Current Ground Test Options for Nuclear Thermal Propulsion

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Rover/NERVA Test Cells

- Test cells “A” and “C” were used to test all reactor/engines except XE’ from 1959-1972 at the Nevada Test Site
- All engines fired upward into open air
- The test cells were re-used after various engine failures

Engine Failure at Test Cell C

- Phoebus 1A was a 1100 MWt engine, which failed from false gauge readings and ran out of LH₂.
- Emergency shutdown LH₂ now used.
- 5 other engines followed Phoebus 1A and were tested at test cell C

Video of engine failure

After waiting six weeks, the decontamination crew cleaned up the test site in two months and prepared for the next test. Average dose .66 rem.[1]
Nevada Test Site Operation Safety and Health Record 1959-1972

• 27 reactor tests conducted
  - Maximum accumulated time reactor: 109 min
  - Nuclear furnace test system – complete containment of radioactive material
  - Maximum single duration test: 62 min
  - Maximum power level: 4,100 MW

<table>
<thead>
<tr>
<th>Test Operations</th>
<th>Incidents</th>
<th>Remedial Action</th>
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<tbody>
<tr>
<td>Test preparation accident</td>
<td>2 workers injured (eardrums &amp; foot injuries) by ignition of leaking hydrogen in confined space</td>
<td>Strict adherence to approved test stand operating procedures</td>
</tr>
<tr>
<td>Test cart, test cell A</td>
<td>Flow-induced core vibration broke portions of fuel elements</td>
<td>Redesigned core, eliminating flow-induced vibration</td>
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<tr>
<td>KIWI A</td>
<td>No injuries to any personnel</td>
<td>Restructuring of LH2 supply system provided back-up, emergency cooldown system</td>
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<tr>
<td>Ejection of fragments of fuel elements from reactor</td>
<td>Exhaustion of hydrogen resulted in major damage to core</td>
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<tr>
<td>KIWI B1B test</td>
<td>No injuries to any personnel</td>
<td></td>
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<tr>
<td>KIWI B4A test</td>
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<tr>
<td>Ejection of fragments of fuel elements from reactor</td>
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<tr>
<td>Phoebus IA test</td>
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• Assessment of operation safety of nuclear rocket ground test program
  - Full-scale nuclear reactor/systems ground test can be conducted without injuries from nuclear processes
  - Full-scale ground test can be conducted in an environmentally acceptable test facility – complete containment of radioactive material

Engine Test Stand-1 (ETS)

• XE' only engine tested at ETS
• 77,000 gallon LH2 run tank
• Structure made of aluminum
• Engine surrounded by clamshell to provide high altitude simulation and reduce radiation effects on facility
• Duct made from 347 SS
• Steam ejectors reduced ambient pressure to 8 psia
• As engine pressure increased to 210 psia, ambient pressure dropped to 1 psia, then rose to 1.6 psia at 510 psi
Current Environmental Regulations

Radionuclides released into the air from DOE facilities are regulated by the National Emission Standards for Hazardous Air Pollutants (NESHAP 40 CFR61.90):

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.

An effluent treatment system is needed for NTP to insure emissions remain within regulations under all possible operating scenarios.

Effluent Treatment Options
Objectives of Effluent Treatment System (ETS)

1. Ensure that radioactive material entering the ETS remains in the subcritical geometry
2. Cool the test article effluent to temperatures acceptable for normal engineering materials used
3. Remove particulates and debris from the effluent stream
4. Remove halogens, noble gases, and vapor phase contaminants from the effluent stream
5. Flare hydrogen gas to the atmosphere
6. During test operations and accident conditions (including impacts of accumulated radiological material in the ETS) the releases are reduced to limits derived from the exposure regulation limits for workers and the public.

Note: Objectives from the Final EIS of the SNTP program 1993 [4]
Nuclear Furnace NF-1

- 44 MW in size and ran on GH2. 4500-5000 MW/m³ power density
- NF-1 test started in Summer 1972 and was last reactor test done before program canceled
- Six runs were made. Final two runs completed without incident
- Exit gas temperature above 4000R for 121 minutes and above 4400R for 109 minutes total
- Composite fuel achieved better corrosion performance, while carbide fuel had cracked extensively near center of reactor
- Only Rover/NERVA reactor test with filtered exhaust before burning hydrogen in flare stack and operated successfully

How did NF-1 Exhaust System Work?

Exhaust System:
- Some water after leaving the reactor is injected into the hydrogen exhaust to reduce temperature to 1100R and help capture many fission products released. Most water cooling reactor goes to holdup tank
- Filter is a two stage radial outflow with wire mesh screen
- The water/gas mixture passed through a series of heat exchangers and water separators. Collected water goes to waste disposal. Process water cooling the steam jenny and heat exchanger is vented to the atmosphere as steam or drained.
- Hydrogen continues through silica gel dryer and heat exchangers
- Dry hydrogen then passes through charcoal trap before the flare stack
- LH2 mixes with the flow to produce temperatures between 250-350R in the charcoal trap
- Collected water is held for radiation levels to drop with time, filtered, then disposed of in subsurface tile field. Contaminated water is filtered before disposal

Reactor:
- Heterogeneous water moderated beryllium reflected reactor containing 49 cells (47 composite and 2 carbide)
- Neutronic control by 6 rotatable drums
- GH2 supplied by tank farm at 3.7 lbs/sec at 690 psi
- Water flow to assembly is 50 lbs/sec
- Emergency water cooling for 200 seconds during shutdown to cool exhaust ducts
Radiation Levels in Effluent Exhaust System

