Current Ground Test Options for Nuclear Thermal Propulsion

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Agenda

- Past Rover/NERVA Ground Test Options
  - Test Cells
  - Engine Test Stand
- Current Environmental Regulations
- Scrubber Options
  - Nuclear Furnace Demonstration
  - ARES Concept
- Borehole Options
  - Nevada Test site
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  - Los Alamos Study
  - NASA concept
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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

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Engine Failure 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]

- Phoebus 1A was a 1100 MWt engine, which failed from false gauge readings and ran out of LH_2.
- Emergency shutdown LH_2 now used.
- 5 other engines followed Phoebus 1A and were tested at test cell C

Dose rates at test cell C after failure. 20% core ejected. [1]

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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

[2]

Test Operations	Incidents	Remedial Action
• Test preparation accident • Test cart, test cell A • KIWI A	• 2 workers injured (eardrums & foot injuries) by ignition of leaking hydrogen in confined space	• Strict adherence to approved teststand operating procedures
• Ejection of fragments of fuel elements from reactor • KIWI B1B test • KIWI B4A test	• Flow-induced core vibration broke portions of fuel elements • No injuries to any personnel	• Redesigned core, eliminating flow-induced vibration
• Ejection of fragments of fuel elements from reactor • Phoebus IA test	• Exhaustion of hydrogen resulted in major damage to core • No injuries to any personnel	• Restructuring of LH_2 supply system provided back-up, emergency cool-down system

- 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

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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 510psia

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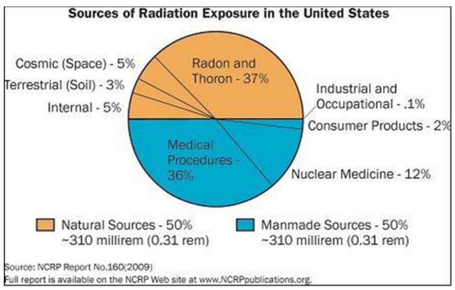
Current Environmental Regulations

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

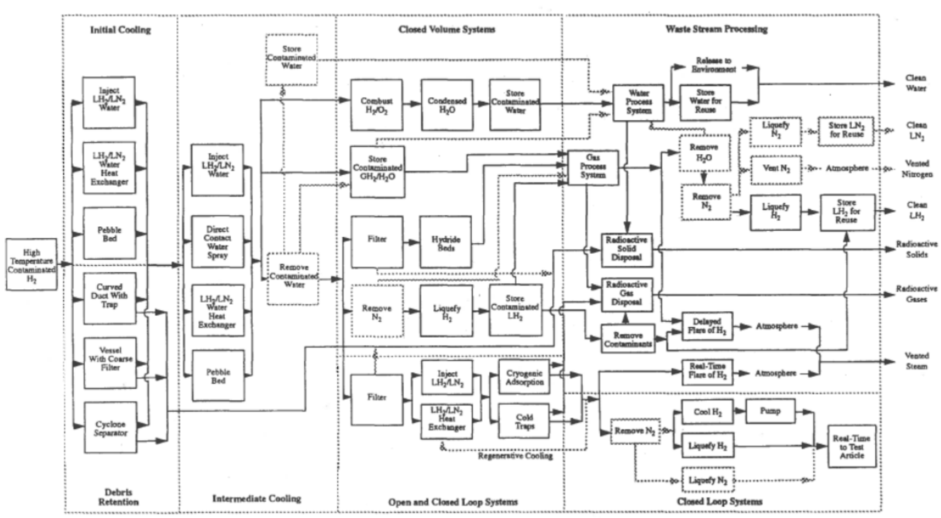
Emissions of radionuclides to the ambient air from Department of Energy facilities shall not exceed those amounts that would cause any member of the public to receive in any year an effective dose equivalent of 10 mrem/yr.



