Low Enriched Uranium (LEU) Nuclear Thermal Propulsion: System Overview and Ground Test Strategy

Presented by: David Coote, NASA/SSC
Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle

- Low molecular weight propellant – typically Hydrogen
- Specific Impulse directly related to exhaust temperature, e.g.: 2850K exhaust temperature translates to ~900 sec Isp

Major Elements of a Nuclear Thermal Rocket

XE-Prime Nuclear Thermal Rocket Prototype
Nuclear Thermal Propulsion (NTP)
Game Changing Development Project Overview

Project Description:
• Determine Low Enriched Uranium (LEU) NTP feasibility and affordability, with good cost and schedule confidence, prior to a decision to proceed with full scale development.
• Demonstrate the technology that enables the development of high temperature, minimum erosion/fission product release fuel elements (FE) using LEU.
• Leverages government, industry and academic expertise and existing facilities.

Roles and Responsibilities
• MSFC: PM, SE & Analysis Lead, Cryo ConOps Lead, FE Testing
• GRC: Cryocooler Testing, Cryo ConOps Support, Sys. Analysis Support
• SSC: Rocket Exhaust Capture System DDT&E
• KSC: Ground Processing ConOps / Propellant Densification
• Aerojet Rocketdyne: LEU Engine Analysis
• AMA: Engine Cost Lead
• Aerospace: Engine Cost Independent Review
• BWXT: Fuel Element / Reactor Design/Fabrication
• DOE: FE / Reactor Design and Fabrication Support

Full Funding Profile (all years):
• Budget vs. Requirements

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*FY 19 est.
• Reviewed past design efforts and testing to construct most affordable path to an NTP for Mars missions
  • Baseline Design
    ▪ 25,000 lbf thrust
    ▪ ~500MW
    ▪ Exhaust capture ground testing
  • Uses Low Enriched Uranium (LEU)
    ▪ Enables the use of commercial manufacturing methods to arrive at best NTP system design to reduce cost with no impact on performance
    ▪ Use of LEU is consistent with US/international efforts to eliminate HEU in all civilian applications
    ▪ Enables tremendous programmatic flexibility, increasing choice of facilities, and project participants

Size comparison: Baseline 25klbf NTP (Left) vs. RL10 (right) Source: Aerojet Rocketdyne
NTP Technology Maturation Plan

Fuel Technology Development

- Fuel Fabrication Technology Development
- Fuel Material Properties Tests
- Fuel Separate Effects Tests
- Fuel Fluence Tests
- Fuel Flux Tests
- Representative Reactor Zero Power Critical Tests

Subscale Systems Demonstrations

- E3 Subscale Facility Design, Modifications & Test Prep
- E3 Subscale Exhaust Capture System Test E3 Test #1
- Non-Nuclear Subscale Engine System Demonstration
- Elements Thermal-Hydraulic Interaction Demonstration
- Components Preliminary Separate Effects Tests (Non-nuclear)

Turbpump Development

- Design Prototype Turbpump
- Manufacture Prototype Turbpump
- Test Prototype Turbpump

NTP Engine Prototype Design & Manufacture

- NTP Engine Preliminary Design
- NTP Engine Prototype Design
- NTP Engine Full Scale Design Update

NTP Reactor Prototype Design & Manufacture

- NTP Reactor Preliminary Design
- NTP Reactor Prototype Design
- Full Scale Reactor Structural / Vibration Test

Full Scale Testing

- A3 Full Scale Reactor Test Facility Design Initial Work
- A3 Full Scale Reactor Test Facility Design & Fab
- A3 Full Scale Reactor Test (Nuclear Facility Controlled LH2 Supply)
- A3 Full Scale Reactor Test (Low Power Reactor Test, Nuclear)
- A3 Facilities Design & Fab

Engine Tests

- H2 Wave Heater Design & Fabrication
- Subscale Test Engine Design

Engine Design

- Engine Requirements & Conceptual Design

Reactor Design

- Reactor Requirements & Conceptual Design

Requirements & Conceptual Design

- We are here

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TRL 3
TRL 4
TRL 5
TRL 6

WBS Number X.X.X.X

TDM Type Ground Demo  Early Flight Systems Ground Dev Through PDR
• SSC has been supporting MSFC since FY14 on the AES/Nuclear Thermal Propulsion (NTP) Project.
  - Project goal is to demonstrate the affordability and viability of nuclear thermal rocket propulsion
  - Current focus is to define an affordable development and qualification strategy
Bore Hole

- Relies on permeability of desert alluvium soil to filter engine exhaust
  - Unresolved issues on water saturation effects on soil permeability, hole pressure during engine operation, and soil effectiveness in exhaust filtering

Above Ground Scrubber and NNSS (Nevada National Security Site) P-Tunnel Scrubber Option

- Engine exhaust is filtered of radioactive aerosols and noble gases and directly flared to atmosphere
  - Nuclear Furnace (NF-1) ground test scrubber successfully tested at the end of Rover/NERVA project
  - DOE and ASME standards available for nuclear air cleaning and gaseous waste treatment

Engine Exhaust Capture

- Engine hydrogen exhaust is burned at high temperatures with oxygen, producing O2 rich steam that is cooled, condensed, and collected for controlled processing and disposal
  - All analyses to date indicate system will reliability and economically accomplish task
  - Subscale test project in design with testing planned for 2019
NTP Project decision to baseline the Exhaust Capture System as the NTP engine ground test approach was based on:

