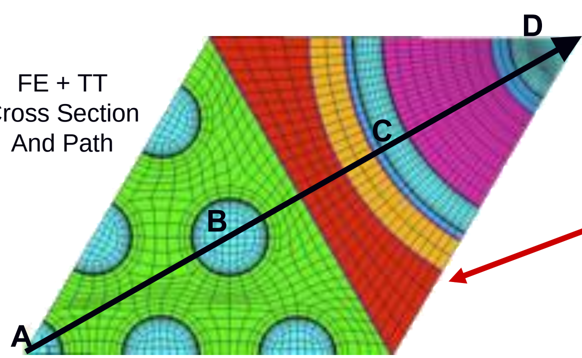


MCNP neutronics for core criticality, detailed energy deposition, and control worth

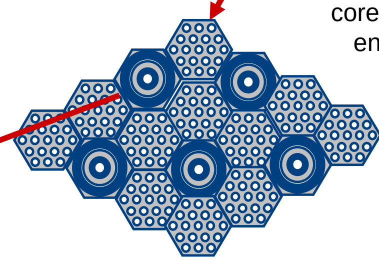



Nuclear Engine System Simulation (NESS) code has been upgraded to use MCNP-generated data

FE + TT Cross Section And Path



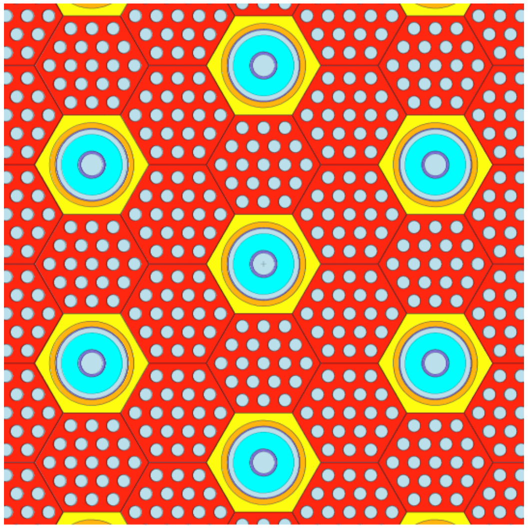

ANSYS Model



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

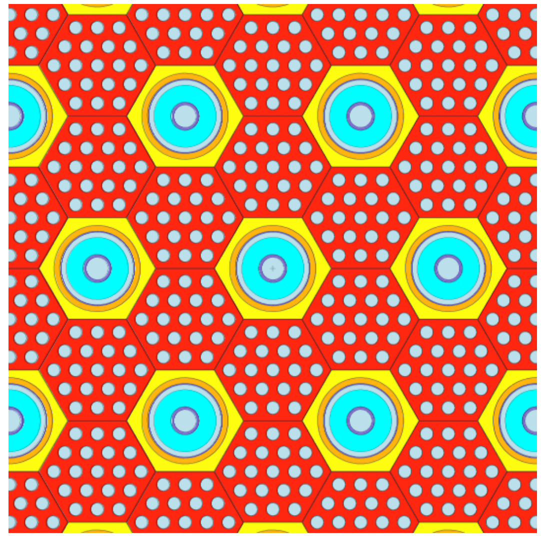
# Fuel Element (FE) – Tie Tube (TT) Arrangements for NERVA-derived Graphite Composite Engines

"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

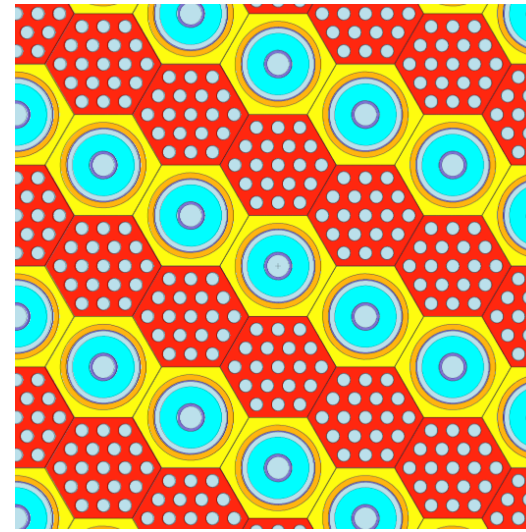
"SNRE" FE – TT Pattern used in Small Nuclear Rocket Engine