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

Effluent Treatment Options

[3]



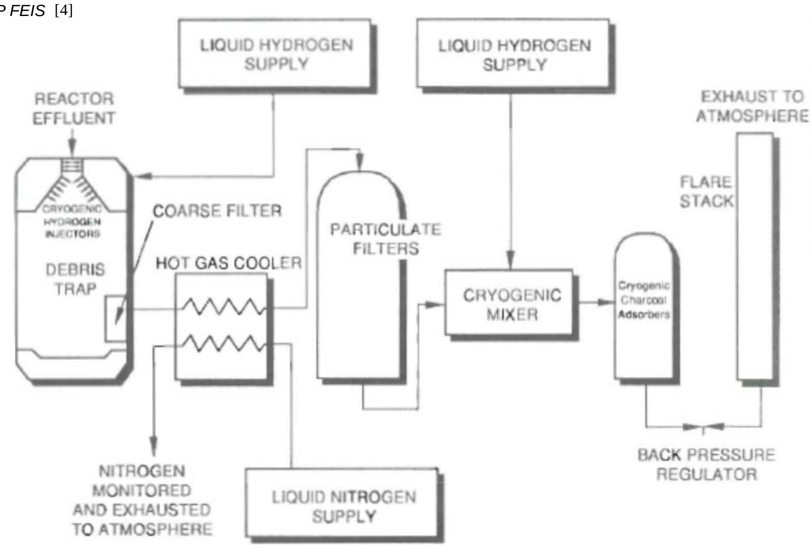
Objectives of Effluent Treatment System (ETS)

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 contaminates 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]

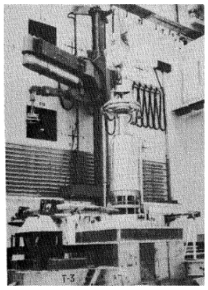
Effluent Treatment System Concept

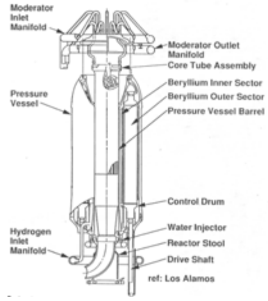
1993 SNTP FEIS [4]

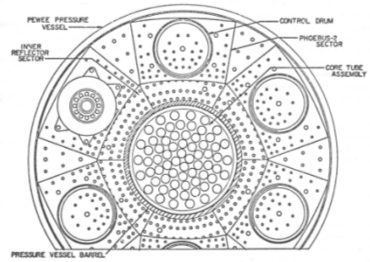


Nuclear Furnace NF-1

[5]





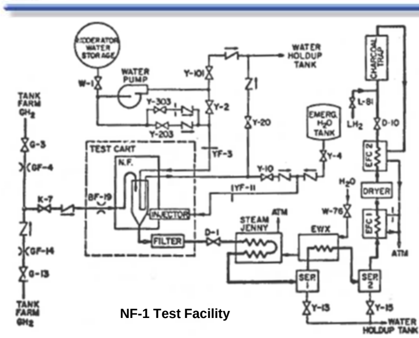


NF-1 Transverse View

- 44 MW in size and ran on GH2. 4500-5000 MW/m^3 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?

[5]



NF-1 Test Facility

Reactor:

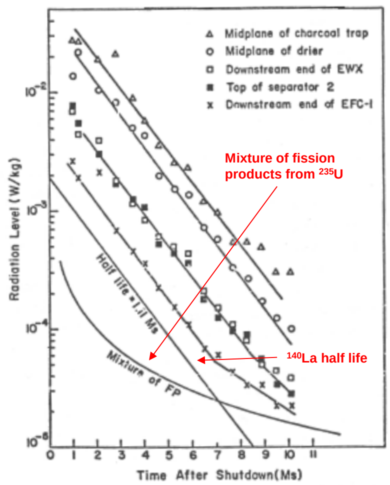
- Heterogeneous water moderated beryllium reflected reactor containing 49 cells (47 composite and 2 carbide)
- Neutronic control by 6 rotatable drums
- GH2 supplied by tank farm at 3.7 lbs/sec at 690 psi
- Water flow to assembly is 50 lbs/sec
- Emergency water cooling for 200 seconds during shutdown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

