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Ground Test Facility for Propulsion and Power Modes of Nuclear Engine Operation

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Abstract
Existing DOE Ground Test Facilities have not been used to support nuclear propulsion testing since the Rover/NERVA programs of the 1960's. Unlike the Rover/NERVA programs, DOE Ground Test facilities for space exploration enabling nuclear technologies can no longer be vented to the open atmosphere. The optimal selection of DOE facilities and accompanying modifications for confinement and treatment of exhaust gases will permit the safe testing of NASA Nuclear Propulsion and Power devices involving variable size and source nuclear engines for NASA Jupiter Icy Moon Orbiter (JIMO) and Commercial Space Exploration Missions with minimal cost, schedule and environmental impact. NASA site selection criteria and testing requirements are presented.

Nomenclature

ATR = Advanced Test Reactor
CEV = Crew Exploration Vehicle
CFR = Code of Federal Regulations
DOE = Department of Energy
DOE-MD = Department of Energy Office of Fissile Materials Disposition
DWPF = Defense Waste Processing Facility
ETS = Effluent Treatment Systems
FMDP = Fissile Materials Disposition Program
HEU = Highly Enriched Uranium
HPS = Heatpipe Power System
INEEL = Idaho National Engineering and Environmental Laboratory
JIMO = Jupiter Icy Moon Orbiter
LEO = Low-earth Orbit
NASA = National Aeronautics and Space Administration
NDR = NERVA Derived Reactor
NEP = Nuclear Electric Propulsion
NRDA = Nuclear Research and Development Area
NTP = Nuclear Thermal Propulsion
PCU = Power Conversion Unit
SAFE = Safe Affordable Fission Engine
SEI = Space Exploration Initiative
SRNL = Savannah River National Laboratory
TRL = Technology Readiness Level

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I. Introduction

On January 14, 2004, President Bush presented a new vision for the space exploration program. Similar to a speech by John F. Kennedy initiating the National Aeronautics and Space Administration (NASA) Apollo Program to land an American on the moon before 1970, President Bush stated to the American public, "[our] goal is to return to the Moon by 2020, as the launching point for missions beyond [1]." He further challenged NASA to build a new spacecraft called a *Crew Exploration Vehicle* (CEV) by 2015, and send spacecraft from earth orbit to "Mars and to worlds beyond." *This* vision is implemented by NASA using a systems engineering approach in Project Constellation, which includes detailed planning for all manned and unmanned missions for the Space Exploration Vision. The report from the *President's Commission on the Implementation of the United States Space Exploration Policy* [2] identified Nuclear Thermal Propulsion (NTP) as the nears term, highest Technology Readiness Level (TRL) advanced propulsion technology available for application in the CEV to get the 2004 Moon-Mars vision implemented within the schedule requirements of Project Constellation [3]. The total propulsion system envisioned for manned and unmanned missions will need to provide high thrust (e.g., 23 to 334 kN, mission optimized) to keep planetary departure/capture times to the minimum and maximize spacecraft system life and durability. The electric power capability from a bimodal nuclear thermal propulsion system can effectively output 10 kilowatts to several hundred kilowatts depending on the scaling of the Brayton Power Conversion Unit (PCU). Nuclear Test facilities will be required to develop systems to integrate with the NTP system.

II. Design Features of Nuclear Propulsion Systems and Testing Status

Four solid core NTP concepts have been studied by NASA and NASA contractors for the Space Exploration Initiative (SEI) missions. The NERVA Derived Reactor (NDR) concept (by the Rocketdyne/Westinghouse team) and the Russian "Twisted Ribbon" concept (Aerojet/Energopool/B&W team), are the only concepts that have verified proof-of-concept through reactor testing [4]. The Pebble Bed Reactor (Aerojet/B&W team) has yet to complete a successful fuel element test. The CERMET (Pratt & Whitney/B&W team), while studied in the 1960's, is essentially a new conceptual design, at an early technology readiness level.

