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GROUND TEST FACILITY
FOR SEI NUCLEAR ROCKET ENGINES*

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Charles D. Harmon
Cathy A. Ottinger
Lawrence C. Sanchez
Larry R. Shippers

Sandia National Laboratories**
Albuquerque, New Mexico

Abstract

Nuclear Thermal Propulsion (NTP) has been identified as a critical technology in support of the NASA Space Exploration Initiative (SEI). In order to safely develop a reliable, reusable, long-lived flight engine, facilities are required that will support ground tests to qualify the nuclear rocket engine design. Initial nuclear fuel element testing will need to be performed in a facility that supports a realistic thermal and neutronic environment in which the fuel elements will operate at a fraction of the power of a flight weight reactor/engine. Ground testing of nuclear rocket engines is not new. New restrictions mandated by the National Environmental Protection Act of 1970, however, now require major changes to be made in the manner in which reactor engines are now tested. These new restrictions now preclude the types of nuclear rocket engine tests that were performed in the past from being done today. A major attribute of a safely operating ground test facility is its ability to prevent fission products from being released in appreciable amounts to the environment. Details of the intricacies and complications involved with the design of a fuel element ground test facility are presented in this report with a strong emphasis on safety and economy.

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Introduction

A major goal of the United States is a manned mission to Mars by the year 2019. Nuclear (fission) thermal propulsion (NTP) has been identified by the Stafford Commission as a critical technology for this mission.¹ The development of a NTP rocket engine has occurred in both the United States and the Commonwealth of Independent States (CIS). In the United States, development was initiated in 1955 as the ROVER/NERVA programs, with testing at the Nevada Test Site (NTS); in the CIS, at the testing facility at Semipalatinsk. Although the U.S. NERVA/ROVER program terminated years ago, the NTP rockets are now being revisited as the enabling technology for SEI manned flight missions. For these advanced missions, nuclear rocket systems have a clear advantage over current large chemical rockets in the area of specific impulse, a measure of the efficient utilization of the propulsion fuel. Solid core nuclear rocket engines will be able to provide specific impulse in the range of 800 to 1000 seconds, which is double the specific impulse of an advanced liquid fuel rocket engine and triple that of an advanced solid fuel rocket engine. Thus, with the same amount of fuel, thrust and velocity, a nuclear engine can transport twice the payload as that of a chemical engine. It is this performance feature that has kindled much interest into solid core nuclear rocket engine designs, i.e., a NERVA derivative and the particle bed reactor (PBR) engine design, for short duration missions to Mars. The need to have the shortest duration time as possible is prompted by the need to (1) reduce the exposure of flight crews to cosmic radiation, (2) mitigate as much as possible the biological effects of microgravity (especially bone loss, which has been observed to be on the order of 5% during an 80-day U.S. space mission), and (3) reduce the psychological, i.e., anxiety, boredom, stress, social withdrawal, etc., and interpersonnel problems that the flight crew will endure as a result of being separated from society for long periods of time.

A successful flight of a nuclear rocket engine requires a ground test facility within which engines can be safely tested to determine optimal engine design. This facility would be used after low power testing of fuel elements has been successfully performed in a conventional facility. The facility would be developed in two phases: (1) a subscale facility in which prototypic fuel element test reactors will be operated to test and qualify the fuel element design and (2) a full-scale facility in which NTP engines can be safely ground tested and qualified for flight testing. Examples of top-level requirements for the Prototypic Fuel Element Test Reactor and the Engine Ground Test Cell are shown in Tables 1 and 2.

Facility Testing

The philosophy of the ground testing activities is to approach prototypical conditions that will be experienced during a test flight in a stepwise manner through a series of tests over a multiyear period. In general, the ground tests are sequenced to commence with fuel-element testing, and progress through multiple assemblies that approach a prototypic assembly qualified for application to a flight vehicle. In the currently ongoing Space Nuclear Thermal Propulsion (SNTP) project, which is

