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**NUCLEAR THERMAL PROPULSION TEST
FACILITY REQUIREMENTS AND DEVELOPMENT STRATEGY**

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Abstract

The Nuclear Thermal Propulsion (NTP) subpanel of the Space Nuclear Propulsion Test Facilities Panel evaluated facility requirements and strategies for nuclear thermal propulsion systems development. High pressure, solid core concepts were considered as the baseline for the evaluation, with low pressure concepts an alternative. The work of the NTP subpanel revealed that a wealth of facilities already exists to support NTP development, and that only a few new facilities must be constructed. Some modifications to existing facilities will be required. Present funding emphasis should be on long-lead-time items for the major new ground test facility complex and on facilities supporting nuclear fuel development, hot hydrogen flow test facilities, and low power critical facilities.

INTRODUCTION

The United States' Space Exploration Initiative (SEI) has as one of its goals a manned mission to Mars by the year 2019. While it will enable a number of space missions, nuclear thermal propulsion (NTP) has been specifically identified as a critical technology for reaching Mars. The National Aeronautics and Space Administration (NASA) has begun to study NTP for this purpose. The NASA Lewis Research Center, the Department of Energy (DOE), and the Department of Defense (DoD) sponsored a workshop on Nuclear Thermal Propulsion in July of 1990 (Clark 1991). In the fall of 1990, a group of six interagency technology panels was formed to evaluate a number of issues related to nuclear propulsion. One of these panels was the Space Nuclear Propulsion Test Facilities Panel, whose purpose was to evaluate test facility needs and considerations for supporting the development of nuclear propulsion systems.

The Space Nuclear Propulsion Test Facilities Panel was divided into two subpanels: One subpanel focused on nuclear thermal propulsion (NTP) facilities and the other on nuclear electric propulsion (NEP) facilities. The Nuclear Thermal Propulsion Facilities Subpanel evaluated facility issues related to nuclear thermal propulsion development. The work of the NTP Facilities Subpanel is the focus of this paper.

NTP FACILITIES SUBPANEL OBJECTIVES

The NTP Facilities Subpanel consisted of volunteer representatives from NASA, DOE, DoD, NASA centers, DOE and DoD laboratories, and private industry, who held monthly meetings during government fiscal year 1991 to evaluate NTP facility requirements and strategies.

The specific objectives of the NTP Facilities Subpanel were to:

1. Define NTP test facility needs based on NTP technology development requirements;
2. Evaluate existing facility capabilities that meet these requirements;
3. Identify new facility development or existing facility modification needs;
4. Identify critical path facility development requirements;
5. Recommend facility development strategies; and
6. Comment on frequently asked questions related to NTP facilities.

In addition to its own expertise, the subpanel interacted frequently with other NASA/DOE/DoD panels that were addressing nuclear thermal propulsion technology needs. Specifically, input from the NTP Technology, NTP Fuel and Materials, and NTP Safety panels was key in developing facility requirements. The NTP Facilities subpanel also solicited information from owners of existing facilities. Data on more than 200 facilities were compiled by Sverdrup, Inc. for NASA Lewis Research Center (see Baldwin 1991). Additionally, the subpanel visited several potential facility sites.

The subpanel compared NTP facility requirements against the capabilities of existing facilities, and discussed and debated development strategy, critical paths, and facility issues. However, no funding was provided to allow a detailed analysis to verify the NTP Facility Subpanel positions.

SCOPE OF EVALUATION

Because high pressure propulsion systems were the only concepts judged to be capable of completing full system ground testing (TRL-6) by 2006, high pressure systems were considered as the baseline, with low pressure concepts considered as an alternative. The NTP Subpanel, therefore, focused on facilities for developing both nuclear and non-nuclear components and systems for solid core concepts such as Nuclear Engine for Rocket Vehicle Application (NERVA) derivatives, particle bed, wire core, ceramic, pellet bed, and Dumbo (see Clark 1991). Facilities for open cycle liquid or gas core systems were not specifically discussed by the subpanel, although some information on early proof-of-principle test facility needs for highly innovative concepts is included in the subpanel report.

The major working assumptions of the NTP Subpanel were:

- A NASA/DOE/DoD Memoranda of Agreement will exist for coordinating nuclear propulsion activities;
- Technical feasibility, schedule times, and cost envelopes will be success-oriented;
- Evolving "innovative" technologies such as open cycle, gas core engines cannot be developed in the near-term, while mainline solid core concepts probably can;
- The current environmental, safety, and health requirements may evolve but will not undergo quantum changes;
- Nuclear tests will be conducted at DOE facilities;
- An open cycle effluent treatment system will work and will be environmentally acceptable;
- Full-scale reactor/engine tests to failure will not be conducted at ground test sites;
- Engines will not be tested at power in clusters at the ground test facility;
- Full expansion-ratio nozzle tests will not be conducted at the ground test facility;
- Reactor assembly and low power critical tests will not be required at the launch site; and
- Unmanned demonstration flights will be conducted in space prior to manned flight.