The NERVA concept was studied extensively in the 1960's and early 1970's in this country. Of the NTP concepts studied for SEI, the NERVA technology and concepts are the most thoroughly proven, tested and developed. No other concept has undergone the extensive full system testing of the NERVA concept. Composite fuels and improved coatings were tested late in the NERVA nuclear furnace tests up to 2700 ^{o}K. NDR system design will accommodate evolution to ternary carbide fuels as they are developed (to 2900-3100 ^{o}K). There is a substantial NERVA database; detailed system design and full system tests have been completed and system improvements identified. NDR concept development is expected to be the lowest technical risk, lowest cost, and shortest development schedule to technology readiness.

A distinguishing feature of the Pebble Bed Reactor is the direct hydrogen cooling of small (400-500 micrometer diameter) coated particle fuel spheres. The fuel is packed between two concentric porous cylinders, called "frits," which confine the fuel but allow coolant flow around the particles. A number of these small annular fuel elements would be arrayed in a cylindrical moderator block to form the Pebble Bed Reactor core. Coolant flow is directed radially inward, through the packed bed and hot frit, and axially out through the inner annular channel. Because of the large heat transfer area of the Pebble Bed Reactor element, bed power densities two to ten times larger than the peak power densities demonstrated in the NERVA program may be possible. Some particle manufacturing capability exists, derived from the high temperature gas-cooled reactor programs and the Air Force SNTP program. A Nuclear Element Test was used to validate fuel particle characteristics in a single fuel element in the Sandia National Laboratory Annular Core Research Reactor. The first test, designated NET-0 was a non-nuclear fueled element which was electrically heated to allow testing of cooperative control and test hardware under prototypical conditions without the additional problems that would be posed by equipment failures in a nuclear activated environment. However, this test, conducted in October 1991, failed due to loose graphite particle fragments that blocked the flow of propellant. Resolution of this anomaly was still pending identification of the source of these particles. According to one interpretation, the particles originated in the electric heaters used to simulate operational thermal conditions. Another interpretation, which would be consistent with prior anomalies, was that the particles resulted from fragmentation of the fuel particles themselves, which would suggest that the present fuel particle design has not resolved the particle structural fragility previously identified in the PIPE-2 test. Very high fuel temperature capability has been claimed for this concept, but must be verified. Since there are relatively low structural loads on the fuel particles, the high strength outer coating on the particle may help to contain fission products. A very large surface-area-to-volume ratio maximizes the heat transfer area for each particle, and the tiny particles have a very short heat transfer path, so the fuel sphere surface temperature can be maximized. A conceptual design study for a man-rated SEI Pebble Bed Reactor system was conducted by the Aerojet/B&W team in 1992. For a 75,000 pounds force engine and a 2770 ^{o}K reactor exit temperature (specific impulse of 915 seconds), the system thrust-to-weight ratio was calculated to be 7.2, including shielding. Proof-of-concept testing of the Pebble Bed Reactor will be required to verify (1) mass loss (particle lifetime) versus temperature at prototypic power generation rates and cooling flow rates, and (2) coolant flow distribution, control, and stability. Currently, no experimental reactor exists that is capable of the very high power densities required to test these fuel elements; the Air Force had initiated a design of a fuel element test reactor, but the SNTP program including this design was terminated. The Pebble Bed reactor concept is considered to have high technical risk because of the early state of the development. The fundamental feasibility of the concept must be established in full power, full hydrogen flow tests, as well as startup and shutdown ramps. The Air Force PIPET reactor was designed for this purpose, but was terminated with the SNTP program.

The Russian “Twisted Ribbon” reactor is a heterogeneous design that uses a hydrogen-cooled ZrH moderator and ternary carbide fuel material. Warm hydrogen from the moderator is used to power the turbine. The relatively cool operating temperature of the moderator and core support should enhance the overall robustness of the design, while permitting the use of low-temperature moderator materials. The fuel element is an axial flow design with a high surface-to-volume ratio. High power densities and minimum core mass characteristics result in power densities of about 0.3 MW/kg. Maximum fuel element operating temperature is expected to be about 3200 ^{o}K. During reactor tests, gas exit temperatures of 3100 ^{o}K for one hour and 2000 ^{o}K for 4000 hours, were reported in Russia. Life of the Russian element at ROVER-NERVA demonstrated temperatures is expected to exceed 25 hours. The design allows for optimization of the power density across the core by changing the spacing of the fuel elements in both the radial and circumferential directions. This provides a more uniform fuel and exit gas temperature at each element, thus reducing the required margins between the design point and the limiting fuel element temperature that must be maintained to provide life and reliability requirements. Thus, this concept may offer the potential for improved performance and longer life (based on the reported test results) than other concepts evaluated, but confirmation and verification of Russian reported results is required.