**Table 1 Example of Top-Level Facility Requirements -
Prototypic Fuel Element Test Reactor.***

1. Test reactor configuration capable of simulating desired prototypical operating and transient conditions to fuel element(s) being tested.	7. Facility has robust instrumentation capability for meeting both operational requirements and experimental data acquisition needs.
<u>Operating Assumptions</u>	8. Facility has capability to test nonfuel components (for example, electronics, valves) in NTP environment (that is, radiation, hot H ₂).
Total Power > 50 MW Power Density: Prototypic value for given concept (2 to 20 MW/L)	9. On-site posttest examination and handling capability is the baseline with off-site inspection/examination capabilities an option, provided the associated handling, packaging, transportation, and posttest examination can be accomplished effectively and in a manner that does not perturb the test articles/assemblies or invalidate the test results.
<u>Test Environment: Hydrogen</u>	10. Facility lifetime and reusability should be sufficient for the entire NTP ground test program.
Exhaust temperature: 1000-3500 K Pressure: 15-1500 psia Duration/Cycles: Sufficient to test elements beyond design basis of engine test article (up to 2 h single burn, 4.5 h cumulative burn, up to 24 cycles).	11. Facility should be kept as simple as possible to reduce test costs.
2. Reactor has capability to test alternate fuel concepts with maximum reuse of components feasible.	12. Facility accommodates interim storage of test articles.
3. Facility is capable of fast turnaround of element tests.	13. Facility accommodates efficient decontamination, decommissioning, and disposal of waste.
4. Reactor complex will comply with all environmental and safety regulations. This includes being able to subject fuel to be tested up to and through failure thresholds as a planned, normal operational event.	14. Facility complies with applicable security and safeguards requirements.
5. Facility can supply process fluids as required for both operations and posttest decay heat removal according to specification.	15. Facility has capability for recovery and reuse after major fuel element failure event.
6. Facility can maintain effluent releases within regulatory limits and as low as reasonably achievable.	

*Example requirements were taken from findings developed by the Nuclear Thermal Propulsion Facilities Subpanel.² This subpanel evaluated facility issues related to nuclear thermal propulsion development and reported to the parent Space Nuclear Propulsion Test Facilities Panel. This parent panel was one of six interagency technology panels formed after a July 1990 NASA/DOE/DoD sponsored workshop on Nuclear Thermal Propulsion (for the purposes of a U.S. manned mission to Mars). See References 3 and 4 for additional information.

**Table 2 Example of Top-Level Facility Requirements -
NTP Engine Ground Test Cell.***

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1. NTP Engine Ground Test Facility will be colocated on same site or facility as Reactor Test Facility with maximum efficient use of same support infrastructure. Multiple test cells are anticipated for redundancy and to prevent scheduling conflicts.
 2. Test cells capable of supporting operations, meeting capability requirements for engine system verification, and engine flight qualification.

Operating Assumptions

Single engine tests with a total power up to 2000 MW

Maximum allowable normal operating exhaust pressure at nozzle exit: TBD

Thrust vector control operations: 0 to 5%

Exhaust mean exhaust temperature range: 1000 to 3500 K

coolant supply: liquid or slush H₂
20 - 40 K
25 to 100 psia

Topping or bleed cycle for turbopump
maximum single burn: 1-2 h
Cumulative reactor run times: 1.5 to 4.5 h
Restarts/Cycles: Up to 24

3. Tests cells can test alternative solid-core concepts.
4. Test cells can simulate or accommodate close coupling of lower portion of propellant tank.
5. Test complex will comply with all environmental and safety regulations.

6. Test complex will supply process fluids as required for both operations and posttest decay heat removal according to specification and will have ability to handle slush hydrogen.
 7. Facility will maintain effluent releases within regulatory limits and as low as reasonably achievable. Flaring of exhaust hydrogen is baseline.
 8. Facility has robust instrumentation capability for meeting both operational requirements as well as experiment data acquisition needs. (~1000 channels of experimental data anticipated).
 9. On-site posttest examination and handling capability is the baseline with off-site inspection/examination capabilities an option, provided the associated handling, packaging, transportation, and posttest examination can be accomplished effectively and in a manner that does not perturb the test articles/assemblies or invalidate the test results.
 10. Facility accommodates interim storage of test articles.
 11. Facility accommodates efficient decontamination, decommissioning, and disposal of waste.
 12. Facility complies with applicable security and safeguards requirements.
 13. Facility has capability for recovery and reuse after major fuel element failure event.
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*See Table 1 footnote.

developing a particle bed reactor (PBR) rocket engine and its open cycle testing facility,⁵ this anticipated test series includes the development steps shown in Table 3.

Facility Structures

The structures required for ground testing activities are identified in Table 4 and are shown schematically in Figure 1. The purpose and general description of the buildings follows:

Receiving and Assembly Facility (RAF) -- This structure will be used extensively for subscale operations in which fuel canisters will be assembled and inspected prior to insertion into the fuel element test reactor. Full-scale activities will be limited mainly to check-out of preassembled engines arriving at the test station. Because of the complexity of nuclear engine designs and the need for cleanliness during assembly, we anticipate that the engines will arrive at the test station almost completely assembled. The RAF will support a wide range of support services such as x-ray inspection, safeguards, machine shop support, etc.