- Radiation levels measured at typical positions in the exhaust system over sufficient length of time
- Measurements taken with gamma ray survey meter
- All components measured decay for 8 Ms with the half life of $^{140}\text{La}$
- High energy gamma rays in the exhaust system was high and slow to decay because of $^{140}\text{Xe}$ (13.1 second half life) leading to the deposition of $^{140}\text{La}$ on the system surfaces.
- ~10 seconds to travel through exhaust system
- Radiation level not attenuated greatly by steel of exhaust system components
- Decay of $^{141}\text{Ce}$ was also noticed throughout the system

NF-1 Exhaust System Lessons Learned

- Overall, the effluent treatment system was successful
- Pressure drop across filter much larger than expected
- Charcoal trap removed both radiokrypton and radioxenon from gas stream
- High energy gamma rays in the exhaust system was high and slow to decay because of $^{140}\text{Xe}$ (13.1 second half life) leading to the deposition of $^{140}\text{La}$ on the system surfaces.
- Decay of $^{141}\text{Ce}$ was also noticed throughout the system
- The cause for various instrumentation malfunctions was not “fruitful”
ARES Nuclear Thermal Propulsion Test Facility Concept

Top View

- Thrust=50k lbf
- Mass flow=57 lbs/sec
- Isp=875 seconds
- Exit area ratio 15:1
- Thrust Chamber Pressure=450 psia
- Total exhaust temperature= 4860R
- Max single run time 1 hour

Engine Test Cell with Exhaust Processing Facility

- Diffuser and LH2 Injection
- Water Heat Exchanger
- LN2 Heat Exchanger
- Debris Trap and Flow Divider
- HEPA Filter
- Absorber Beds
- Flare Stack

How does the ARES Concept Work?

- Diffuser slows the flow down to subsonic velocity
- LH2 spray injection brings exhaust down to 1800R, 93 lbs/sec
- Debris trap is two stage with large and small debris screens
- Flow divider divides the exhaust stream into as many as four parallel paths
- Water heat exchanger brings gases down to 590R, 3.5 Mgalons
- HEPA filter array to catch fine particulates
- Liquid nitrogen heat exchanger to bring down temperature to 180R, ~9 Mgalons
- Absorber beds use 8300 lbs of charcoal each
- Flare stack releases hydrogen and burns with the atmosphere
Borehole Option at Nevada Test Site (NTS)

• SAFE-Subsurface Active Filtering of Exhaust. Proposed by Steve Howe in the late 1990’s.
• Direct NTP into borehole and allow soil to filter exhaust of radioactive particulates and noble gases. NTS has unused boreholes ~1200’ deep and ~8’ diameter
• Eliminates many above ground scrubber sections
• Soil permeability is the driving factor for feasibility
• Exhaust entering borehole must be <600 C to avoid damage to borehole casing and alluvium soil

Engine firing down a borehole

Effluent Treatment System

How does Borehole Concept Work?

• Various soil models predict Alluvium permeability having potential to keep back pressure within 30 psia for long duration engine burns
• Exposing the exhaust to the borehole soil at deep locations will take the noble fission product gases (e.g., $^{85}$Kr) a long time to reach the surface

Mass fraction of $^{85}$Kr between 1hr and 100 years without hydrogen buoyancy. Up to two hours of injection. [8]
Past Borehole Test Results at NTS

A variety of soil models were used to determine borehole performance, but each had limitations. An investigation of other past borehole tests at NTS, which could be related to SAFE.

Preliminary Findings:
- The bottom half of the borehole only takes away a few more psi of total pressure with permeability. [10]
- Permeability seems best 300-600’ depth [11, 12]
- Permeability drops with source pressure at all depths. [11]
- Flow from laminar to turbulent reduces permeability [11]
- Research tests with alluvium soil represented by graded glass beads shows air permeability dropping with increased water content [13]
- Tracer gas (SF6) reached surface within a day about 180’ from bore hole due to possible cracks, geology variability, and atmospheric pressure changes [9, 10]

Borehole Concept at Idaho National Lab (INL)

- Impermeable interbeds above the water table and below the surface allows the exhaust to travel horizontal between the impermeable layers
- Preliminary results indicate better permeability than at NTS
Total Containment Concept

- Assume 5000 MW engine operating for 33 minutes
- Oxygen is injected in hydrogen exhaust to produce water vapor and then condense to room temperatures
- Residual gas can be chilled further and stored as a liquid for months between tests
- Requires 2 Gg of LOX and 8 Gg of cooling water
- Burner design a formidable problem
- Scheme worthy of closer examination

NASA Preliminary Concept for Total Containment

How it works:
- Hot hydrogen exhaust from the NTP is run into a water cooled diffuser.
- The diffuser transitions the flow from supersonic to subsonic to allow more efficient burning in the afterburner
- O2 rich afterburner-burns all H2. Products include steam, excess O2 and a small fraction of noble gases (e.g., xenon and krypton)
- Heat exchanger and water spray pulls heat from steam to lower the temperature and condense to liquid
- Water tank farm collects H2O and radioactive particulates. Drainage is filtered.
- Heat exchanger-cools residual gases to LN2 temperatures (freezes and collects most noble gases). Starts the flow of LOX
- LOX dewar stores LO2. Drainage via boil-off
- Meets any standards/regulations for post test release

Strategy:
- Fully contain NTP exhaust during burns to achieve as low as reasonably achievable (ALARA) for the best public and political support
- Slowly drain containment vessels after radiation levels drop to favorable levels. Use licensed filters.
Conclusions

- Current environmental regulations make ground testing more complex than open air tests done for Rover/NERVA

- The current NTP engine design is much lower thrust than was used in past ground test studies (50-100 klbf) for the various concepts.

- The smaller the engine and shorter the burn time, the lower the facility cost

- The selection of the most affordable ground test facility needs to also consider the entire ground test facility infrastructure required for the various exhaust handling concepts

References