Affordable Development and Qualification Strategy for Nuclear Thermal Propulsion

Gerrish, H. P., Doughty. G. E.
NASA – Marshall Space Flight Center

Bhattacharyya, S. K.
RENMAR Enterprises Inc.

July 17, 2013

49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit and 11th International Energy Conversion Engineering Conference
Agenda

- How does NTP work
- Lessons learned from past programs
- Development needs
- Programmatic considerations
- Fuels development
- Ground testing
- Other development needed
- Possible prototype flight test
- Logic flow for cost and schedule
- Summary
How does Nuclear Thermal Propulsion (NTP) Work?

- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor
- Specific Impulse directly related to exhaust temperature
- NTP Specific Impulse (~900 seconds) doubles over chemical rockets (~450 seconds) due to lower molecular weight of propellant
How does NTP Work?

Major differences between NTP and Chemical Propulsion:
- NTP reactor exposes the engine components and surroundings with a radiation environment (gamma rays and neutrons), which drops with time after shutdown
- Long start-up (minutes) and extremely long shutdown (tens of hours for cooldown)
Lessons Learned from Past Programs

1. Technical feasibility of NTP established with Rover/NERVA program (1955-1973), Space Nuclear Thermal Propulsion (1987-1993), Cermet program (1960’s to early 70’s), and Russian (former USSR) fuel development program.

2. Several classes of fuels had the potential to meet the demanding requirements (e.g., carbon based and Cermet).

3. Heat transfer from fuel to propellant critical to maximize performance. Various fuel geometries investigated in the past (e.g., hexagonal cross section with multiple through holes, particle bed, twisted ribbon).

4. Current engine design requirements within limits of past programs.

5. Rates of fuel erosion acceptable in the past, but not acceptable today.

6. Other non-nuclear engine components (e.g., turbopumps, valves, etc.) have been qualified for chemical engines. Influences from radiation exposure is small and generally understood from past NTP tests.

7. Many mission analysis studies have been done in the past to determine how best to utilize NTP.

8. Past NTP programs terminated before flight test due to lack of mission.

9. Numerous program starts and stops wastes effort and causes work to be redone by new teams.

10. Recent lessons learned from the J-2X program (human rated in-space chemical engine)
Cost

- Latest Mars mission analysis shows fewer SLS launches for NTP vs chemical
- Cost saving from a single mission covers most of NTP development costs


- $7.6B FY13 invested in Rover/NERVA, but the investment covered a large variety of engine designs and test facilities. Current approach is focused on one small engine design and utilize a few existing facilities
- Developing chemical engines is also not cheap

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust (lbs)</th>
<th>Period</th>
<th>Development Cost FY12</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-1</td>
<td>1500K</td>
<td>‘59-'66</td>
<td>~$3.0B</td>
</tr>
<tr>
<td>SSME</td>
<td>470K</td>
<td>‘72-'81</td>
<td>~$4.1B</td>
</tr>
<tr>
<td>J-2</td>
<td>200K</td>
<td>‘60-'66</td>
<td>~$2.6B</td>
</tr>
<tr>
<td>RL10A-3</td>
<td>15K</td>
<td>‘58-'63</td>
<td>~$0.9B</td>
</tr>
</tbody>
</table>
Development Needs

• Concept of Operations (Con-Ops) determines the overall functional activities which need to take place to design, develop, test, and fly a nuclear rocket. Identifying low TRL long lead components is critical.

• Engine requirements from mission analysis and NASA standards including human rating. JANNAF guidelines recommend 6 engines be developed for chemical engines, with 2 for flight certification.

Current NTP baseline design requirements:

• Thrust ~ 25k-35k lbf
• Isp ~ 900 seconds with hydrogen
• Longest single burn ~ 45 minutes
• # Start-ups ~ 4
• Cumulative run time ~100 minutes
Development Needs (Cont’d)

• Status of database from past work
  – Rover/NERVA Program: 20 reactors built and tested. 44 MWt to 4100 MWt. Operation from a few seconds to a few hours (cumulative). Peak temperature attained was 2750K in composite fuel. One unresolved issue was the leakage of fission products from the coated fuel.
  – SNTP Program: modified TRISO particle with UC$_2$ kernel and various coatings. Several non-nuclear and irradiation tests performed. Early tests showed flow instabilities needing more work.
  – Russian (former USSR) Program: extensive nuclear and non-nuclear tests on a variety of fuels. Reported 3100K achieved. Difficult to verify results.

