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**TEST FACILITIES FOR EVALUATING
NUCLEAR THERMAL PROPULSION SYSTEMS**

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Abstract

Interagency panels evaluating nuclear thermal propulsion (NTP) development options have consistently recognized the need for constructing a major new ground test facility to support fuel element and engine testing. This paper summarizes the requirements, configuration, and baseline performance of some of the major subsystems designed to support a proposed ground test complex for evaluating nuclear thermal propulsion fuel elements and engines being developed for the Space Nuclear Thermal Propulsion (SNTP) program. Some preliminary results of evaluating this facility for use in testing other NTP concepts are also summarized.

INTRODUCTION

Over the past several years, representatives of the Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE) have participated in a series of panels to evaluate a number of issues related to nuclear propulsion, including an assessment of facility requirements by the Space Exploration Initiative (SEI) Nuclear Thermal Propulsion (NTP) Facilities Subpanel (Allen et al. 1991 and 1992a). One recommendation of these panels is that extensive testing is needed to support development work. One consistent theme further documented in the conclusions and recommendations from these interagency panels is that major new facilities are needed for conducting extensive ground test evaluations of new nuclear propulsion fuel element and engine concepts.

The Space Nuclear Thermal Propulsion (SNTP) program is being conducted by the U.S. Air Force Phillips Laboratory to develop technology for a high-performance NTP engine. The program involves extensive nuclear and nonnuclear technology development and testing activities. Because of the limitations in simulating prototypical test conditions in existing facilities for the high-performance particle bed reactor (PBR), the development of a new ground test complex where first elements and later engines can be tested is a high priority. The ground test facility under development to meet the nuclear testing requirements of the SNTP program has explicitly considered the recommendations of the SEI NTP Facilities Subpanel. An overview of the philosophy used in developing the facility design, including issues such as expansion support and operational capabilities, was recently presented at the Nuclear Technologies for Space Exploration Symposium (Allen et al. 1992b). The present paper further expands the available open literature to discuss development issues that have been raised, including fission product confinement approach, primary coolant effluent treatment, baseline facility operating envelopes, facility expansion options, and multiple user support.

Fission Product Confinement

Unmitigated release of fission products is prevented by use of concepts such as 'defense in depth.' This includes administrative, physical, and operational controls and measures. Administrative programs range from those that provide a high degree of assurance that the program adheres to all applicable laws and regulations to the conduct of in-depth safety analyses including planned probabilistic risk assessments. Physical controls for ground-based testing of NTP concepts involve multiple barriers including fuel coatings, primary confinement systems, and secondary confinement systems. Hydrogen coolant effluent treatment system concepts involve real-time processing or hold-up (delayed-time) processing. Actual designs implemented will have to balance nuclear safety (that is, minimize the potential for radioactive material release), hydrogen safety, and cost. Any design carried forward for the SNTP program will conform to program safety goals, which have stricter requirements than those established by public law. In addition to administrative controls and physical barriers, operational procedures will be developed to further reduce risks and potential consequences. An example would be strict control on the total radionuclide inventory allowed to be generated and kept on site. All procedures will comply with applicable DOE Orders.

Physical barriers to be employed that will prevent the unmitigated release of fission products are diagrammed in Figure 1. As can be seen, extending the defense-in-depth philosophy into the area of physical barriers with due regard to single-failure criteria is easily accomplished on a conceptual level. Development of functional and performance requirements and implementation into a cost-effective design is a much more complex undertaking. As implemented for the SNTP program, the primary confinement barrier around the reactor looks much like a reactor vessel in a conventional power plant design, but is functionally much different. The mechanical structure used to support and direct flow through the multiple stage filtration system also serves as the balance of the primary confinement barrier. The secondary barrier includes the test cell structures, which may serve multiple functional needs (for example, weather protection and shielding).

FIGURE 1. Depiction of the Use of Multiple Physical Barriers and Single-Failure Criteria in Preventing the Unmitigated Release of Fission Products.