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

Radiation Levels in Effluent Exhaust System

[5]



Radiation Levels in Effluent Cleanup System after NF-1 Test

- 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}La
- High energy gamma rays in the exhaust system was high and slow to decay because of ^{140}Xe (13.1 second half life) leading to the deposition of ^{140}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}Ce was also noticed throughout the system

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NF-1 Exhaust System Lessons Learned

[5]

- 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}Xe (13.1 second half life) leading to the deposition of ^{140}La on the system surfaces.
- Decay of ^{141}Ce was also noticed throughout the system
- The cause for various instrumentation malfunctions was not “fruitful”

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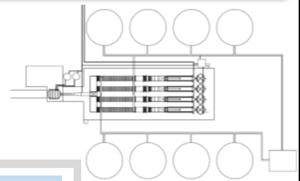
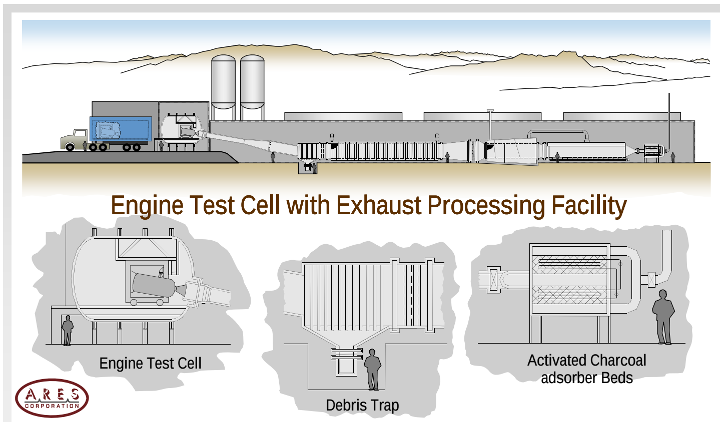
ARES Nuclear Thermal Propulsion Test Facility Concept

[6]

- 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

Top View





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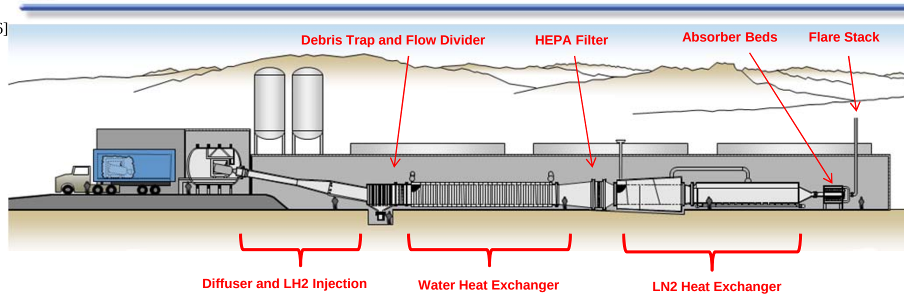
How does the ARES Concept Work?

[6]



- 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 Mgallons
- HEPA filter array to catch fine particulates
- Liquid nitrogen heat exchanger to bring down temperature to 180R. ~.9 Mgallons
- Absorber beds use 8300 lbs of charcoal each
- Flare stack releases hydrogen and burns with the atmosphere

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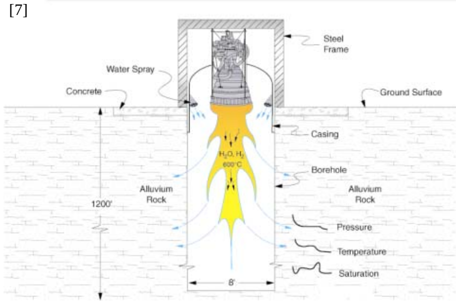
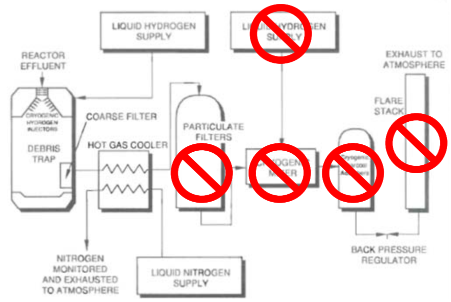
Borehole Option at Nevada Test Site (NTS)