Fast Reactor CERMET Concepts were studied and some concept design work was done in the 1960’s; fuel processing and fabrication techniques were studied extensively for the nuclear airplane program. Refractory metal structural integrity may result in improved fission fragment retention by this fuel compared to other concepts; however, this must be verified in nuclear tests. Similarly, the rugged construction may offer improved shock loading. Thus, the concept may provide additional safety margins, compared to other concepts. Pratt & Whitney/B&W conceptual design study results indicate potential high temperature performance (2850 ^{o}K reactor exit gas temperature, with specific impulse of 944 seconds). For an engine thrust of 250,000 pounds force system, the thrust-to-weight ratio was calculated to be 5.1 with shielding. Higher thrust levels and lower temperatures were also evaluated. If a requirement for very low release of fission fragments from the reactor is imposed for any reason, the CERMET concept could be the only way of meeting the requirement. An important effort early in the technology development project will be to evaluate fuel lifetime versus temperature versus fission fragment release for each fuel type in an actual nuclear, hot hydrogen environment, to provide the basis for selecting this concept method.

Thus, of the United States NTP concepts, only the NDR concept has a detailed design completed for a manned mission, and only the NDR has demonstrated full system technology readiness in actual nuclear tests. While the other concepts may offer certain performance advantages on paper, these advantages must be proven by testing, and a detailed design of an astronaut-rated system must be completed.

The unmanned Jupiter Icy Moon Orbiter (JIMO) mission also included in Project Constellation has as one its objectives the demonstration of nuclear electric propulsion (NEP) flight system technologies that will enable a range of revolutionary planetary and solar system missions [5]. Specifically, the NASA Science Definition Team reports a space system composed of three basic modules including the reactor module providing over 100 kW of continuous power with notional heat pipe cooled reactor, its radiation shield, two Brayton Power Conversion Units, the reactor instrumentation and controls [6]. Los Alamos National Laboratory proposed a SAFE-400 space fission fast reactor concept [7] including a 400 kWt Heatpipe Power System (HPS) producing 100 kWe to power the JIMO space system using two Brayton power systems – gas turbines driven directly by the hot gas from the reactor. The HPS fast reactors have been developed since 1994 at the Los Alamos National Laboratory as a robust system with emphasis on high reliability and safety. The reactor contains fuel modules of 97% enriched uranium nitride fuel within its rhenium cladding. Each fuel module has a central heat pipe filled with sodium vapor. Energy from fission is conducted from the fuel pins to the heat pipes, which carry it to the heat exchangers and thence to the hot gas (72% helium and 28% xenon) to the Brayton Cycle power conversion systems to produce electricity. The electricity produced is used to power the propulsion system and science packages included in the mission. Nuclear Test facilities will be required to encompass the testing of the fuel and performance testing of completed NEP integrated systems.