Process Fluids

A primary coolant system intended for use in the development, demonstration, and qualification of NTP fuel elements, reactors and/or engines on the ground must meet a set of unique functional requirements as outlined below and as shown schematically in Figure 2:

1. Provide an adequate, redundant, highly reliable supply of cryogenic hydrogen at required pressures, temperatures, and flow rates (hydrogen supply - stage 1).
2. Interface with the primary heat source (for example, reactor or engine - stage 2).
3. Cool the hot primary flow to temperatures compatible with structural and heat exchanger materials. Catch any core debris material resulting from failures (planned or unplanned) and maintain it in a coolable, subcritical configuration. Allow access for remote/robotic retrieval of core debris. Provide initial, coarse-filtering to prevent downstream heat exchanger plugging and act as a getter for plate out of fission products with boiling points above the cooldown temperature (debris trap - stage 3). This stage may also include a diffuser for pressure recovery during nozzle tests, use injection cooling (for example, hydrogen or water) with a secondary function of providing the pumping power for a jet pump, or both.
4. Provide additional cooling of exhaust flow to temperatures compatible with downstream particulate filters (gas cooler - stage 4).
5. Filter out particulates entrained in the exhaust flow (particulate filter - stage 5).
6. Retain any fission products still in volatile form (for example, noble gases such as krypton and xenon) for a sufficient time to allow for decay (volatile fission-product holdup - stage 6).
7. Dispose of cleaned effluent (waste stream processing - stage 7).

Stages 3 through 7 comprise what is generally referred to as the effluent treatment system (ETS).

FIGURE 2. NTP Ground Test Coolant System Block Diagram

Each stage, as defined herein, can have its functional requirements met by various design concepts and technologies. For example, consider the following. Stage 4, the gas cooler, could be implemented using injection cooling, heat exchangers, pebble beds, boilers, or some combination of these. Stage 6, the volatile fission-product holdup process, could have a design based on storage of all gaseous hydrogen in the process stream through the use of tanks, hydrogen storage by reaction and retention in a hydride bed, liquefaction and bulk storage of process hydrogen, real-time removal of fission products by use of cryogenic filter beds, or through combustion of hydrogen (with oxygen) to form water, which is then stored in bulk. Stage 7, waste stream processing, is linked strongly with Stage 6 design choices, and it may involve flaring of hydrogen, treatment of potentially contaminated waste water (for example, calcination or filtration and recycling), reuse of liquefied hydrogen on the supply side of the system in a closed-loop mode of operation (either real time or at a lower resupply rate consistent with the desired test frequency), or bottling and disposal of volatile species removed from the hydrogen. Likewise, design considerations at any stage will influence the rest of the process train (for example, use of water injection in stage 3 or 4 would require driers as part of stage 7 if cryogenic temperatures are involved).

Design decisions are also related to other factors such as operations tempo (for example, consumable resupply rates and costs), initial capital investment, safety, and performance requirements. Nominal design goals to meet SNTF program needs are:

- Provide element test durations of 500 s for 220-MW power levels,
- Provide element test durations of 70 - 110 s for 550-MW power levels,
- Support tests of 100 - 1000 s for 1-GW engine-demonstration power levels,
- Remove 99.9% of entrained solids,
- Remove 99.5% of all volatile fission products (for example, nobles such as krypton and xenon)

- Support tests for chamber pressures to 7 MPa,
- Support testing to simulate throttled operations, and
- Test low-expansion ratio nozzles only (prototypical nozzles to be truncated near throat section).

Final design performances will be based on the requirements of DOE Orders and public law (for example, DOE 5480.6, DOE 5480.RD, and 10CFR50 Appendix A). A simplified diagram of the coolant system conceptual design developed for the SNTP program can be found in Figure 3. Further details concerning the development of this system can be found in Shippers and Allen, 1992, and Shippers and Brockmann, 1993, including discussions of various trade study decisions that eliminated certain options introduced above.