Fuel Element Reactor Test Cell -- Although this test cell is simple in nature, its layout is extremely important with respect to safety and restricting emissions to acceptable levels. Following is a description of the most complex issues:

1. The test cell must insure that reactor effluent (even in the event of fuel element failures) will be directed into an effluent treatment system (ETS) designed to limit emissions, prevent criticality excursions, control posttest shutdown, and allow inspection.
2. An inerted or hydrogen depleted atmosphere around the test reactor must be maintained. This issue is paramount with respect to industrial safety. Current concepts inert enclosed regions and use fans in nonenclosed regions to prevent accumulations of leaking hydrogen gas.
3. The test cell must have ample shielding to reduce radiation doses to operational personnel. Any minimally shielded line of sight pathways (cable trenches, etc.,) must be avoided between the test cell and the control bunker. Since skyshine is also an important dose contributor, a shield cover needs to be used during testing operations. The main interface of the test cell with the ETS will be a debris trap located below the test stand for vertical firing orientations. This region will include an exhaust (effluent) quencher, debris trap, criticality mitigating devices, and coarse material filter banks.

Control Bunker -- This structure will be the only test station structure in which personnel may be present during an operational test. It will be used for both subscale and full-scale testing and will be heavily shielded. The radiation shielding requirements will attenuate direct radiation, skyshine, and worst-case accident scenarios.

Table 3 SNTP Particle Bed Reactor Ground Test Series

<u>Facility Test Phase</u>	<u>Test Series</u>
Subscale	Particle Bed Reactor <u>I</u> ntegral <u>P</u> erformance <u>E</u> lement <u>T</u> ester (PIPET)/Core A -- In this test series, two or more cores will be tested in a sequence of tests, which allow engine designers to determine fuel element performance and qualify the fuel element design methodology. Testing will procede in order to determine the fuel element capabilities, which then will be used to identify its design safety margin. A major facility will be the Effluent Treatment System (ETS), which will ensure that emissions from the test reactor will not exceed acceptable levels.
Subscale	PIPET/Core B -- In this test series, two or more cores will be tested in a sequence of tests that allow engines designers to determine the fuel element moderator capabilities and qualify the moderator design methodology.
Subscale	PIPET/Core C -- In this test series, two or more cores will be tested in a sequence of tests to qualify the reactor fuel canister material and design methodology. These canisters may be made of new structural materials (special components of carbon-carbon) because of the unique neutronic properties of the materials. Since the engine pressure vessel may also be constructed of the same material, this qualification testing will be important.
Full-Scale	Engine Integration Test (EIT) Series -- This series of tests will demonstrate the propellant management system without an operating reactor in the loop.
Full-Scale	Ground Test Series Series -- These tests will demonstrate a complete engine operation with feed and control hardware and full compliment of instrumentation including the prototype planned flight sensors. Tests will allow engine designers to optimize the engine design prior to the QTA testing.
Full-Scale	Qualification Test -- An engine that simulates the operation of the complete engine system at near prototypical flight conditions.

Table 4 Ground Test Facility Structure

Facility Test Phase	Facility Structure
Subscale	Receiving and Assembly Facility Fuel Element Reactor Test Cell Control Bunker Dry Storage Cells Fuel Element Reactor Effluent Treatment System Coolant Supply System
Full-Scale Additions	Engine Test Cell Ground Test Engine Effluent Treatment System Technical Evaluation Center Disassembly Building Engine Integration Test Cell

Figure 1. Ground Test Facility Structures (solid line structures are those required for subscale activities and dotted line structures are additions for full-scale activities).

Dry Storage Cells -- Adjacent to the Fuel Element Reactor Test Cell will be dry storage cells that will be used for interim storage of fuel elements canisters. After testing and thermal cooldown, irradiated fuel canisters will be stored for periods of several months prior to shipment to facilities capable of performing post-irradiation examinations (PIEs) of the fuel.

Fuel Element Reactor Effluent Treatment System -- The effluent treatment system reduces the concentration of contaminants in the reactor exhaust stream to acceptable levels prior to release to the environment.

The system functions for an open loop ETS are:

A schematic drawing for the current ETS concept is shown in Figure 2. There are alternate systems for dealing with effluent cleanup. The leading alternates include (1) venting the effluent into a closed chamber and slowly treating and releasing the effluent after reactor test operations and (2) using a closed loop system in which hydrogen effluent is cooled, filtered and recirculated. Trade studies indicated that these alternatives are more complex and expensive to implement than a full capacity open loop system for the expected flow rates in the Fuel Element Test Reactor (on the order of 50 – 100 lbm/s). For large flow rates, the open loop ETS is promising because its design can be scaled to passively handle the effluent. However, the open loop ETS will not allow full expansion-ratio nozzle tests and will have a system backpressure on the order of several hundred psi (ETS size scales roughly with the inverse of operating pressure).

