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Assessment of Space Nuclear Thermal Propulsion Facility and Capability Needs

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Abstract: The development of a Nuclear Thermal Propulsion (NTP) system rests heavily upon being able to fabricate and demonstrate the performance of a high temperature nuclear fuel as well as demonstrating an integrated system prior to launch. A number of studies have been performed in the past which identified the facilities needed and the capabilities available to meet the needs and requirements identified at that time. Since that time, many facilities and capabilities within the Department of Energy have been removed or decommissioned. This paper provides a brief overview of the anticipated facility needs and identifies some promising concepts to be considered which could support the development of a nuclear thermal propulsion system. Detailed trade studies will need to be performed to support the decision making process.

Introduction: Nuclear Thermal Propulsion (NTP) rocket stages have been shown, in past and recent mission studies, to greatly reduce the propellant mass and number of launches from earth for deep space missions and manned missions to Mars. This is because NTP systems have a large specific impulse (Isp) advantage over the best chemical rocket engines. The Isp for NTP systems is about double that of the best liquid oxygen/liquid hydrogen rocket engines. NTP systems also have an advantage in that the required velocity to perform the transient to Mars from Earth orbit and the required deceleration at Mars can be accomplished with much smaller propellant load and a shorter transient time. The propellant load reduction in turn translates to fewer heavy lift flights from the Earth's surface to assemble a Mars mission vehicle. Reducing the number of lifts from the Earth reduces the risk of delay and potentially missing a departure window. The development of an NTP system rests heavily upon being able to fabricate and demonstrate the performance of high temperature nuclear fuel as well as demonstrating an integrated system prior to launch. A number of studies have been performed past identifying the facilities needed and the capabilities available to meet the needs and requirements identified at that time. Since that time a number facilities and capabilities within the Department of Energy have been removed or decommissioned and new requirements for construction, permitting and operations emplaced.

Background: Since the early 1970's very little development of NTP fuels and materials or fabrication and test capabilities that could support such a system have occurred. While the debate continues between mission pull and technology push, two key questions that need to be answered are what facilities and equipment are needed to fabricate the various fuels, materials and sub-systems of an NTP and how do we identify the critical set of requirements needed to qualify a nuclear rocket engine for launch in the most cost effective and realistic timeframe?

An extensive nuclear thermal rocket technology development effort was conducted between 1955 and1973 under the Rover/NERVA Program. Candidate fuels for NTP applications included both graphite based fuels and CERMET (W-UO2) fuel) types. The major design effort was on the NERVA graphite fuels and reactor systems. Numerous engine ground tests were conducted during the NERVA program. Fuels development and engine development activities were carried on in parallel early in the program with complete engine tests effectively serving as fuels development tests. The desire for lower costs, shorter lead times and less release of radioactive materials into the environment encouraged development of the Nuclear Furnace test reactor. The Nuclear Furnace tests required a smaller number of fuel elements for a critical reactor configuration and multiple fuel element types could be tested simultaneously. Fuel performance could be demonstrated before conducting a full engine test. The facility also demonstrated an effluent treatment system.

In the Early 1990's a team of experts from NASA, DOE, DOD, and the private industry assembled to:

- Define NTP test facility requirements,
- Evaluate existing facility capabilities to meet these requirements,
- Identify new facility development or existing facility modification needs,
- Identify critical path facility development requirements, and
- Recommend facility development strategies.

The team identified a list of facilities and capabilities that were needed to support NTP development effort[1]. An initial assessment of the availability of facilities that can currently meet the identified facility categories is provided:

Table 1 NTP Facility Need and Current Capability Assessment[1]

Facility Category	Definition	Current Capability
Fuel Fabrication Facilities	Facilities for development and eventual production of enriched uranium nuclear NTP fuel materials and fuel elements	Fuel production facilities do not exist Limited laboratory scale equipment is available for fabrication of material coupons and segments and coatings
Test Facilities for Unirradiated Fuel and Materials	Fuel and material testing and characterization laboratories capable of handling unirradiated uranium fuel and materials	Capability exists at DOE and NASA centers.
Hot Hydrogen Flow Test Facilities	Facilities featuring materials or subsystems in a flowing hot hydrogen environment without nuclear heating. The facility should be able to heat elements or components up to 3200 K. Hot hydrogen flow test facilities include the following three types: 1) Fuels and Materials / low flow rate used for material and fuel coupon or segment tests 2) Equipment Development / high flow rate used for testing of partial or full	Compact Fuel Element Testing (CFET) and the other is the Nuclear Thermal Rocket Element Environmental Simulator (NTREES) at NASA facilities for unirradiated material. None exist at DOE facilities or for irradiated material.