FIGURE 3. Simplified Line Diagram Of The Baseline Reactor Coolant System.

Baseline Facility Operating Envelopes

Although much of a facility's design has little impact on cost, schedule or operating constraints (for example, receiving docks or office space), certain key, capital intensive, programmatic equipment items may. The major equipment in this category for the planned SNTP facility is the coolant supply system and the effluent treatment system as shown in Figure 3. The current design has been baselined as documented for the formal preliminary design review (PDR) conducted in February 1992 (Beck, 1992). Although the PDR design was developed and optimized for a set of specific requirements (for example, the element test requirements listed above), its capabilities are actually defined by a set of performance envelopes. A set of nominal envelopes have been developed that will be presented and which have several conservatisms built in and do not represent a 'run-the-tank-dry' condition. For example, both the reactor coolant supply tanks and the ETS coolant supplies contain a set aside volume to support startup and shutdown. Some of the other conservative assumptions used in developing these envelopes will be presented in the following discussions.

The reactor coolant system has two major run-time subsystems, a primary coolant supply and an auxiliary coolant supply. Both are driven by blowdown systems in the baseline design for purposes of reliability (thus safety) and initial installed costs. The simplicity of a blowdown system also allows greater flexibility for short run times and low flow rates associated with the testing of new or innovative fuel elements. The primary coolant flow is that hydrogen used in direct contact cooling of the reactor fuel ('test article'), and may likely be the only coolant supply used in an engine demonstration test. Auxiliary coolant flow is available when it is desired to cool non-core components (for

example, radial reflectors) in fuel-element development reactor configurations ('test bed'). In existing (PDR) design concepts, the auxiliary flow exits the test bed at a relatively cold temperature (<500 K) to allow a broader material selection base, while the primary coolant exits the test article at temperatures that are typical of engine design goals (for example, ~ 3000 K). Limitations on full-power run time based on available primary coolant as a function of the primary mass flow rate and required supply pressure (at the test article inlet) are shown in Figure 4. Limitations on full power run time based on available auxiliary coolant as a function of the auxiliary mass flow rate and required supply pressure (at the test bed inlet) are shown in Figure 5. To place the baseline reactor coolant storage capacities and maximum flow rates in perspective, Figures 6 and 7 provide a comparison to the original test cell hydrogen installations of the ROVER/NERVA program (Aerojet 1969, DeStefano 1969, Edeskuty 1964, Kirk 1973, and Lyon 1973).

FIGURE 4. Primary Coolant Supply Baseline Blowdown System Run-Time Envelopes At 50 K Supply Temperature.

FIGURE 5. Auxiliary Coolant Supply Baseline Blowdown System Run-Time Envelopes at 50 K Supply Temperature.

FIGURE 6. NTP Facility Baseline Hydrogen Storage Capacities.

FIGURE 7. NTP Facility Baseline Maximum Coolant Supply Rates.

Limitations imposed by the ETS include maximum process train flow capacities, ETS coolant supply volumes, and back pressures required at the reactor exit (debris trap) that drive the exhaust flow through the remainder of the ETS. It must be recognized that the fundamental purpose of the ETS is to remove particulate and volatile fission products from the exhaust gas in order to meet current public safety and environmental concerns. Particulates can be removed by rapid decreases in the stream velocity (as in the debris trap), or by impact and flow redirection (as in both the debris trap and particulate filter media). Volatile species such as xenon and krypton can be removed at cryogenic temperatures through contact with adsorption media. Although all three components thus have maximum design velocity limits, the adsorber bed is limiting in the current design with a maximum volumetric flow of hydrogen of $75.1 \text{ m}^3/\text{s}$ at 160 K. At this constant temperature, constant velocity design point, as the system mass flow decreases the operating pressure can also be reduced to maintain a constant volumetric flow. Operating pressures above the limits thus calculated are acceptable since a higher system pressure gives a higher density, which decreases the volumetric flow rate and velocity; this gives a longer residence time and attendant improved fission-product removal efficiencies. Within this definition of filter performance, limitations on inlet flow can be derived including the primary coolant flow, the auxiliary coolant flow, and the necessary quench mixer flow required to lower the mixed mean outlet temperature of the reactor to 1100 K, which corresponds to a temperature compatible with standard process train materials. From a conservative capability standpoint, the performance envelopes have assumed an auxiliary flow exit temperature of 1100 K, in effect not allowing auxiliary flow to help the quench mixer flow in cooling the primary exhaust to 1100 K (maximizes the quench mixer flow and total debris trap exit flow rates). This is shown schematically in Figure 8. Increasing auxiliary coolant flow rates reduces the allowable primary coolant rate because a portion of the allowable process train flow capacity is used by the auxiliary flow.