III. Status of Nuclear Test Facilities for Space Nuclear Power Systems

The test facilities at the Nuclear Research and Development Area (NRDA) in Nevada consisted of three reactor test cells, the Engine Test Stand, two large assembly/disassembly facilities and two remote control rooms [8]. These space reactor test facilities used in the 1950s and 1960s have been deactivated and facilities reassigned to other functions. Furthermore, these facilities no longer comply with current environmental and nuclear facility safety standards and regulations regarding nuclear propulsion system testing for the reactor concept levels envisioned. A NASA Subpanel Final Report [9] evaluating NTP facilities determined that using the existing rocket test cells on the NRDA is anticipated to cost as much as new facilities. In addition, the NRDA is significantly degraded and within view of the Yucca Mountain Nuclear Waste Repository complicating NEPA review of both facilities. These facilities had been used for the NERVA project. The difficulty in applying new NERVA technology for current NTP engine concepts is the scaling up of the Nuclear Furnace process to the power levels that are needed for new missions. The test process involved cooling the reactor nozzle exhaust with a water spray, dehydrating the cooled gases, and then removing the noble gases from the hydrogen with activated charcoal filters. The final product was a clean stream of hydrogen gas. Previous studies [4] [10] of a full scale facility used a 60 psia driving pressure out of the engine to force the effluent through the scrubbing system. Cost estimates made during the Space Exploration Initiative (SEI) program in 1991 ranged from $100 million to $500 million for such a scrubber facility. In addition, the tons of filter material that trap the few grams of fission products would have to be handled and stored. The ability of the effluent scrubbing system to process the required hydrogen flow for nuclear engine testing would need to be demonstrated after facility modification to answer questions of effluent dispersion and temperature gradients before NTP engine testing is initiated. Once hydrogen flow for nuclear engine testing has been verified, testing with required hydrogen flow and radioactive tracers would verify ability of the scrubbing system to remove radioactive material prior to NTP engine testing.

IV. Nuclear Test Facilities for NTP Engines

Nuclear technology development for Commercial Space Exploration NTP engines will initially focus on fuels development, production, fuel property determinations, and establishment of a consistent temperature, life, fission product release data base, utilizing existing DOE reactor facilities [4]. The NASA Subpanel Final Report for NTP Test Facilities defined test facility requirements, evaluated existing facilities, identified facility modifications required, and identified critical path facility development requirements. A major working assumption of the Subpanel was that evolving technologies such as open cycle gas core could not compete in the near term with main line solid core concepts. Thus, solid core concepts reactors are the baseline for achieving a technology readiness level TRL of 6 by 2008. TRL 6 requires an integrated system demonstration/validation in a simulated environment. It is also assumed that all nuclear testing will be performed at DOE facilities. Concept and technology development should be focused on the manned Mars vehicle mission application. A suitable open-cycle effluent treatment system will be installed and tested at a DOE facility for a full size NTP ground engine system test. It is assumed that full scale reactor/engine tests to failure will not be required on the ground. Full expansion-ratio nozzle tests with the NTP engine should not be required to be tested on the ground. It is also assumed that neither reactor assembly nor low-power critical tests will be required on the ground at the launch site. Reactor assembly tests and low-power critical tests will be accomplished in Low Earth Orbit (LEO) after assembly of the mission vehicle is complete. An unmanned flight demonstration program will be conducted in space prior to a manned flight.

Authorization to possess and utilize highly enriched uranium HEU for NTP solid core nuclear fueled engines must be obtained from the DOE Fissile Materials Disposition Program (FMDP) so that the disposal of surplus weapons-usable uranium in this manner is approved. DOE-MD authorization for DOE facilities to proceed with the release of excess HEU maintained at Savannah River Site for nuclear fuel development in support of the NASA Commercial Space Exploration Vision implementation is required prior to NTP test facility planning. The utilization of Savannah River National Laboratory SRNL located on Savannah River Site to produce the nuclear fuel and act as the lead laboratory for excess HEU disposition in support of NASA initiatives and testing thereof will minimize logistic and nuclear proliferation concerns. The Savannah River Site has an established record for successfully fabricating nuclear fuel for the production reactors as well as in the Navy Nuclear Fuel fabrication program. Although Savannah River Site does not have a current fuel fabrication mission, the SRNL Strategic Materials Technology Department still has a Fuel Fabrication Laboratory with experienced personnel, access to materials and equipment available to develop new fuels and forms for NTP concept reactors including, developing improved fabrication procedures, pilot plant fabrication of test cores, fabrication of test fuels and fuel elements. After approval from DOE is received for the Fuel Fabrication Laboratory to process the HEU into fuel elements, the nuclear fuel elements and reactor materials produced by SRNL as well as reactor internals materials produced at Y-12 and other DOE facilities for NTP engines may be tested in Idaho National Engineering and Environmental Laboratory INEEL's Advanced Test Reactor ATR. These will be tested in various test positions and conditions with high neutron flux, using a variety of fast- to thermal-flux ratios, various power tilt scenarios, varying power profiles, abnormal operations and repeated startups.