Coolant Supply System -- The coolant supply system uses a tank layout shown in Figure 1. For subscale testing activities, the system uses a blow-down scheme in which high-pressure liquid H₂ Dewars are pressurized by gaseous H₂ tanks and are used to feed high-pressure cryogenic hydrogen to a mixer. High-pressure ambient temperature GH₂ is also fed to the mixer. Control valves regulate the temperature and pressure of the coolant feed to the test reactor (Figure 3). This coolant supply concept allows active control of the temperature and pressure of the reactor coolant. The blow-down scheme also provides a reliable coolant feed that does not require a system pump, which would require a large power source and would add possible system failure mechanisms. For full-scale activities, which include ground testing and qualification of the engine design, the hydrogen coolant supply system would receive additional LH₂ (for coolant feed) and GH₂ (for decay heat removal) tankage. For these activities, low-pressure LH₂ feed will be supplied to a turbopump assembly (TPA) or an engine hot bleed TPA, which in turn will supply the high-pressure feed for the engine.

Figure 2. Typical Effluent Treatment System for an Open Loop System

Figure 3. Blowdown Coolant Supply System Concept

Engine Test Cell -- The engine test cell will be similar to the fuel element reactor test cell in that enlarged coolant feed pipes and effluent treatment systems will service the test cell. A major addition may be the engine vessel support structure. Should the engine vessel be fabricated from lightweight carbon-carbon composites, it may not be possible to support thrust loads with vessel wall connections since these composite materials are weak in shear strength capabilities. In this case an overhead strut support structure will be used.

Ground Test Engine Effluent Treatment System -- This system will be a scaled-up version of the subscale ETS (scaling is roughly proportional to the total power) and the design will be optimized by using operational experience gained with the subscale ETS.

Disassembly Building -- The on-site disassembly building will be constructed during the full-scale additions. This disassembly facility will permit tested engines to be dismantled into components small enough for post-irradiation examination (PIE). Limited PIE capabilities will be maintained within the disassembly building when fast turnaround PIEs are needed. Otherwise the disassembled components will be sent to existing PIE facilities across the country.

Engine Integration Test (EIT) Cell -- This test cell will support non-nuclear tests of the engine management system and turbopump assemblies. This test cell will use LH₂ feed from the coolant supply system and will test with a nonnuclear engine simulator.

Previous Testing History and Present Requirements

Ground testing of nuclear rocket engines has successfully been done in the past during Project ROVER at the Nevada Test Site (NTS), Mercury, Nevada. The facilities used for the assembly, testing, and disassembly of the engine reactors are still in place at the Nevada Research and Development Area (NRDA), Jackass Flats, NTS. The majority of the facilities, however, have had many of the critical and high-cost components (tankage, valves, I&C, etc.) removed. Several of the structures could be refurbished to original working conditions at acceptable but significant costs; however, current requirements would prevent open cycle NTP testing in any of the NRDA facilities in their original design form.

Preliminary estimates indicate that corrective modifications to meet new standards would cost more than that needed to build new structures. These major corrective measures to the ROVER testing facilities are required to meet the National Emission Standards for Hazardous Air Pollutants (NESHAPs). In total there are in excess of 100 standards, regulations, and DOE orders that must be considered in the design, construction and operation of a nuclear fuel and engine test complex. Table 5 is a partial list of those standards and regulations. In addition, this facility does not meet current safety, fire protection, and OSHA requirements.

One potentially usable facility at NRDA may be the Engine Maintenance and Disassembly (E-MAD) facility. This structure has been kept intact and is potentially usable.

Currently there are two DOE sites (Nevada Test Site and Idaho National Engineering Laboratories) being considered for testing solid core nuclear rocket engines. The site selection will no doubt be based on the capability of the location to best meet environmental requirements.

Conclusion

A facility to perform nuclear thermal rocket fuel element development and engine ground testing has been presented. The major structures and support systems have been discussed. Flexible modular designs are employed to allow for future expansion and evolution of testing requirements. NTR ground testing was performed in the 1960s and early 1970s. While the facility design employs the experience gained in this early testing, more stringent environment requirements make direct application of the previous facility designs and operating procedures unacceptable. These increased environment requirements lead to the need for additional major facility systems (ETS) and have a significant facility cost impact.

**Table 5 Partial List of Standards,
Regulations and Orders for NTP Ground Testing**

- National Environmental Policy Act (DOE Order 5440.1C)
- General Environmental Protection Programs (DOE Order 5400.1)
- Hazardous and Radioactive Mixed Waste Program (DOE Order 5400.3)
- Radiation Protection of the Public and the Environment (DOE Order 5400.5)
- National Emission Standards for Hazardous Air Pollutants (NESHAPs)
- Occupational Safety and Health Act (OSHA) Standards
- 10 CFR 50, Appendix A General Design Criteria for Nuclear Power Plants
- 10 CFR 100, Reactor Site Criteria
- Safety of Department of Energy-Owned Nuclear Reactors (DOE Order 5480.6)
- General Design Criteria (DOE Order 6430.1A)
- Radiation Protection for Occupational Workers (DOE Order 5480.11)

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