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

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

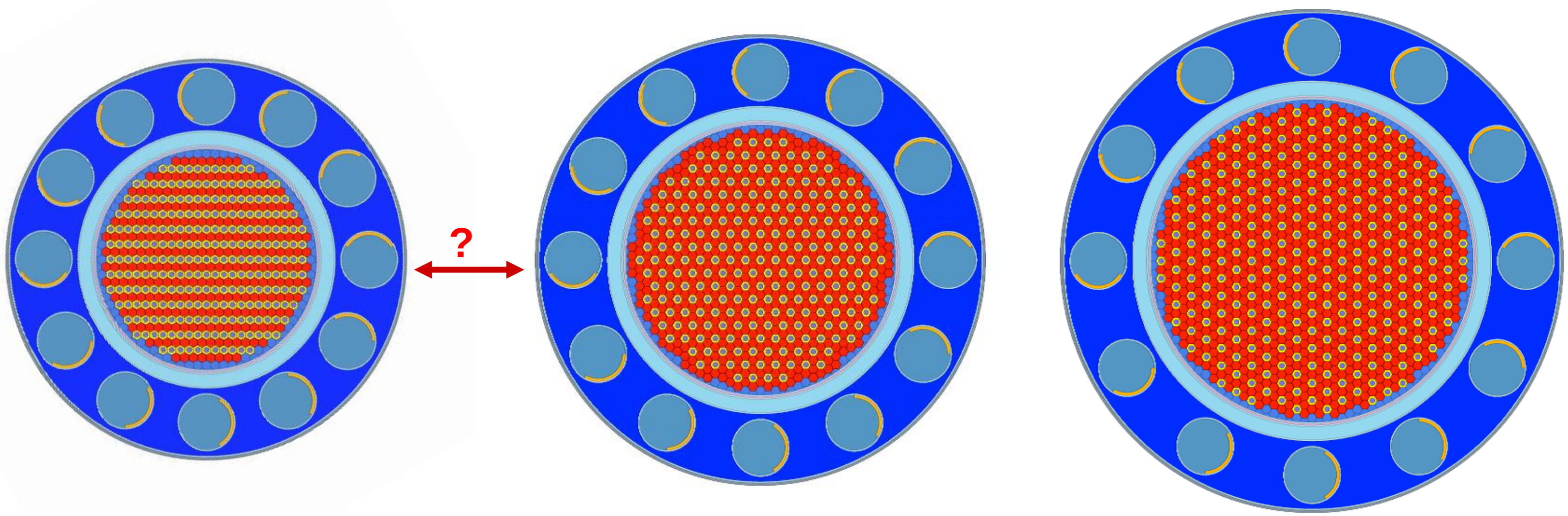
**NOTE**: An important feature common to both the Sparse and SNRE FE – TT patterns is that each tie tube is surrounded by and provides mechanical support for 6 fuel elements

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

# 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

# Performance Characteristics for "Small-to-Full Size" GC NERVA-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

# 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

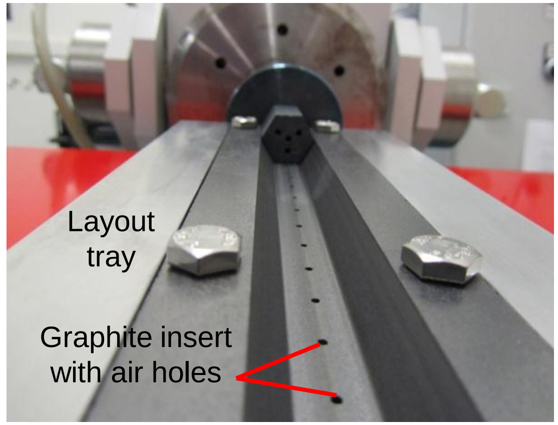
**Addressing Ground Test Challenges**

- Utilize the SAFE borehole or tunnels
- 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