NTP DEVELOPMENT TEST LOGIC

The NTP Subpanel, based on its own discussions and on input from other NASA/DOE/DoD Nuclear Propulsion panels, developed the summary test logic shown in Figure 1.

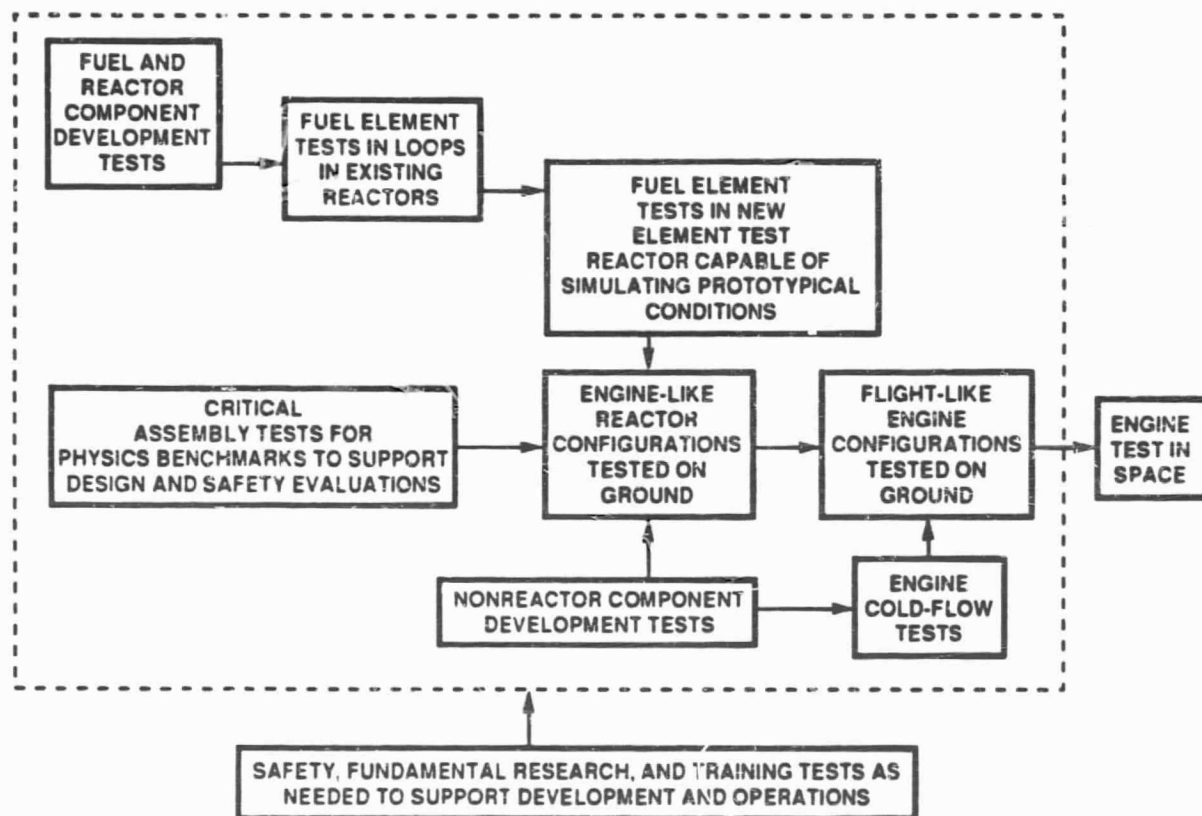


FIGURE 1. Summary Test Logic for NTP Development.

The other NASA/DOE/DoD panels provided extensive input to the facility requirements. Figure 2 shows the NTP Facilities Subpanel interaction with other panels.

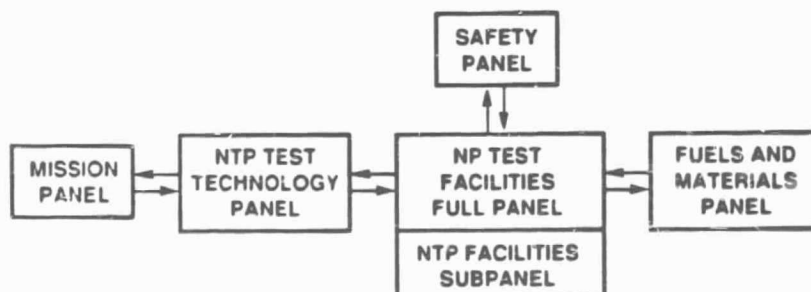


FIGURE 2. NTP Facilities Subpanel Interactions with Other NASA/DOE/DoD Panels.