FIGURE 8. Reactor and Debris Trap Cooling Flow Schematic.

For 3000 K primary exhaust gas temperatures, process train capacity limits on primary mass flow rates are shown in Figure 9 as a function of the auxiliary flow ratio (auxiliary coolant mass flow rate/primary coolant mass flow rate). Also shown are the full-power test duration limitations under these maximum flow conditions as a result of ETS hydrogen coolant storage volume capacities. In practice, actual primary mass flow rates will be a function of reactor power, and will likely be less than the maxima indicated in Figure 9. Test durations for runs with 3000 K primary exhaust gas temperatures as a function of primary mass flow rate and the auxiliary flow ratio are provided in Figure 10. Debris trap minimum operating pressures for a 3000 K primary exhaust gas temperature as a function of primary mass flow rate and the auxiliary flow ratio are provided on Figure 11. Figures 10 and 11 actually represent only a subset of the family of curves available to describe ETS performance. Primary exhaust gas temperature is also a strong driver of operational limits. As an additional example of the ETS operational envelope, Figures 12 and 13 provide available test durations and back pressure as functions of primary exhaust gas temperature for the case of no auxiliary flow. This would be the typical mode of operation for engine demonstration tests where non-core components are regeneratively cooled.

FIGURE 9. Baseline ETS Flow Capacity and Duration Limits for 3000 K Primary Exhaust Temperature.

FIGURE 10. Baseline ETS Test Duration Limits for 3000 K Primary Exhaust Temperature.

FIGURE 11. ETS Debris Trap Operating Envelopes for 3000 K Primary Exhaust Temperature.

FIGURE 12. Baseline ETS Test Duration Limits for the Case of No Auxiliary Flow as a Function of Primary Exhaust Temperature.

FIGURE 13. ETS Debris Trap Operating Envelopes for the Case of No Auxiliary Flow as a Function of Primary Exhaust Temperature.

Expansion Options

Previous sections of this paper relayed information concerning the planned SNTP baseline facility installation. Design activities, however, have explicitly considered provisions for expansion in test capability in order to handle possible changes to basic requirements (for example, provide prototypical testing of regeneratively cooled nozzle sections), changes in fuel types (that is, assure no fundamental design choice prevented test of, or required major capital investment in order to test, SEI fuels for NASA), or changes in test frequency or duration. Flexibility in accommodating differing test article designs and requirements includes modular test reactor designs, process fluid expansion options, and facility/site structures and systems options. A discussion of some of these follow.

Test Reactor

The test reactor by design contains two major subsystems - a test bed and a test article. Conceptual plan and elevation cross sections of the test bed are provided in Figure 14. The test bed nominally provides:

1. A primary fission product confinement barrier.
2. Interfaces between the test article and other programmatic equipment (for example, coolant supply, effluent treatment, and instrumentation and controls).
3. An experiment volume in which the test article (fueled portion of the reactor) is tested.
4. Independent reactivity systems to bring the overall reactor system to the desired preoperational reactivity state; control startup, shutdown, and operational transients; and provide scram capability. Test articles are designed for ease of removal to enable rapid test turnaround, ease of reconfiguration, and minimal worker exposures. Reactivity controls within the test bed are designed for ease of removal, so that test articles containing their own reactivity control mechanisms can take advantage of the confinement and programmatic equipment interfaces without having to rely on other design features. Test article design options can thus be seen to include:
 1. A hybrid core design where a previously qualified test article has a single fuel element replaced with a new design.
 2. A new test article that makes use of all inherent features found in the test bed.

is something missing here?