[7]



Engine firing down a borehole



Effluent Treatment System

- 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

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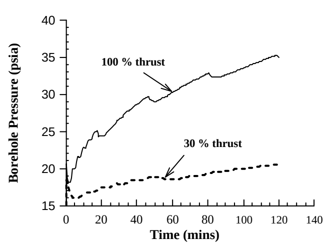
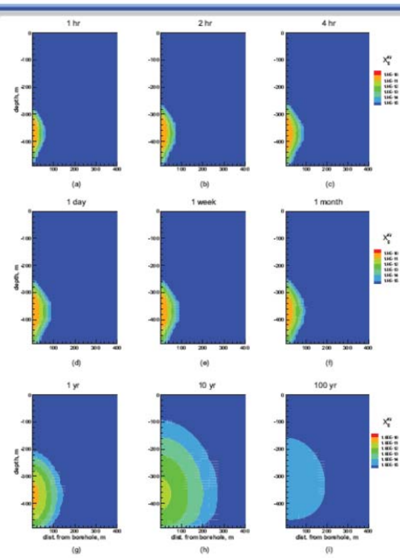
How does Borehole Concept Work?



100% thrust (162 lbs/sec water, 1.41 lbs/sec excess H2) and 30% thrust (45.2 lbs/sec water and .73 lbs/sec excess H2). [7]

- 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]

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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.

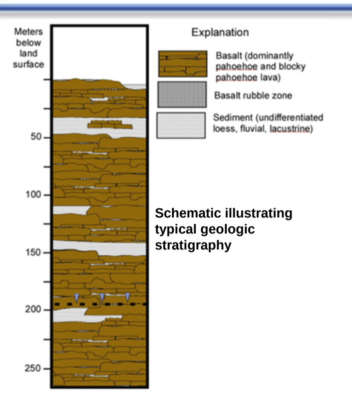
Field Measurements of Alluvium Permeability. Air Injector Setup at subscale hole. [9]

Preliminary Findings:

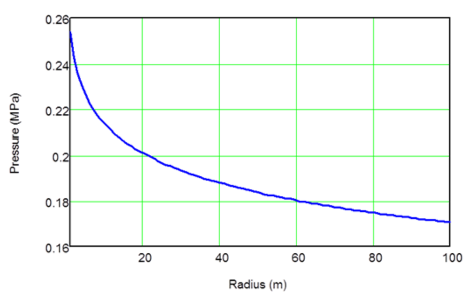
- The bottom half of the borehole only takes away a few more psi of total pressure with permeability. [10]
- Permeability seems best 300-600' depth [11, 12]
- Permeability drops with source pressure at all depths. [11]
- Flow from laminar to turbulent reduces permeability [11]
- Research tests with alluvium 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)

[14]



Schematic illustrating typical geologic stratigraphy



Soil pressure distribution after 2 hours of engine run time

- 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

[15]