The subpanel established 19 categories of test facilities which it used to guide data collection on test locations and to evaluate current capabilities. These categories were:

1. Fuel Fabrication Facilities;
2. Unirradiated Fuel Materials Test Facilities;
3. Unirradiated Materials Test Facilities;
4. Hot-hydrogen Flow Test Facilities;
5. Fuel Irradiation Test Facilities;
6. Material Irradiation Test Facilities;
7. Fuel Element Loops in Existing Reactors;
8. Low-power Critical Facilities;
9. Prototypic Fuel Element Test Reactor;
10. Reactor Test Cell;
11. Engine Ground Test Cell;
12. Remote Inspection/Post-irradiation Examination Facilities;
13. Component Test Facilities without Hot-hydrogen or Irradiation Environments;
14. Control System Test Facilities;
15. Component Safety Test Facilities;
16. Training and Simulator Test Facilities;
17. Engine Integration Test Facility;
18. Flight Test Facilities; and
19. System-level Safety Test Facilities.

The Hot-hydrogen Flow Test Facilities category was further divided into:

- a. Fuels and Materials Hot-hydrogen Flow Test Facilities;
- b. Hot-hydrogen Flow Test Facilities for Turbopump Development;
- c. Hot-hydrogen Flow Test Facilities for Nozzle Development; and
- d. Hot-hydrogen Flow Altitude Simulation Facility for Nozzle Demonstration.

For each of the 19 categories, the NTP Facilities Subpanel identified test objectives, top-level facility requirements, details of facility capability needs, and potentially available existing facilities.

FACILITY ISSUES

The NTP Facilities Subpanel discussed a number of issues that affect facilities development. The following paragraphs summarize some of the topics discussed. Environmental, safety, and health considerations were the top priority of the subpanel discussions.

Test Issues

The scope of an appropriate flight qualification ground testing program was considered a key issue in defining the requirements for a new ground test complex. The number of test cells required, test cell throughput requirements, potential source terms for environmental impact assessments, and posttest hardware handling and storage requirements depends on the amount of testing needed for flight qualification. This concern over the amount of testing extended to both full engine and fuel element testing. Multiple test cells are recommended, but the subpanel did not suggest an exact number.

The subpanel evaluated the impact of bypassing fuel element testing. Fuel element testing at lower powers, lower power densities, shorter test durations, and lower fuel temperatures is possible in several existing test reactors. A few of these reactors (such as the Idaho National Engineering Laboratory's Advanced Test Reactor) approach some nominal nuclear rocket operating conditions, but have significant shortfalls that will leave unanswered key fuel element development questions for some baseline concepts. The uncertainty is even greater for advanced innovative reactor concepts. Such questions will require prototypic fuel element

test reactors or full engine tests for answers. The subpanel recommended including the element test reactor in the test program.

The subpanel did not take a position on qualification testing of large area ratio nozzles (nozzles with ratios as high as 500 to 1). Due to large physical dimensions coupled with low nozzle exit plane pressures, ground testing may not be feasible.

The subpanel evaluated the need to test a complete stage on the ground and determined that only a close-coupled representative section of the tank bottom would be required. Any portion of the nozzle that is regeneratively cooled should be included in the ground test unit.

The subpanel did not identify the need for a specialized facility for safety testing at the full systems level. This position was consistent with the conclusions of the safety panel. However, the subpanel recommended that vibration tests simulating dynamic flight environments be performed on subcritical systems.

Test Reactor/Engine Issues

A facility to accommodate the needs of all possible reactor configurations would be prohibitively expensive. Because solid core concepts were considered to be the only concepts capable of producing near-term results, the subpanel defined a minimum set of facilities needed to develop a solid core nuclear rocket. The subpanel recommended that the reactor/engine test facilities should be designed for single engine tests at power. Multiple reactors would only be ground tested in clusters in low-power critical experiments.

The NTP Facilities Subpanel did not resolve the question of whether a driver reactor or a self-driven element test reactor would be needed. The advantages of a driver core include greater integrity for a larger portion of the core, separation of experiment coolant from driver elements, a potentially smaller effluent treatment system, and potentially lower long-term test costs. The advantages of a self-driven core include the potential for testing more experimental fuel elements at the same time, more flexibility to test different experimental fuel element designs, and the elimination of the development cost of driver reactor fuel. In addition, there would be no reactor to maintain when the experiment is removed and no large permanent build-up of long-lived fission products in a driver core. The subpanel recommended that the driver/self-driven element test reactor decision be left to the facility designer.