• Key development items needing long lead development effort
  – Start with two candidate fuels (composite and cermet) before down select.
  – Full-scale NTP ground test facility with fission product containment.
Programmatic Considerations

- National Space Policy regarding space nuclear power requires a nuclear safety launch approval process with approval by the president or his designee
  - Requires Nuclear Environmental Policy Act (NEPA), Presidential Directive/National Security Council Memorandum #25(PD/NSC-25), radiological contingency planning, and risk communication.
  - Processes have been previously used for radioisotope thermoelectric generators (RTG’s).
  - Similar process will be used for NTP.
  - Cost and schedule understood.

- Safeguards and Security
  - Previous NTP programs used highly enriched uranium with U235 quantities identified as category 1 and requires top national security.
  - Current strategy investigating engine designs with lower U235 quantities having lower strategic significance to reduce the security cost and complexity.
The performance criteria that will be imposed on the fuels are listed below.

a) Fabrications with acceptable quality assurance and control
b) Temperature stability (>2700K for 1000+ s)
c) Mechanical/Structural strength
d) Chemical compatibility with hot hydrogen
e) Transient performance (multiple restarts)
f) Comfortable margins to failure
g) Fission product retention under operating conditions
h) Easily adaptable to bimodal applications in the future
i) Robustness for use in wider applications (e.g. high power steady state or nuclear electric propulsion systems)

Candidate fuels will be examined under non-nuclear tests, irradiation tests, and zero power tests.
The National Emission Standards for Hazardous Air Pollutants (NESHAP 40 CFR61.90), which states “Emissions of radionuclides to the ambient air from Department of Energy facilities shall not exceed those amounts that would cause any member of the public to receive in any year an effective dose equivalent of 10 mrem/yr”.

Nuclear Furnace successfully demonstrated exhaust filtering in 1972

SNTP exhaust filtering concept
Ground Testing

Other fission product filtering concepts being investigated

Sub-surface active filtering of exhaust (SAFE) concept

Hot hydrogen injection chamber built by Aerojet Corporation and used by NASA for Lox augmented NTR testing. Possible Test rig for SAFE subscale testing using hot gas chamber22
Other Development Needed

- **Turbomachinery**-bearing selection, possibilities of saturated hydrogen, throttleability, and radiation exposure

- **Valves**-acceptable leakage, radiation exposure, and future manufacturers

- **Nozzle Extensions**-investigate use of chemical nozzles by similarity, nozzle cooling for an engine cluster

- **Avionics, Actuators, and Power Generation**-radiation exposure

- **Analysis Tools**-integrated reactor and rocket engine modeling

- **Cryogenic Fluid Management**-minimize hydrogen boil-off, coupling of stage lines, thermal management, and zero-g liquid acquisition
Other NTP Propellant Options

- 4 SLS Launches with NTP using Hydrogen as propellant
- 7 SLS Launches with NTP using Methane as propellant

Other propellant options have significantly lower Isp and require significantly more SLS Launches per mission.

Note: Results based on:
- 1000 psia chamber pressure
- 4850 R chamber temperature
- 150 area ratio nozzle
Possible Prototype Flight Test

Prototype flight test demonstrates the following:
• Full nozzle expansion,
• Radiate heat to space,
• Perform thrust vector control with engine operating,
• Validate reactor operation without effects from facility surroundings
• Monitor radiation effects on stage
• Exposure to space environment effects
• Engine inspection with space telerobotics

Also, Lessons Learned from ARES 1-X
Logic Flow for Cost and Schedule

Initial Con Ops from NERVA/SNTP Program

Functional Facility Capability Needs Established

Specific Quantified Facility Reqmts Defined

Candidate Facility Solutions Identified

Trade Studies to Assess Candidates (includes cost)

Facility Solutions Defined and Costed

Key Design Parameters

Iterative Loop

Vehicle Concept Established by Mission Analysis (From Task#2)

Full System DDT&E Approach Defined

DDT&E Approach Cost & Key Cost Drivers Identified

Facility Limitations

Revised Con Ops and DDT&E Approach

Trade Studies to Assess options to Key Cost Drivers

Updated System DDT&E Plan with Cost

NOTE: Facility assessment must consider needs of complete system life cycle not just DDT&E phase.
Accounting for all the factors which influence the development plan and quantify the factors based on experience, analysis, analogies or similarities, will build greater justification with less uncertainty to have an authority to proceed with NTP development.