3. A new test article and reactivity control systems, only making use of the confinement barrier and subsystem interfaces of the test bed.
4. Replacement of the entire test bed/test article assembly with a new reactor design.

FIGURE 14. Simplified Drawing of the Test Bed Preliminary Design.

Process Fluids

The SNTP reactor coolant process train baseline design has limitations that include flow capacities and full-power test durations. Expansion of the operating envelopes can take several forms:

1. Add coolant tankage and/or pumps in order to increase run times.
2. Add additional process trains and/or components in parallel with the baseline installation in order to increase the maximum flow capacities (and thus maximum power level).
3. Build a new process train.

Option 1 above has been analyzed in detail, and plans and cost curves exist for expanding test times to that which would support a full-power test of a 1-GW engine for 1000 s. Actual additional equipment to be installed is a function of final specifications, as blowdown versus pumped option cost curves cross at the 500 to 600 s test duration window. Options 2 and 3 are not required to meet the current program goals, but lay down space on the site plans has been set aside in the eventuality that such expansion is desired (see Figure 15).

ETS backpressure limits can conceptually be reduced with at least two different options or some combination thereof. A variable diffuser designed for pressure recovery can be added into the debris trap or a hydrogen powered jet pump might be used in the debris trap, in the cryogenic mixer stage, or in both. Detailed trade studies will have to be employed to determine appropriate design options if high-expansion ratio nozzles are to be tested in this facility.

Facility Structures

The planned baseline facility will have only one test cell. However, if a significant increase in planned test rates were to occur, conceptual plans and order-of-magnitude cost estimates exist for building additional test cells. Because of the actual test durations (as opposed to test cell occupancy) and level of capital expenditures required to build items such as new process trains, it is envisioned that any additional test cells would tie into and use the baseline programmatic equipment items. However, as mentioned, site plans do provide for additional systems such as effluent treatment process trains. Other expansion options provided for include floor space and HVAC support for instrumentation and control system expansion, safeguards and security systems to protect category-1 special nuclear material (SNM), and nonnuclear test stands for integration and testing of flight-like propellant management systems.

FIGURE 15. SNTP Baseline Facility Conceptual Site Plan Illustrating Laydown Space for Optional Expansions.

Multiple User Support

The SNTP facility and programmatic equipment preliminary design was developed for and meets Air Force (AF) needs. There are similarities in NTP test requirements between the AF and NASA, but some differences exist. The AF has made the decision to pursue the development of an NTP test facility that will meet national needs, and there have been recent AF/NASA/DOE activities aimed at meeting this goal (Department of Energy 1992).

All of the AF performance goals outlined in above are met or exceeded by the baselined PDR design. Operations of the baseline element test reactor at a 220-MW power level can be sustained for ~1000 s, operations at 550 MW are possible for ~400 s, and operations of a 1-GW engine are supported for ~200 s. The actual run-time envelope for any configuration of coolant tankage is approximated by a constant energy production value. This fact, plus consideration for certain design margins, explains the difference between actual and specified system performance. To demonstrate support for throttled tests, a generic PBR 1-GW engine was evaluated to establish throat pressures as a function of percent throttle condition, and compared against ETS backpressure requirements. As shown in Figure 16, system flow characteristics have at least a margin of 2 in assuring choked flow exists in the throat of the chamber-exit nozzle.