	length components. 3) Equipment Development / Low and High flow rate for testing of irradiated fuel and components	
Fuel and material Irradiation Test Facilities	Reactor or radiation source facilities that provide a gamma or neutron fluence to a test specimen of uranium fuel material and structural or non-fuel-bearing material	Advanced Test Reactor and High Flux Isotope Reactor are available No fast reactors are available within the US lead test assembly capabilities exist at both INL and ORNL.
Low Power Critical Assembly Test Facilities	Low power, flexible geometry, variable material volume fraction reactor facility for physics benchmark, design confirmation, and safety tests.	Critical facilities have been established at the Device Assembly Facility at the Nevada National Security Site
Prototypic Fuel Element Test Reactor	Test reactor in which all desired performance parameters (time, temperature, pressure, power density, etc.) can be achieved together for experiments on one or more prototypic fuel elements.	None
Reactor Test Cell	Portion of a Reactor/Engine Test Facility where early "engine-like" reactors would be tested at high powers on the ground	None
Engine Test Cell	Portion of a Reactor/Engine Test Facility where "flight-like" nuclear rocket engines would be tested at high powers on the ground	None
Remote Inspection/Post-Irradiation Examination Facilities	Hot cell facilities where post-test examinations of radioactive fuel, reactor, and engine components will be conducted	Hot Fuel Examination Facility at INL is capable of performing PIE examinations of fuel elements and fuel segments. No facilities exist for engine assembly or disassembly of engine components.
Component Test Facilities without Hot Hydrogen or Irradiation Environment	Facilities that can simulate structural, thermal, and cycling environments during startup,	None

	continuous lifetime operation, and shutdown on system components. However, environments would not include irradiation or hot hydrogen	
Control System Test Facilities	Simulation laboratory to develop and test engine/system control system	None
Component Safety Test Facilities	Test facilities that can subject system components to anticipated malfunctions or accident environments	None
System-Level Safety Test Facilities	Test facilities that can simulate on the complete engine all realistic malfunctions and severe or accident environments	None
Training and Simulator Test Facilities	Facilities for operator/astronaut training. Emergency sequences would be simulated for training.	None
Engine Integration Test Facility	Cold flow test facility for complete engine system. Facility would use a hot gas to simulate nuclear heating and to evaluate potential pre-flight and flight problems. No nuclear critical operations or nuclear heating would occur.	None
Flight Test Facilities	Ground facilities at launch site or operations control center required for launch support or operations specifically as a result of having nuclear propulsion systems	None

The 1990 assessment concluded "This study revealed that the United States has a wealth of test facilities available for supporting NTP development. While some modifications will be required to support specific NTP development actions, there is a solid base of existing facilities available to satisfy a large majority of the test needs. Of the six test categories where no existing facilities were clearly identified, three are anticipated to either not be needed (e.g. system-level safety test facilities) or could be incorporated into other categories, or modifications to existing facilities (e.g., flight test support facilities or training and simulator test facilities) could be made."[1]

Current Day Assessment: Much of the report's findings regarding the type of infrastructure and equipment needed are valid today. However, since the time of this assessment much has changed regarding the availability and operation of the facilities and infrastructure to support the development of an NTP system today. Some facilities identified in the study no longer exist or have changed enough in capability that they are not viable for use. Three facility and capability needs central to any renewed NTP development effort have been identified in all historical and recent assessments. They are:

- NTR fuel fabrication capabilities to include process methods,
- Test facilities for fuel and material design, development and qualification, and
- A ground test facility for a system reactor and engine development and qualification effort.

The following paragraphs provide a general assessment of existing capabilities and future needs in these three areas.