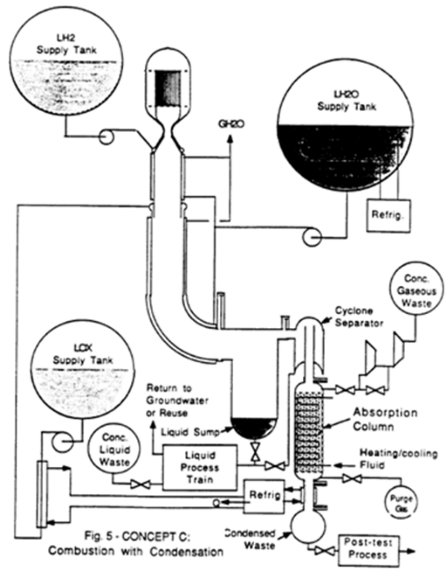


Fig. 5 - CONCEPT C: Combustion with Condensation

- 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

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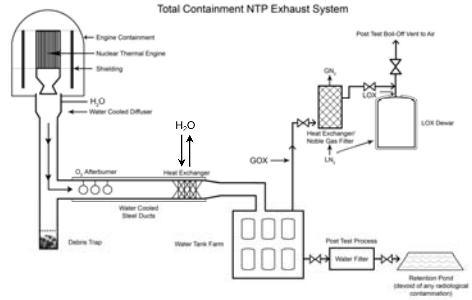
NASA Preliminary Concept for Total Containment

Total Containment NTP Exhaust System



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.

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
- O_2 rich afterburner-burns all H_2; Products include steam, excess O_2 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 H_20 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 LO_2. Drainage via boil-off
- Meets any standards/regulations for post test release

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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

1. Dewar, J.A., “To the End of the Solar System- The Story of the Nuclear Rocket”, Second Edition, Apogee Books 2007, p19, 56, 74, 83, 84,182, 207,
2. Gunn, S. V., “Development of Nuclear Rocket Engine Technology” MSFC NTP short course, 1992, section 14 page 4, 6, 27
3. Shipers, L.R., and Brockman, J. E., “Effluent Treatment Options for Nuclear thermal Propulsion System Ground Tests”, SAND—92-2085C, October 1992.
4. ”Final Environmental Impact statement Space Nuclear thermal Propulsion Program Particle Bed Reactor Propulsion Technology Development and Validation,” US Air Force May 1993.
5. Kirk, W. L., “Nuclear Furnace-1 Test Report”, LA-5189-MS, 1973, pp 3, 6, 10, 21-24, 73, 74
6. French, J. V., LaRue, P. F., “Nuclear Thermal Propulsion Ground Test Facility Concept Definition”, ARES Report 050250112-004, May 2006.
7. Howe, S. D., Travis, B., Zerkle, D. K., “SAFE Testing Nuclear Rockets Economically”, STAIF 2003 paper#242.
8. Howe, S. D., et al., “Ground Testing a Nuclear Thermal Rocket: Design of a subscale Demonstration Experiment”, INL/CON-12-26693 July 2012.
9. Morris, G. A., Snoeberger, D. F., Morris, C. J., Du Val, V. L., “Field Measurements of Permeability of NTS Alluvium in Area 10”, Lawrence Radiation Laboratory, UCID-15919, October 1971.
10. Snoeberger, D.F., Morris, C.J., and Morris, G.A.:“Field Measurements of Permeability in NTS Area 9,” Lawrence Radiation Laboratory, University of California, August 23, 1971
11. Keller, Carl, Engstrom, Dale, and West, Francis: “In Situ Permeability Measurements for the Event in U1-C,” Los Alamos Scientific Laboratory of the University of California, November 1973.
12. Snoeberger, D.F., Morris, C.J., and Morris, G.A.:“Field Measurements of Permeability in NTS Area 9,” Lawrence Radiation Laboratory, University of California, August 23, 1971
13. Springer, David, Loaiciga, Hugo, Cullen, Stephen, and Everett, Lorne:“Air Permeability of Porous Materials Under Controlled Laboratory Conditions,” Published in Ground Water, Vol. 36, No. 4, July 1998
14. Howe, S.D., McLing, T., McCurry, M., Plummer, M., “Final Report - Assessment of Testing Options for the NTR at the INL”, March 2013
15. Bohl, R., Hanson, D., and Edeskuty, F., “Planning for Ground Testing of Nuclear Rockets Engines with Today’s Environmental Awareness,” AIAA-1990-2517, pages 8-11.