As a prelude to expanded efforts in demonstrating support capabilities for NASA/DOE interests, several preliminary test article (reactor core) designs based on NERVA technology were developed with MCNP (Briesmeister 1986) to demonstrate criticality and controllability. This included both fuel-element development designs based on NERVA technology and small core-qualification designs of varying element lengths and numbers, different loadings, and different reflectors. The nuclear performance characteristics of these core designs were determined using the PDR test bed design that was shown earlier in Figure 14. The test article designs were then evaluated against the baseline system model in order to determine operational limits for each concept. Power densities assumed were consistent with the 4.7 MW/L of the ENABLER design (Gunn 1990, and Livingston and Pierce 1991), which exceeds the performance demonstrated in NF-1 (Kirk 1973, and Lyon 1973). Further discussion of several of these test article designs follows.

One of the NERVA-derivative fuel-element test article design options considered would use the PDR test article design, but replaced the PBR elements with NERVA fuel-element clusters. A NERVA cluster, as used here, consists of six hexagonal fuel blocks surrounding a central support element. This test article concept used the short, 0.889-m long element and a fuel loading of 16.4 w/o uranium (0.598-g U/cm^3). A cross section of the core is provide in Figure 17, where it is seen that eight clusters surround a center cluster. The effective neutron multiplication factor (k_{eff}) for this design is > 1.1 . The performance of this design was such that the outer clusters operated "derated" (that is, the center cluster power level was 14% of the total core power of 36 MW), as suitable for an element development

FIGURE 16. Chamber, Throat, and Debris Trap Back Pressure Versus Thrust Ratio.

FIGURE 17. Test Article Conceptual Design for NERVA-Derivative Fuel Element Development Tests.

program. The outer clusters were also assumed to be over cooled to 2000 K, compared to the nominal center-cluster exit temperature of 2700 K. When this design was placed within the system operational envelopes, even considering auxiliary flow rates in excess of 1.5 times the primary flow rate, test durations of over 1 hour were found to be possible.

For a core-design qualification test article, a range of fuel-element lengths, core diameters, and fuel loading options were considered. One example, shown in cross section in Figure 18 is a 170-MW design that uses the 132-cm long NERVA-derivative fuel elements with a uranium loading of 5.2 w/o (0.181-g U/cm³). The neutronics performance for this concept can be summarized as follows. For the condition with the safety rods up, control drums opened, and hydrogen in the core, $k_{\text{eff}} = 1.045$. For the condition with the safety rods up, control drums opened, and no hydrogen in the core, $k_{\text{eff}} = 1.012$. For the condition with the safety rods down, control drums opened, and hydrogen in the core, $k_{\text{eff}} = 0.909$. For the condition with the safety rods up, control drums closed, and hydrogen in the core, $k_{\text{eff}} = 0.954$. At auxiliary flow ratios within the range of 0 to 1.5, test durations of ~1000 s are supported for this design by the baseline facility and systems.

For comparison purposes, these two NERVA test designs have maximum full-power run times plotted versus power level in Figure 19 along with several PBR test options. In addition, a run time versus power level envelope is shown for a generic, 3000 K exhaust temperature, no auxiliary flow test reactor. Although these calculations and similar evaluations of other concepts are only preliminary and do not consider many design issues that would require further analysis if a design was to be carried forward, they do indicate that the baseline SNTP test reactor and supporting equipment can accommodate alternate NTP fuels testing.

FIGURE 18. Test Article Conceptual Design for NERVA-Derivative Core Qualification Tests.

FIGURE 19. Baseline Facility Test Durations.

SUMMARY

A facility has been designed that meets the performance and operational requirements of the SNTP program and, from a cost engineering standpoint, provides a minimum capital and life cycle cost solution. Furthermore, the baseline facility has a sufficient test envelope to enable development testing of alternate NTP fuel designs. If more frequent tests at higher powers (2 GW), with longer run times (1 hour), and with high-expansion ratio nozzles (subatmospheric pressures at the nozzle exit) are desired, design configurations, decisions, and changes would have to be evaluated in terms of overall performance and costs, including due regard for the environment, safety, and health.

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