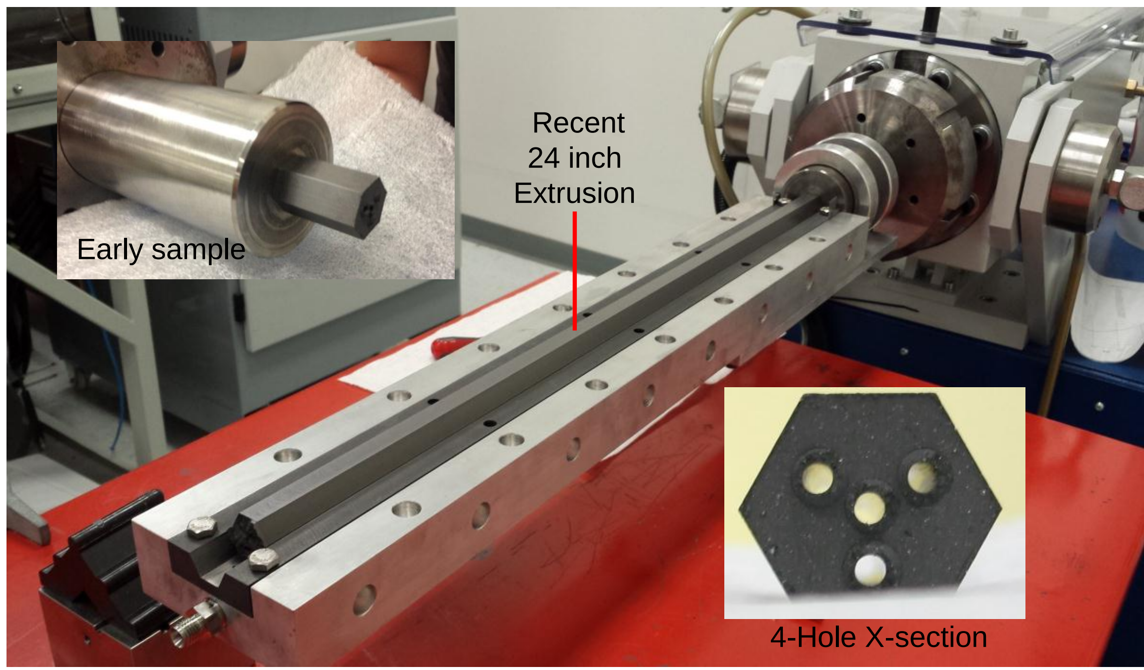
# Equipment Assembled at ORNL for Fabrication of Graphite Composite (GC) Fuel Elements

