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

• 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
## Key Milestones

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## Foundational Technology Development

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

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

### NTP Technology Development and Demonstrations

- Fuel Element Fab, Testing, Validation and Production; Irradiation Testing / PIE; Other Tech Development
  - Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts
  - Primary / Secondary Fuels Selection

### NTP Test Facilities Development

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

### 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.

### Notional

- Small NTP Stage for Lunar Flyby Mission
- Fuel Element Irradiation Testing in ATR at INL
- Potential Demos / Mars Flights
  - 2029-30 - Lunar/EM-L2 Flights
  - 2031-33 - Mars Cargo Flights
  - 2033-35 - Mars Crewed Flight

### Affordable SAFE Ground Testing

- at the Nevada Test Site (NTS)

### Glenn Research Center

- at Lewis Field
Rover / NERVA Reactor Core Configuration:
SNRE Fuel Element / Tie Tube Bundle Arrangement

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

FE Length: 35 – 52 inches
Temperature Distributions at Five Axial Stations
(Numbers Indicate Cold to Hot End Stations)

FE + TT
Cross Section And Path

ANSYS Model

Temperature Distribution Across FE and TT

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 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

“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 full-size 25 klbf Composite Engine Design

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

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

## Performance Characteristics for “Small-to-Full Size” GC NERVA-derived Engines

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<th>Performance Characteristic</th>
<th>Small Citicality Limited Engine</th>
<th>SNRE Baseline</th>
<th>Baseline +</th>
<th>25 klb, Axial Growth Option Nominal</th>
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*Varies with thrust level, chamber pressure, NAR and TPA/TVC layout
NTP Fuels and Engine Development Sequence

Fuel Specimens
- Fabrication and characterization
- High temperature testing including hot $\text{H}_2$ 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 $\text{H}_2$ 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 $\text{H}_2$ 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

Glenn Research Center at Lewis Field
Equipment Assembled at ORNL for Fabrication of Graphite Composite (GC) Fuel Elements

Graphite FE extruder with installed vent lines for DU capability

Layout tray
Graphite insert with air holes

19 and 4-Hole Extrusion Dies
Extruder with 4-Hole Die

Recent 24 inch Extrusion
4-Hole X-section

Glenn Research Center at Lewis Field
ORNL CVD Furnace for Applying Baseline ZrC Coating along with Alternative Coating Concepts

ORML 6-zone CVD Coating Furnace

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 H₂ permeation.
- Mo-Nb layers expected to reduce H₂ permeation.
- Mo₂C 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

Glenn Research Center at Lewis Field
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

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

Non-nuclear Components

DAF @NNSS
DAF @NNSS
DAF @NNSS
DAF @NNSS
DAF @NNSS
DAF @NNSS
DAF @NNSS
DAF @NNSS

Pressure Vessel, Reactor Control
Nozzle, Pump, H2 Feed Lines
Control / Data Acquisition, H2 Supply
Borehole
U1a Tunnel
P Tunnel

FE, components extraction at test site using Portable Hot Cell
Limited FE and components shipment to INL for PIE
@NNSS entomb in tunnel
@INL following PIE

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 klbf NTP Engine and Stage for 2025 Lunar Flyby FTD Mission

LOX / LH$_2$

RL10B-2

F $\approx$24.75 klbf

211 cm / 6.9 ft

Retracted Length 194.1 in 493 cm

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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Glenn Research Center at Lewis Field
2025 Small NTPS FTD Mission: “Single-Burn Lunar Flyby”

- SNTPS FTD Launch on Delta 4 M (5,4)
- DCSS delivers SNTPS to LEO
- Single-Burn TLI sends SNTPS to the Moon
- Lunar Gravity Assist sends SNTPS into Deep Space
- Earthrise Final Farewell Pictures

- IMLEO ~9.90 t
- F ~7.52 kIbf, 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

- 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
## Notional NTP Ground & Flight Test Demonstration Milestone Schedule

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The schedule is based on the 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 klbf) 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