Hot hydrogen propellant testing can be performed on unirradiated nuclear fuel at DOE facilities for technology validation and propellant management. A proposed fuels and materials Hot Hydrogen Test Facility would be constructed to meet desired hydrogen flow parameters with the ability to conduct blowdown or closed loop experiments. Turbo pumps to feed the NTP will be tested at existing NASA Hot Hydrogen Flow Test Facilities. Similarly, NTP engine nozzles can be tested at existing NASA Hot Hydrogen Flow Test Facilities for nozzle development.

Irradiation testing to produce a qualified nuclear fuel for NTP reactor service will be conducted at the INEEL Fuel Irradiation Test Facility. Here, material from SRNL and other DOE facilities will be loaded into capsules and seal welding of these capsules performed as required. INEEL is the operator of the ATR where nuclear fuel tests are performed, and as such, has the responsibility for ensuring that the tests are designed and executed in accordance with all applicable safety and regulatory requirements to determine the effect of irradiation on candidate NTP fuels, to evaluate steady-state and transient performance data, and to obtain safety data (e.g. fission gas release) on candidate fuels in a hydrogen environment. Specifications, drawings, reactor data, and other guidance provided by INEEL will be used by SRNL as a basis for ensuring that the test design meets the requirements of the ATR. INEEL will perform the necessary tests and calculations and provides the documentation to permit the test material insertion, conduct the test irradiation, and remove test material at prescribed burnups. INEEL is responsible for the packaging, safeguards and security, emergency response, appropriate notifications, and transportation to SRNL of irradiated test materials for disassembly and examination. Post-test examination of the fuel and reactor materials radiated in the ATR will be performed by SRNL, INEEL and other DOE facilities as necessary to ensure suitability of fuel form for mission propulsion requirements as determined by NASA HQ and NASA Glenn Research Center.

Single nuclear fuel elements may be tested in a Fuel Element Test Loop in the ATR and TREAT DOE reactors or at Savannah River Site by SRNL in a nuclear fuel element test facility that can accommodate all reactor concepts under consideration. Test conditions for the nuclear fuel and materials will reproduce anticipated operating conditions with a flowing pressurized hydrogen loop in a relevant environment to the extent possible (surface and centerline temperatures) as specified in detailed Design, Functional, and Operational Requirements Documents. Fuel element and materials performance test data from various concepts is an important evaluation factor for final nuclear engine concept selection for mission assignment.

The Los Alamos Critical Experiment Facility (LACEF) at Los Alamos should be used for low power criticality tests to obtain benchmark physics and design confirmation on specific reactor design concepts.

At least one of five DOE production reactors rated at 2800 MW in storage at Savannah River Site should be modified for use as a Prototypic Fuel Element Test Reactor, referred to as the "nuclear furnace" during the NERVA program. Test objectives are to obtain performance data on several types of fuel elements under prototypical NTP operating conditions, obtain data on design margins by testing fuel elements up to and through failure thresholds, obtain safety performance data including fission product release rates, and perform technological validation of fuel elements as required by the NASA Subpanel Final Report for NTP Test Facilities. At least one of the above existing DOE Reactor facilities at Savannah River Site should be modified for use as the NTP Reactor Test Facility and NTP Engine Ground Test Facility to obtain performance data on complete reactor configuration(s) operating under prototypical conditions (as close to flight conditions as can be reasonably achieved on the ground), obtain safety performance data from normal operating conditions, including fission product release rates, reactivity coefficients, and flow stability, obtain information on off-normal operations and operations at the qualification level, and verify control algorithms and statistical data on component and hardware performance. The Savannah River Site was selected from the sites listed in the NASA Subpanel Final Report Sites based on its ability to satisfy all specified capability needs including an operating Waste Management Facility in the Defense Waste Processing Facility DWPF to immobilize any fission product or other nuclear waste generated by the NTP engine testing. Test fuel will nominally be stored for five years to assist in post-test analysis of any anomalies that arise during the NTP testing. After completion of the test program, the fuel will be reprocessed to recover the unburned uranium. The H canyon at Savannah River Site can be modified to reprocess the test fuel. Recovered uranium will be added to the government stockpile or used to fabricate additional NTP fuel as required. SRNL will be responsible for packaging, transportation, safeguards and security emergency response, and appropriate notifications of nuclear fuel transfer to INEEL, other DOE facilities involved in testing, and ultimately to NASA controlled launch facilities.