Graphite FE extruder with installed vent lines for DU capability



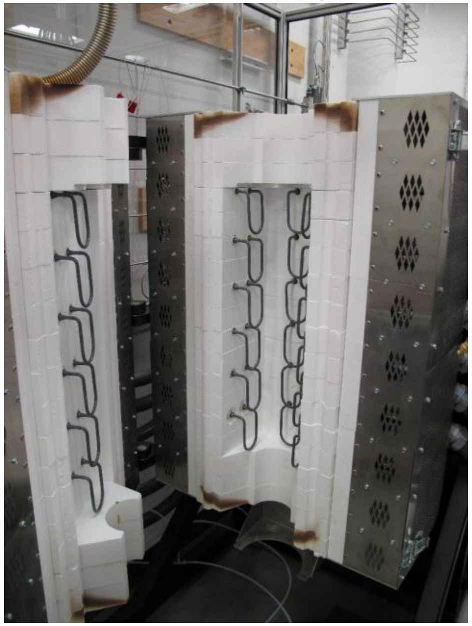


Extruder with 4-Hole Die

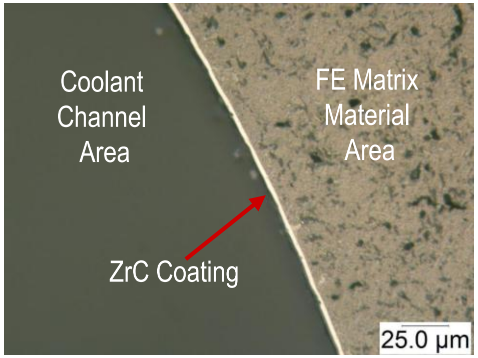


# ORNL CVD Furnace for Applying Baseline ZrC Coating along with Alternative Coating Concepts

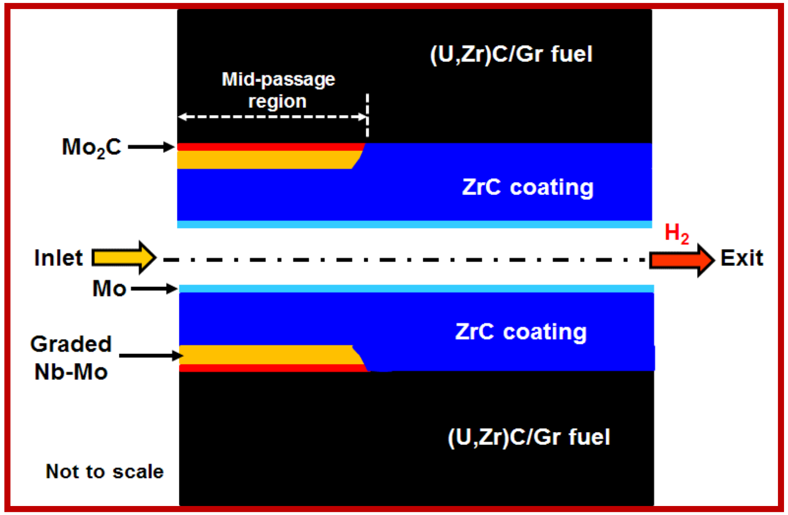
ORNL 6-zone CVD Coating Furnace



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

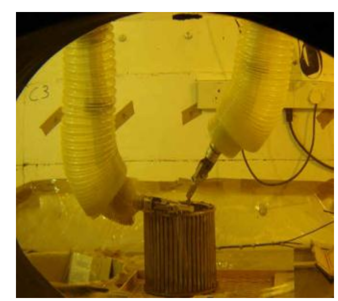
| Fuel Element Fabrication | Core Assembly | Reactor Assembly | Engine Assembly | Engine Ground Testing | Disassembly and PIE | Disposal / HEU Recovery |
|---|---|---|---|---|---|---|
| ORNL / Y-12 | DAF @NNSS | DAF @NNSS | DAF @NNSS | Borehole | FE, components extraction at test site using Portable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