1. Its ability to reliably assure containment of potentially liberated reactor radionuclides and fuel element debris

2. Availability of existing NASA rocket propulsion test infrastructure uniquely suited to accommodate system requirements

3. Decision to baseline LEU reactor engine
   • Substantially minimizes the cost of site security and site licensing

Recently initiated NTP Project study is re-reviewing Ground Test Options
LEU NTP Based on Liquid Rocket Engine Technology

- LEU NTP has synergy with current cryogenic fluids system technology development (e.g., Mars lander chemical propellant storage)
  - Engine operates similar to current liquid rocket engines (LRE) (e.g., expander RL10)
    - LEU NTP hydrogen flow-rates for 25,000-lbf engine similar to current expander cycle engines
    - Not a high pressure, complex SSME type propulsion cycle
  - Major systems just like O2/H2 and O2/CH4 engine designs
    - Similar turbine design, pump and chamber pressures, nozzle-chamber heat loads, nozzle size

Turbomachinery Sized Per RL60 (e.g., RL10 Derivative)
NTP Ground Test Strategy
Engine Exhaust Capture System

Strategy:
- Fully Contain engine exhaust
- Methodically drain containment vessels after test to ensure proper filtration

Preliminary system sizing and performance analysis of this concept have been completed and no operations performance issues have been identified.

How it works:
- Hot hydrogen exhaust from the NTP engine flows through a water cooled diffuser that transitions the flow from supersonic to subsonic to enable stable burning with injected LO2
  - Products include steam, excess O2 and potentially, a small fraction of noble gases (e.g., xenon and krypton)
- Water spray and heat exchanger dissipates heat from steam/O2/noble gas mixture to lower the temperature and condense steam
- Water tank farm collects H2O condensate and any radioactive particulates potentially present in flow.
  - Drainage is filtered post test.
- GO2 condenser cools residual gas to LN2 temperatures, condenses O2 and noble gasses.
  - LOX Dewar stores LO2 and noble gases, to be filtered post test.

All system operating pressures and temperatures and fluid supply and flow requirements are well within existing chemical rocket propulsion test capability and experience.
Engine Exhaust Capture System

**Preliminary System Sizing - 25 klbf Engine**

**Notes/Assumptions:**
- 25,000 lbₚ thrust (500MW)
- 28 lbm/s GH₂ Flow.
- Nozzle Exhaust Temp: 2850 K
- Test Duration: 1 hour
Facility located at SSC’s A3 Test Stand (Current NTP Project Baseline)

- Most of the infrastructure required by the NTP engine exhaust capture ground test facility is already in place:
  - Tower, test cell, propellant, HPIW, data acquisition and controls infrastructure, the Test Control Center, electric power, etc.
  - Major modifications, procurements, and construction work will be required and are captured in a ROM estimate.

ROM estimate to prepare stand for NTP engine test is under development
Nuclear Thermal Propulsion Technology Development

• Evolving Baseline Scope for NTP Ground Test Activities at SSC

  • **Current, Non-Nuclear Test Project at SSC’s E3 (FY18/19)**
    • **Sub-scale Engine Exhaust Capture System**
      • Project and funding approved for Phases 1 & 2
      • Phase 1 underway with testing in FY19

  • **Phase 3: Tunable Hydrogen Wave Heater follow-on (FY20)**

• **Non-Nuclear NTP Engine Development Tests**
  • **Sub-Scale Turbopump Testing**, potentially starts in 2-3 years
  • **Sub-Scale Reactor Simulator**, potentially starts in 4 to 6 years

• **Nuclear Systems Test**
  • **NTP Engine Testing**, start testing in 12-14 years
  • **NTP engine PowerPack testing**
  • **Full Flow, non-nuclear test** (a depleted uranium reactor, hot hydrogen flow) to evaluate flow characteristics and structural integrity of the engine before testing an actual NTP engine.
  • **NTP reactor multi-element test** (<20 MW testing vs 500MW of the full scale NTP engine)
Nuclear Thermal Propulsion Technology Development

• Evolving Baseline Scope for NTP Ground Test Activities (continued)

• Potential New Facilities
  • Zero-power reactor facility/project, a new facility for nuclear reactor element quality evaluation
  • Engine Maintenance and Disassembly Facility (EMAD), a new facility for engine assemble and post test disassembly and evaluation.
NTP Engine Exhaust Capture System Testing
Nonnuclear Subscale Demonstration Testing

Facility being designed to demonstrate the feasibility, safety, efficacy, and affordability of the RECS concept.

Key Subscale Test Program Goals

- Demonstrate efficacy of the RECS concept
- Verify H2 afterburning
- Understand system startup and shutdown transients
- Assess alternative design and technology infusion options
- Develop and validate test ops procedures
- Supports nuclear site licensing regulatory and NEPA/EIS processes
- Builds public confidence in test safety

Nonnuclear RECS Subscale Demonstration Testing is currently the #1 priority for augmented STMD/GCD NTP Program funding (within the current congressional budget):

- Phase 1 (FY18-19), $6.7M, Initial Design, Construction, and GH2 operating temperature = 1,600°R/1,140°F
- Phase 2 (FY19-20), $2.0M, GH2 temperature increase to 5,000°R/4,540°F
E3RECS3 Project Preliminary Phase 1 and Phase 2 Development Schedule
Summary

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NTP Engine Ground Test Exhaust Capture System Project baseline based on:
1. Its ability to reliably assure containment of potentially liberated reactor radionuclides and fuel debris
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3. Decision to baseline LEU reactor engine
   - Substantially minimizes the cost of site security and site licensing
   - Subscale ground test demonstration project underway

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