V. Nuclear Test Facilities for NEP Engines

In 2003 NASA's Project Prometheus began comprehensive efforts to develop advanced technologies for space use. Various electric propulsion technology concepts have been studied that will enable new missions, particularly when combined with power generated by a space nuclear reactor [12]. The first proposed mission application, the Jupiter Icy Moon Orbiter JIMO has focused on a 100 kW class spacecraft utilizing an NEP engine [13]. The lower power levels of the NEP engine easily fit within the Test Facility of the NTP engine above, but more emphasis is placed on the reliable and efficient electrical output capability of the NEP system in a challenging environment for missions that are decades long. Test Facility needs for a SP-100, 100 kW class spacecraft reactor system were previously defined [8]. Specific Technical Facility Support Criteria for the Nuclear Reactor Test are required.

Reactor Containment

The containment for the reactor test facility should conform to the technical testing requirements similar to those guidelines required in commercial facility leak test programs as identified in 10 CFR Part 50, Appendix J. Shielding should be provided to limit radiation exposure and protect the operating personnel during all phases of the reactor test program. The shielding should allow the operating personnel to safely remain in the control area in the event of an accident. Containment atmosphere sampling systems should detect any radioactive release during reactor operation. Abnormal releases should alert the operator to initiate corrective action. The containment should be equipped with an isolation system for use in the event of an abnormal incident. A filter system should be provided as a containment support system to reduce and contain radioactive airborne particulate.

The containment should be designed to accommodate an inadvertent loss of primary coolant and resulting mitigation of an incident. The containment design criteria should include maximum expected values for the mission life of the facility. These might include ratings of MWt or a few tons of sodium potentially being released into the containment during testing.

Cell Facility Design

To minimize schedule delays, a higher rated system than current concepts should be identified and the reactor test cell facility for the higher rated system be designed to accommodate the physical dimensions of a larger reactor and have greater heat rejection capacity. Handling equipment should also be designed for the increased weight. In the case of the higher rated system a trade-off will be required between increasing the distance of the test site from population centers and enhancing the capabilities of the reactor test facility. The reason for such a trade-off is the more severe conditions which will be encountered for the follow on larger NEP/NTR systems compared to the 100 kW class system with regard to neutron fluxes and gamma fluxes, neutron reflection, neutron activation of materials and gamma heating.

The reactor test stand, shielding, test vehicle containment vessel and vacuum structure would be required at any test location. Test cell criteria should include size and load carrying capability of containment space envelope, handling capabilities, auxiliary systems, heat rejection, vacuum, vibration input, instrumentation and controls, environmental simulation and transportation.

Maintenance Assembly and Disassembly

Assembly of components and subsystems would be expected to take place in the following types of areas: 1. Vendor or other off-site facilities of remote site locations, 2. An uncontaminated area of the test facility, 3. A high bay or maintenance area of the test facility, or 4. A containment room. For assembly work where one or more components is radioactive, assembly would be done in a high bay or maintenance area, either manually or remotely depending on the radiation level. For retrofitting test equipment with new components in sites, the work would be performed remotely.

The disassembly operation would be carried out either in place or away from the test cell, perhaps in a secondary containment building where gas cleanup equipment is available, or in a large hot cell.

After reactor disassembly, some components should be subjected to post-test examination in the maintenance area. Others, fuel elements in particular, would be examined in available hot cell facilities in which nondestructive and destructive positive radiation examination can be conducted.