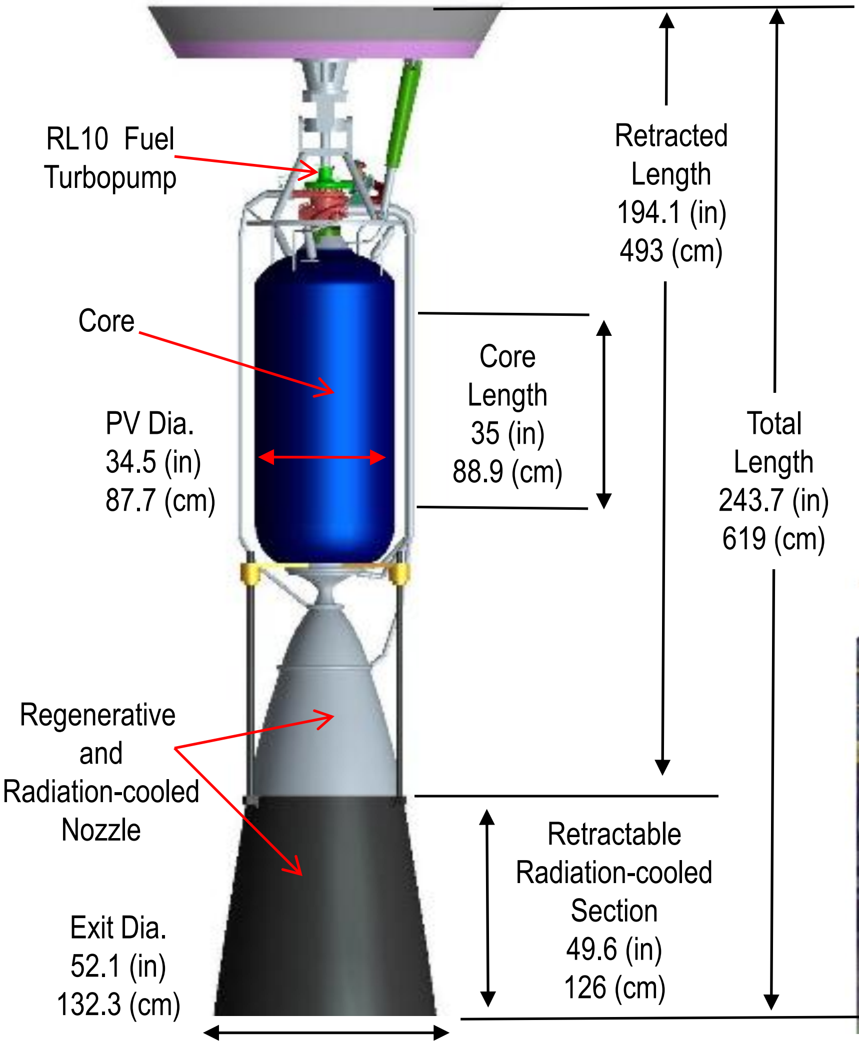
*Spent High Activity Radioactive Sources (SHARS)

