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**

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Glenn Research Center
at Lewis Field
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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 klbf) engine that utilizes a “common” fuel element design scalable to the higher thrust (~25 klbf) 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 klbf) 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
---|---|---|---|---|---|---|---|---|---|---|---|---|---|---

Key Milestones
- ATP
- Fuels Selection
- GTD Engine Tests
- 7.5-klbf Engine FTD

Notional

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
  - Primary / Secondary Fuels Selection
  - Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts

NTP Test Facilities Development
- 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

Ground Test Facility (GTF)
- Prel. & Final Design
- Construction & Asset Installation
- Check-out

Test Articles for Ground & Flight
- GTA1 Ground Test Article 1
- GTA2 Ground Test Article 2
- FTA Flight Test Article
- FTD Flight Tech Demo

GTD - Ground Tech Demo
GTA1 - Ground Test Article 1
GTA2 - Ground Test Article 2
FTA - Flight Test Article
FTD - Flight Tech Demo
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### Foundational Technology Development

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- In-House & Contractor System Concept Definition, Design, and Analysis
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### Ground & Flight Technology Demonstrators

#### Ground Test Facility (GTF)
- Prel. & Final Design
- Construction & Asset Installation
- Check-out

#### Test Articles for Ground & Flight
- Detailed Design
- Fabrication & Subsys. Assembly
- Subsys. Test / Engine Assem.
- GTA1
- GTA2
- GTA
- FTA

### Notes
- Affordable SAFE Ground Testing at the Nevada Test Site (NTS)
- NTR Element Environmental Simulator (NTRES)
- Small NTP Stage for Lunar Flyby Mission
- Fuel Element Irradiation Testing in ATR at INL

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

ANL-200
- 1.092 inch (2.774 cm)
- 61 Coolant Channels per element

GE-710
- 0.928 inch (2.356 cm)
- 91 Coolant Channels per element

NERVA
- 0.750 inch (1.905 cm)
- 19 Coolant Channels per element

Rover / NERVA* Program Summary
(1959-1972)

The smallest engine tested, the 25 klbf, “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 klbf
- H₂ exit temperatures achieved
  - 2,350-2,550 K (in 25 klbf Pewee)
- Iₚₑ 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 klbf NRX-A6 - single burn)
  - ~ 2 hrs (50 klbf 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

Improved ZrC-coated Particle Fuel in Graphite is NERVA Backup

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

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

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

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

Performance, Size & Mass estimation

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

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

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**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.

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


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


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

## Overview

- **Engine System**
  - Thrust (lbf)  
  - Chamber Inlet Temperature (K)  
  - Chamber Pressure (psia)  
  - Nozzle Expansion Ratio (NAR)  
  - Specific Impulse (s)  
  - Engine Thrust-to-Weight

- **Reactor**
  - Active Fuel Length (cm)  
  - Effective Core Radius (cm)  
  - Engine Radius (cm)  
  - Element Fuel/Tie Tube Pattern Type  
  - Number of Fuel Elements  
  - Number of Tie Tube Elements  
  - Fuel Fissile Loading (g U per cm$^3$)  
  - Maximum Enrichment (wt% U-235)  
  - Maximum Fuel Temperature (K)  
  - Margin to Fuel Melt (K)  
  - U-235 Mass (kg)

## Performance Parameters

<table>
<thead>
<tr>
<th>Performance Characteristic</th>
<th>7,420-lbf Option</th>
<th>SNRE Baseline</th>
<th>Axial Growth Option</th>
<th>Radial Growth Option</th>
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<td><strong>Engine System</strong></td>
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| **Reactor**                |                  |              |                    |                     |
| Active Fuel Length (cm)    | 89.0             | 89.0         | 132.0              | 132.0               |
| Effective Core Radius (cm) | 14.7             | 29.5         | 29.5               | 29.5                |
| Engine Radius (cm)         | 43.9             | 49.3         | 49.3               | 49.3                |
| Element Fuel/Tie Tube Pattern Type | Dense       | SNRE       | SNRE               | SNRE               |
| Number of Fuel Elements    | 260              | 564          | 564                | 564                 |
| Number of Tie Tube Elements | 251             | 241          | 241                | 241                 |
| Fuel Fissile Loading (g U per cm$^3$) | 0.60        | 0.60         | 0.25               | 0.25                |
| Maximum Enrichment (wt% U-235) | 93             | 93           | 93                 | 93                  |
| Maximum Fuel Temperature (K) | 2860            | 2860         | 2860               | 3010                |
| Margin to Fuel Melt (K)    | 40               | 40           | 190                | 40                  |
| U-235 Mass (kg)            | 27.5             | 59.6         | 36.8               | 36.8                |

**NOTE:** Fuel Matrix Power Density: 3.437 MWt / liter

**SOTA “Pewee-class” Engine Parameters**

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

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

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

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

Right: Layoff base / Graphite insert

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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.

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

Aerial View of the DAF at the Nevada Test Site

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Non-Nuclear Subscale SAFE Bore Hole Feasibility Test

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 \( \sim 10^{-9} \text{ gms/cm}^3 \).

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 NCPS effort for \( \sim \$2M \).

Component inventory and cost breakdown for subscale test being reevaluated by GRC and DOE to identify potential savings.

SAFE: Subsurface Active Filtration of Exhaust

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.

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
Small NERVA-derived 7.42 klbf NTR Engine Layout and Dimensions

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

RL10 Fuel Turbopump

Core

PV Dia.
35.9 (in)
91.2 (cm)

Core Length
35 (in)
88.9 (cm)

Retractable Length
180.6 (in)
459 (cm)

Total Length
227.6 (in)
578 (cm)

Core

Exit Dia.
52.1 (in)
132.3 (cm)

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

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

Retracted Length
180.6 (in)
459 (cm)

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at Lewis Field
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

Source: Russ Joyner, Aerojet Rocketdyne, GRC-funded work 2011

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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

- IMLEO ~12.72 t
- F ~7.42 klbf, $I_{sp}$ ~900s,
  F/W$_{eng}$ ~1.87
- LH$_2$ mass ~5.07 t
- Stage dry mass ~7.40 t
- PL ~250 kg
- Burn time ~20.9 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

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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
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

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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 klbf) 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

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