Typical NEP Power Systems Reactor Test Criteria

Typical NEP reactor test criteria include: 1. heat reject of 1.9 MWt, 2. vacuum test to $10^{-8}/10^{-9}$ Torr, 3. vacuum chamber of 14 foot diameter by 30 foot length, 4. vibration test to shuttle loads and 5. environmental simulation of thermal conditions to be provided by vacuum pumping.

Environmental and Safety Compliance

It is assumed that the reactor development test program will be required to comply with the environmental and safety regulations prescribed for Department of Energy (DOE) owned nuclear reactor facilities. DOE Orders including 5440.1A, NE-5810, 5480.1 and 6430 should be reviewed for applicability to new or modified DOE nuclear reactor facilities. Typical federal requirements to be reviewed for applicability to new or modified DOE nuclear reactor facilities include 10 CFR 20, 10 CFR 50, 10 CFR 100, 10 CFR 71, 40 CFR 190 and 49 CFR 170.

Ancillary and Support Services

Ancillary and support services must be considered in any facility design. Transportation (rail, air, road, or barge), power, human services, housing, and technical support facilities (shops, laboratories) are required at any reasonable site. Sites with existing facilities, adequate electrical transmission lines, emergency power generation which is qualified as reliable during abnormal environmental events (tornado, seismic event), and adequate makeup and cooling water sources are important for ancillary support. In-plant radiation monitoring and established health physics equipment would additionally be required.

Disposition of Radioactive Materials, Waste Processing and Disposal

The radioactive materials resulting from the testing will be categorized as either HIGH or LOW LEVEL Radioactive Waste. The fuel (core) is High Level Radioactive Material and should be stored on-site in a prequalified storage facility until it can be reprocessed in DOE facilities to recover the uranium.

Contaminated components and liquids that contain radioactive nuclides will be volume reduced as is economically practical prior to packaging and shipment to a federally owned low level waste burial site.

Decommissioning planning is a must in the facility design to assure minimum contamination of retired facilities in order to maintain low cost for program deactivation following mission test completion.

Radioactive gaseous waste treatment design and operation should be based on specification and analysis as required by applicable DOE Orders.

VI. Lessons Learned from Prior Nuclear Test Facilities

SNAP and NERVA Program

Experiences from the NERVA and SNAP Test Programs should be reflected in the design and operation of future space reactor test facilities. The nuclear reactivity of fast reactors being considered for future space missions can be perturbed by the effect of neutron reflection from nearby structures. A potentially more troublesome aspect of the heavily shielded test cell is the difficulty of evaluating the performance of an apparatus shield in the presence of substantial scattered radiation. Neutron-induced radioactivity and gamma heating of test-cell concrete and other facility structures can present severe operational problems and must be considered in the design of such a test facility.

The design of a test facility for advanced (closed-cycle) space reactors should consider factors which would dictate specific orientation of the test article.

Space simulation and prevention of refractory metal degradation resulting from exposure to air at high temperature may require a high vacuum (10^{-8} to 10^{-9} Torr) environment. Some difficulties were encountered in the NERVA program (Engine Test Stand) in sealing the structure surrounding the engine test article in order to achieve a partial vacuum. Innovative engineering will be necessary in designing a test facility which is required to produce a high vacuum environment and yet provide convenient access to the test article for pre- and post-test examination.

Prior program experience on NERVA and SNAP revealed the importance of a capability to perform maintenance or repair operations on a highly radioactive test article. (Such a capability appears even more desirable for future space reactor development programs.)

Consideration should be given to early SNAP-8 testing methods which used a simulated radiator integrated with the reactor system and provided an equivalent heat sink without the need for initial vacuum testing.

A successful development program depends on a reliable test facility with sufficient flexibility to accommodate unanticipated problems and requirements. This was achieved in previous space nuclear system test facilities by the use of redundancy in critical systems and components and by the separation of major subsystems within the test facility to facilitate access during testing. Such a feature is particularly desirable when extended endurance tests are involved. Testing of a fully integrated system could be attempted when the design of the major subsystems has been validated.