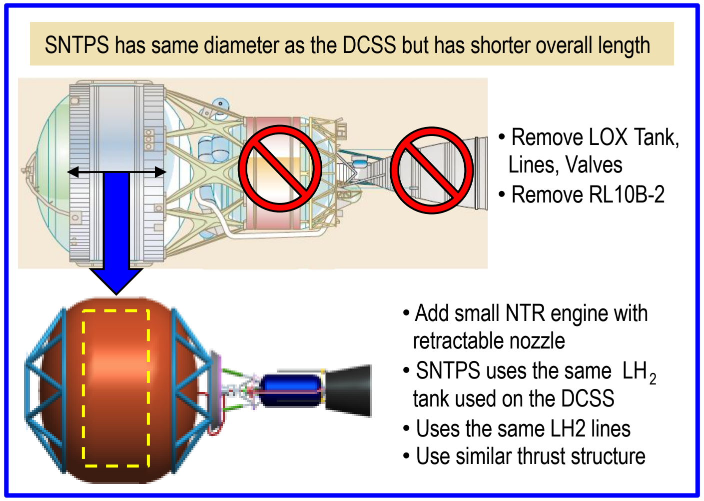


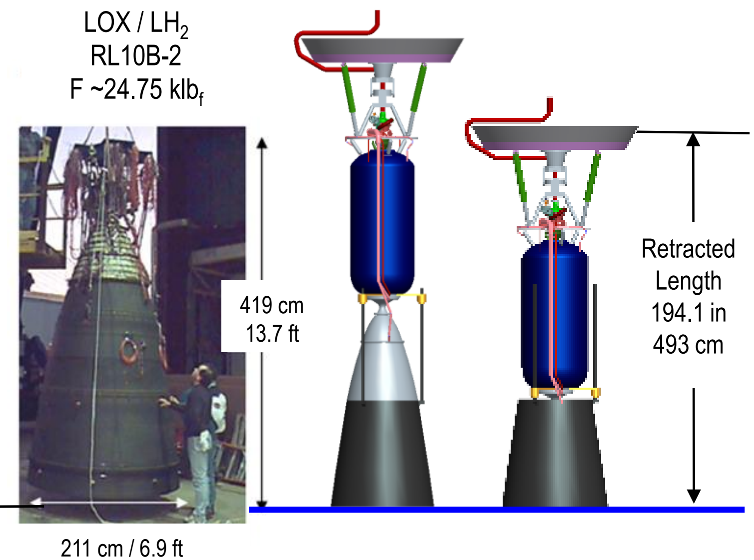
# Other Possible Facilities and Nuclear Tests

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



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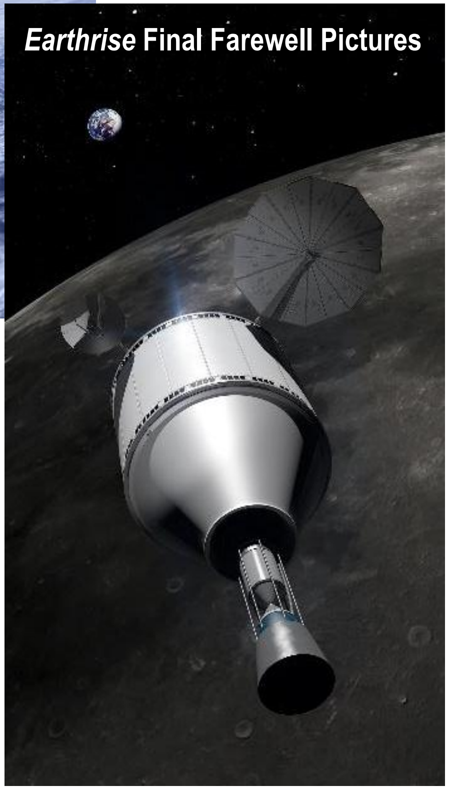
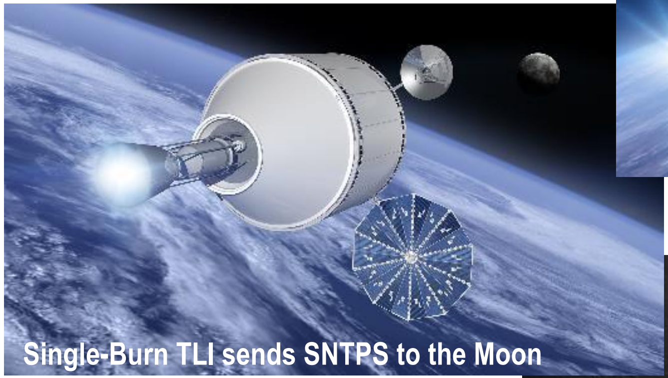
# 2025 Small NTPS FTD Mission: "Single-Burn Lunar Flyby"

- 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
- $\Delta V_{TLI}$ / 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