<u>Fuel fabrication facilities</u> – The top level facility requirement is that it must be a Category I Nuclear Facility capable of processing core load quantities of high enriched uranium (HEU) fuel elements per year while fully complying with all environmental, safety and health requirements. The fuel fabrication procedures must be defined and demonstrated, the technical basis for the specification identified and techniques to demonstrate compliance and quality assurance understood. There currently are two existing HEU facilities that are capable of supporting such an effort. However, additional floor space and equipment would be needed in either facility. Oak Ridge National Laboratory is currently working to recapture the extrusion and coating processes for NERVA fuel and the Marshall Space Flight Center is developing process fabrication techniques for a W-UO2 CERMET fuel. Both of these efforts are limited to using either a uranium surrogate or depleted Uranium. Both are using laboratory scale equipment for their development efforts. Once a fabrication process has been defined and demonstrated, the production facility requirements regarding equipment scale and production specification and measurement techniques will need to be defined. It is estimated that it would take 8 years before the first fuel production runs could be established.

<u>Test facilities for fuel, material and reactor systems</u> – Facilities and equipment are needed characterize the fuel and material for its chemical, thermal, and structural properties and for evaluations needed to improve performance and design data and understand how the fabrication process affects these parameters. Equipment such as measuring the thermal stability of the fuel and coatings at elevated temperatures (3000 - 3500 K), stress resistance, material creep, component compatibility, and effects of hydrogen penetration, chemical interaction and formation, and mass loss are needed. In addition as identified in earlier studies nuclear system component development and testing (instrumentation, control, materials, valves, pumps, etc.) facilities will be needed. Some of this equipment may be available at DOE Labs or NASA research centers, but none as of yet are dedicated to this project. A program systems study is needed to determine what types of experiments and facility equipment is needed and how it would fit into a complete fuel and reactor system development effort. An integral part of any testing program will need to be the development of a number of fuel modeling codes to predict fuel and material performance and guide the types of tests as well as the neutronic, thermal, mechanical and chemical measurements needed.

<u>Hot hydrogen test facilities</u> – The use of electrical heating in combination with exposure to hot hydrogen gas can be very beneficial in the early development phases of fuel behavior, reactor-propellant surface interactions, component design, and system design. But these methods must be verified and validated in some manner. Since these approaches use externally-generated inductive, resistive, or convective heating methods, the energy deposition profile within the fuel elements will not match the energy deposition profile that corresponds to internal fission-generated heating. The

use of those electrical heating methods also includes some risk of introducing new failure modes that would not be present in the real operating environment. Some progress has been seen in this area in the past decade. MSFC has developed two systems to support hot hydrogen testing. One is the Compact Fuel Element Testing (CFET) and the other is the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)[2]. The purpose of the NTREES facility is to perform hot hydrogen non-nuclear testing of NTR fuel elements and fuel materials at prototypic high flow rates and temperatures. Electrical heating and other conventional test methods cannot duplicate the effects of irradiation and the effect of fission fragments accelerating fuel migration or breakdown of the fuel structural integrity so irradiation testing is essential to the development of nuclear fuel for NTP. Hot hydrogen test facilities to test fuel that contain LEU or HEU materials need to be developed as well as fuel that has been irradiated these should be built so they can be supported by existing Hot Cells and fuel PIE and nuclear fuel diagnostic equipment.

Fuel and material irradiation test facilities – The irradiation test facilities and capabilities in the United States have dramatically reduced since the 1990 assessment. The remaining operational test reactors are the Advanced Test Reactor at Idaho National Laboratory and High Flux Isotope Reactor at Oak Ridge National Laboratory[2]. There are no fast spectrum test reactors operational in the United States. The primary challenge in irradiation test design for NTP fuels and materials will designing the test assemblies to operate at the very high temperatures at which an NTP system operate and match as closely as possible the neutron energy spectra and the fuel energy density. It is unlikely that a low flow or purge hydrogen flow rate can be accommodated into the reactor test assembly due to safety concerns. Capabilities exist at both ORNL and INL to design, build, instrument, and install the test assemblies into the test reactors. Significant time may be needed to complete the design and safety analysis to permit there types of tests to be conducted. However, the ability to build and understand fuel performance through computational analysis and models is one area where todays capabilities and understanding far exceed what was available in the 1970s and even 1990s. Using multi-physics codes such as the INLs BISON can be used to effectively model the fuel performance and determine the effect material or fabrication processes have no the fuel performance. Using such analytical codes enable the use of separate effects fuel data to be used to determine the fuels system performance. So the number and types of nuclear irradiations and PIE analysis may be sufficient to determine the performance and boundaries of a certain fuel type so as to qualify it for use in a larger reactor core or engine systems test. But the development of the model and benchmarking of the model needs to proceed jointly with the fuel fabrication and fuel testing efforts.