SNTP Program

Design and operation of the Ground Test Facility for the SNTP was anticipated to require a major engineering effort to provide a system capable of removing fission products from the engine exhaust, which would primarily consisted of hydrogen propellant, with a flow rate of approximately 50 kg/sec. The facility had to be capable of handling both normal operating conditions, as well as off-normal conditions that might arise from a catastrophic engine failure. Xenon and Krypton would remain in gaseous form, and could be removed by cold traps or by carbon or zeolite absorption beds. Alkali metals such as Cesium and Rhubidium, and halogens such as Iodine and Bromine, could react with steel duct liners and condense at relatively low temperatures, but they may remain water soluble, and thus surfaces could be decontaminated with wash water. Strontium and Silver will condense on duct surfaces, and silver contaminants removed by mechanical scrubbing. Two approaches were evaluated for this objective: 1. Storage of exhaust gases for slow processing after engine tests were completed. Tunnels at the Nevada Test Site constructed to support nuclear weapons testing were considered for this purpose, and 2. On-line cleanup of the exhaust gases with subsequent release to the atmosphere, as was done in the Nuclear Furnace program in the early 1960's. Although location of the Ground Test Facility underground might provide an additional margin of safety, there are a number of questions concerning the use of existing tunnels or new tunnels at the Nevada Test Site for this purpose. These tunnels were constructed to support underground nuclear tests, and may still be required for this application. They are located several dozen kilometers from existing nuclear rocket test facilities at the Nevada Test Site, which complicates logistic of their use. Given the large volumes of gas that would be released during engine tests, the existing volumes of these tunnels does not appear to be adequate to contain exhaust gases at acceptable pressures. This shortcoming would be magnified by the containment requirements posted by off-normal operations. During normal operations, the tunnels would be contaminated by fission products. The Nuclear Furnace System included water sprays for cooling engine exhaust, with boilers and condensers to cool the bulk of the resulting water vapor. Filters, dryers, and hydrogen cooling would be used to condense the remaining water vapor. Charcoal beds would be used to remove Xenon and Krypton gases from the hydrogen flow, which was then flared to the atmosphere. The SNTP Effluent Treatment System was intended to be capable of removing 99.9% of particulates and volatiles, and 99.5% of halogens and noble gases from the propellant effluent stream.

Commercial Nuclear Development

Some areas may require additional program analysis and planning based on “LESSONS LEARNED” in the commercial nuclear industry. Recognizing this project may be “defense related” with regard to the nuclear fuel production utilizing HEU mandates strict security relative to classified information. It would be beneficial to review aspects of security and proliferation including emergency planning, community education, institutional factors, contract labor relations, “State” position concerning defense programs, “Environmental Impact Statement” compliance versus environmental assessment, jobsite access, and availability of experienced personnel with reactor operations skills, analytical skills, and contractor needed skills.

VII. Conclusion

The planning for the ground test program for NTP and NEP engines should be based on assessment of the following factors: 1. Mission performance test goals; 2. Current federal order requirements; 3. Compliance with applicable institutional and regulatory requirements stressing site environmental qualification; 4. Analysis of previous “Lessons Learned” from past NERVA and SNAP programs; 5. Technical program support services; 6. Analysis of pertinent regulatory requirements of similar nuclear programs; 7. Applicable “Lessons Learned” from past commercial nuclear industry and federal experience; 8. Test program safeguards, security, and public health and safety; 9. Site program readiness; and 10. Public acceptance of the space program and the proposed test site. These factors should be weighted when analyzing existing sites or selecting new sites for the NTP and NEP engine testing.

Ultimately, system test requirements must be the driving factor for facility design and site selection. Integration of “Lessons Learned” and site environmental/institutional acceptability with the planning/design will be required to achieve a realistic cost effective program for the NTP and NEP engine test and demonstration at Savannah River Site or other DOE nuclear facility. Early planning and integration of these variables into the DOE program for NASA nuclear engine test facilities will assure a systematic progression of selection, test, development and final mission completion.

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