Lunar Gravity Assist sends SNTPS into Deep Space

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

# 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

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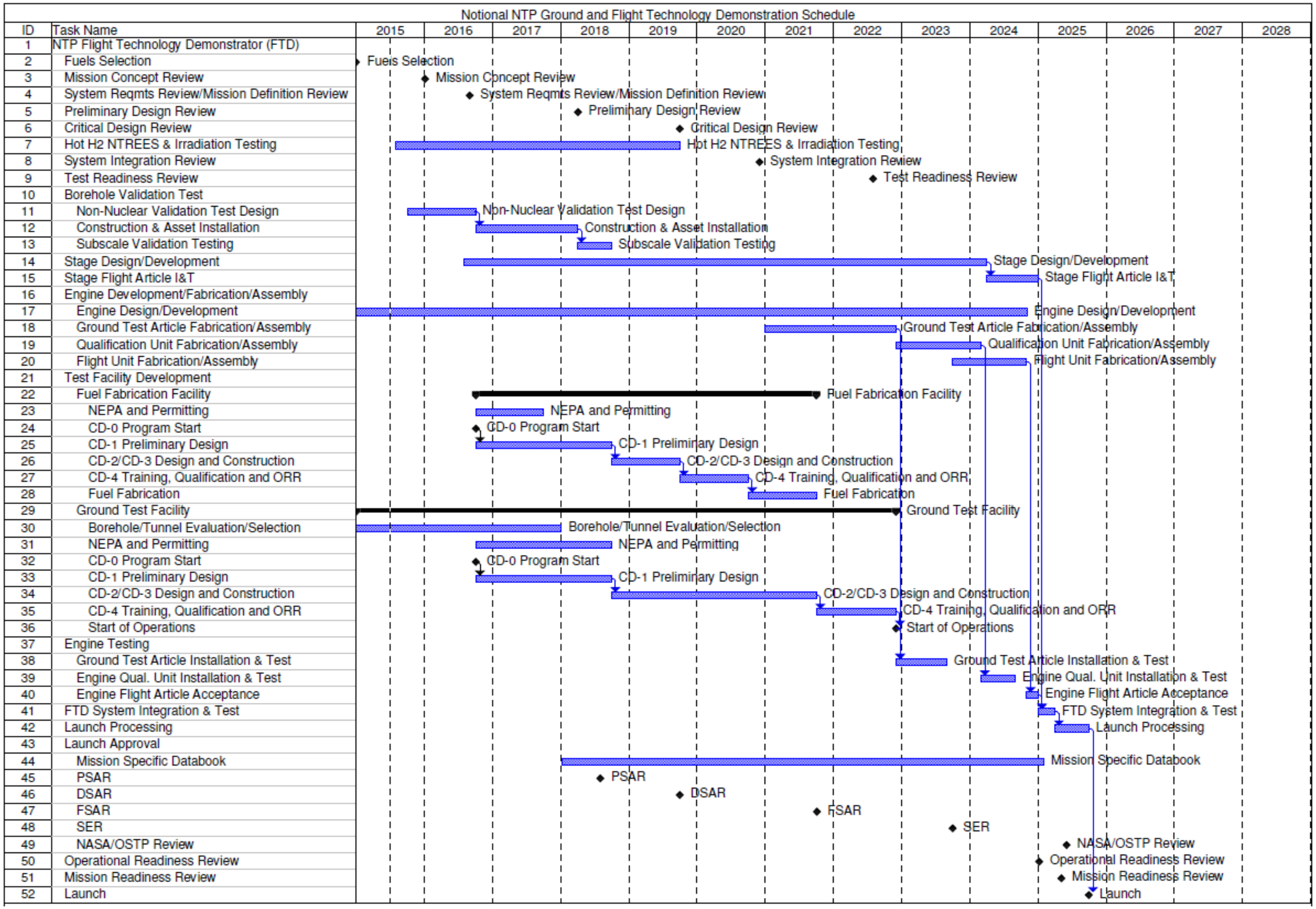
Oak Ridge National Laboratory

Idaho National Laboratory

# Notional NTP Ground & Flight Test Demonstration Milestone Schedule




NPR 7120.8 WBS for NASA Research and Technology Development Program utilized

# 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 single-burn "lunar flyby" chosen to keep things simple and more affordable; small size engine and stage can also reduce development costs and allow utilization of existing, flight proven engine hardware (e.g., hydrogen pump, nozzle, $LH_2$ tank, etc. )
- 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