Ground test facilities – Developing the capability to conduct large system testing of an NTP has been recognized as one of the largest and most costly aspects associated with developing a NTP flight system. Any current or future NTP development effort will be subject to vary different constraints than what was conducted in the past Rover/NERVA program. An exhaust effluent treatment system to trap fission products and radioactive noble gases released from the fuel during power testing will be required due to federal state regulations, in particular the National Emission Standards for Hazardous Air Pollutants (NESHAP), that respond to increased awareness of the consequences of environmental releases.

In the late 1980s and early 1990s, as part of the Space Nuclear Thermal Propulsion (SNTP) Project, Sandia National Laboratory evaluated a number of effluent treatment systems for the SNTP ground test facility. Based on the operating environment for the SNTP Program, Sandia selected a process that minimized the use of water in cleaning up the effluent [3]. Due to the extensive conceptual design effort performed by Sandia, this concept has subsequently been accepted as a baseline for future evaluations of nuclear thermal propulsion systems (Figure 1). This concept used a large amount of liquid hydrogen and liquid nitrogen. For every pound of hydrogen flowing through the reactor, three additional pounds were needed to cool the effluent and allow the trapping of the noble gases in the cryogenic traps. Though the test program was also based on a 550 MWt reactor, the test period was relatively short, ~1000 sec at full power. [4]

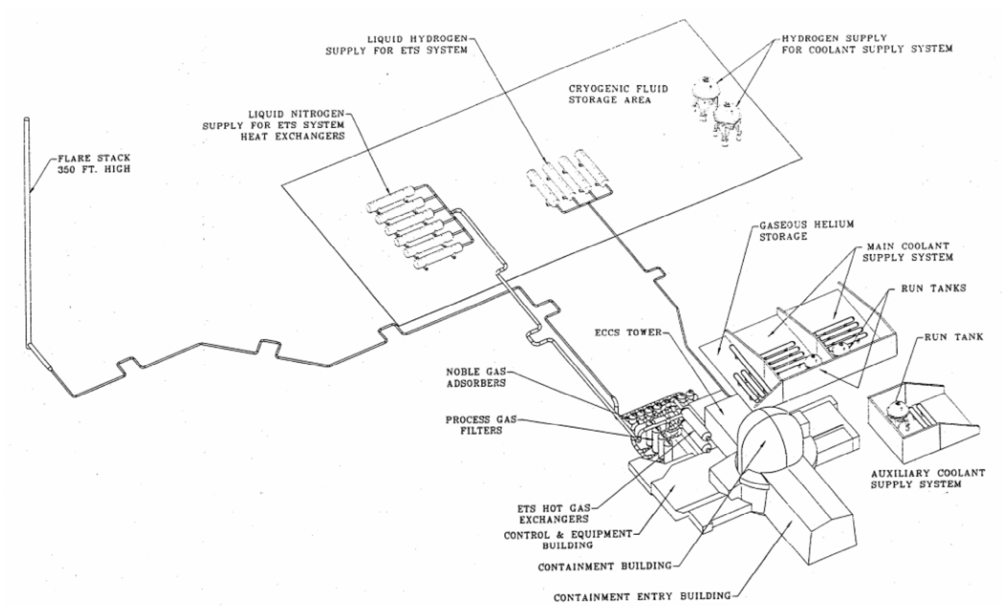

Figure 1 – NTP Ground Test Facility and Effluent Treatment System

In 1995, DOE supported a study of a system to trap and collect the hot hydrogen effluent and store it during the test duration. The study was based on an 11.5 MWt reactor operating for 5 hours (Fluor, 1995). Based on this design case, other options were scaled, including a 550 MWt reactor operating for 500 sec. The hydrogen was stored in large steel tanks until the effluent could be treated and liquefied for recycling in the next test. The effluent treatment collection system was limited in size and depending on the test duration, the pressure in the effluent treatment system could build to 200 psig. For the baseline study of a 5 hour test, hydrogen recovery was expected to take 5 days.

The effluent treatment system for the NTP system has very few development needs, but system studies to evaluate the scale-up costs, operations and technical viability of these options are needed. The SAFE concept has the potential to significantly reduce the capital costs for a nuclear ground test, but several sub-scale feasibility tests are needed to understand the feasibility and performance of such a system before it is considers a viable alternative. [4]

Additional facilities and operations would be needed in addition to the reactor test facility. A control room or building with associated instrumentation, controls, and data acquisition system will be required. A facility for engine assembly, checkout and storage prior to placement in the test cell would also be needed. For disassembly, examination, and preparation for disposal of the NTP after completion of the test program, access to a shielded hot cell facility will be required. A shielded enclosure would also be required to load the NTP reactor or reactor fuel and components into shipping containers for transfer to a hot cell for examination.

An alternative to the complex effluent treatment system described above is the Subsurface Active Filtration of Exhaust (SAFE) Facility[5]. The NTP concept for SAFE would be sealed at the surface, and as effluent is discharged into a bore-hole, the pressure would build to the point where the gas and water vapor from the effluent cooling system would be driven into the porous soil or rock at a rate equal to the mass flow from the NTP. At equilibrium pressures, the NTP could be operated for long periods over a wide range of power levels (Figure 2).

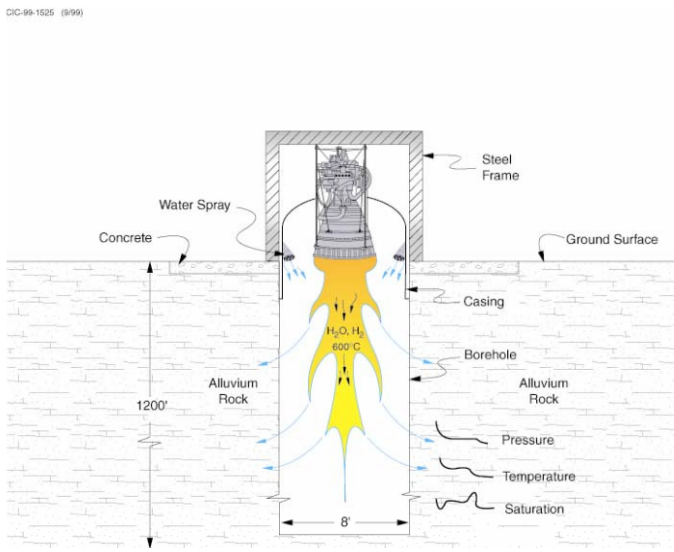

Figure 2 – Subsurface Active Filtration of Exhaust Concept[5]

Initial studies of the SAFE concept indicate it would need a borehole eight feet in diameter by 1200 feet deep. This is a typical borehole used for underground weapons tests. The upper 100 feet would be steel encased, with the remainder of the borehole would be uncased and open to the NTS alluvial soils. Cooling water would be sprayed into the borehole to limit the exhaust temperature and prevent damage to the steel structure. Simulations indicate that a maximum back pressure buildup in the borehole would be 36 psi.[4]

Facilities that do not exist –The following facilities do not currently exist. It is unknown at this time how much of this would need to be built or its function assimilated into a new complex such as the ground test facility or facilities for the fabrication of flight unit or engine integration with a launch system.

- Prototypic Fuel Element Test Reactor
- Control System Test Facilities
- Component Safety Test Facilities
- System-Level Safety Test Facilities

- Training and Simulator Test Facilities
- Engine Integration Test Facility
- Flight Test Facilities

A detailed systems study is needed to determine above the three critical facility capabilities are needed to support a mission or can their function be incorporated into facility to be built or added to existing structures that will be used in support of an NTP program. A separate effort is needed to identify, define, and obtain some uniform consensus of the test, qualification, safeguards and safety requirements needed to first qualify a nuclear rocket engine and second have a clear understanding of the required facility operations, analysis, and approval process for the launch of a reactor system. Pursuing these efforts early in the development program allows for effective integration of these requirements and facility options into the design of new facilities ensures that appropriate cost and schedule management techniques can be applied so that coats are identified upfront and developed as needed.

References:

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