The element test reactor should be designed to permit the evaluation of different fuel concepts, as the cost for multiple element test facilities is prohibitive. The fuel test facility should be developed modularly.

Site Requirements Issues

Some facilities could take as long as ten years from the start of the program to full development. If an early flight test becomes a requirement, the program would be forced to accept significantly higher risks in the first space flights since full system ground testing could not be conducted.

Low pressure rocket engine test facilities are complicated by the very low nozzle exhaust pressures of such engines. In past and present test facility concepts, the exhaust pressure serves as the driving pressure for an effluent treatment system. The proper method for maintaining high standards of effluent scrubbing of fission fragments with low rocket exhaust pressure is not clear, but may require a fundamentally different effluent treatment system design. Much work remains to identify low pressure effluent cleanup options.

The rocket development hardware tested on the ground must be retained and stored after all posttest evaluations are completed, because the requirement for very high rocket reliability demands that development hardware be available to resolve subsequent development, qualification, and/or flight anomalies.

Fuel loading and zero-power critical testing of flight reactors must be conducted at facilities qualified for nuclear operations. The subpanel recommended that this be done at the reactor manufacturing and assembly location.

Site Location Issues

Planning for the fuel element test reactor facility and full system ground testing must begin as early as possible in the project. The environmental and safety concerns for such a facility are significant, and a highly sophisticated test site with an effluent treatment system that minimizes radionuclide release is essential. The site will also require expensive, long-lead-time, special order equipment. Years will be required for facility design, synthesis, and approval before equipment can be assembled and actual site construction completed.

Ground tests will generate waste from three principal sources: (1) the filters used for effluent treatment systems, (2) radioactive fuel, and (3) non-nuclear hardware. In addition, at the conclusion of the development program the ground test site and its equipment will have to be decontaminated and decommissioned. The NTP Facilities Subpanel recommended that the program minimize waste and that the test site be colocated with a site having low-level waste disposal capability.

RESULTS

The NTP subpanel study revealed that the United States has a wealth of test facilities available for supporting NTP technology 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 test needs.

Facilities Status

The subpanel found that NTP facilities could be divided into four major groups: (1) those that do not exist; (2) those that exist but need modification or equipment purchases; (3) those that exist and can be used as is, but may need later modification or equipment purchases; and (4) those that exist and for which no modifications are anticipated to be needed. Table 1 divides the 19 categories into their respective groups.

TABLE 1. Current Status of NTP Facilities.

No current facilities	Exist but need modifications or equipment purchases
Prototypic Fuel Element Test Reactor Reactor Test Cell Engine Ground Test Cell Flight Test Facilities System-level Safety Test Facilities Training and Simulator Test Facilities	Fuel Fabrication Facilities Unirradiated Fuel Materials Test Facilities Hot-hydrogen Flow Test Facilities Fuel Element Loops in Existing Reactors Remote Inspection/Post-irradiation Examination Facilities Low-power Critical Test Facilities
Exist but may need eventual modification or equipment purchases	Exist and need no modifications
Fuel Irradiation Test Facilities Material Irradiation Test Facilities Engine Integration Test Facility	Unirradiated Materials Test Facilities Component Test Facilities without Hot-hydrogen or Irradiation Environments Control System Test Facilities Component Safety Test Facilities

As Table 1 shows, the only facility categories that do not currently exist are the Prototypic Fuel Element Test Reactor, Reactor Test Cell, Engine Ground Test Cell, Flight Test Facilities, System-level Safety Test Facilities, and Training and Simulator Test Facilities. Of these six, three (Flight Test Facilities, System-level Safety Test Facilities, Training and Simulator Test Facilities) are anticipated to not be needed or could be incorporated into other categories. Modifications to existing facilities also could be made to accommodate these categories. Therefore, only the Prototypic Fuel Element Test Reactor, Reactor Test Cell, and Engine Ground Test Cell would be new constructions.

Tables 2 and 3 show examples of the top-level requirements for the Prototypic Fuel Element Test Reactor and the Engine Ground Test Cell. The NTP Subpanel report (Allen 1991) contains such detailed requirement listings on all 19 of the test facilities categories.

It should be noted that the lead-time and cost of facility construction or modification are very dependent on the test capabilities required. In the case of the Prototypic Element Test Reactor and the Reactor/Engine Test Complex the key drivers are:

- Environmental and safety regulations;
- Total reactor power or thrust level;
- Test run time;
- Reactor power density;
- Exhaust temperature;
- Exhaust backpressure; and
- Tests to performance margins that include potential fuel failure. (This is primarily an issue for the element test reactor.)

Colocation of Similar Test Functions

The NTP Subpanel members agreed that the reactor and engine ground test facilities, which generate neutrons and large amounts of energy, should be colocated on the same site. The subpanel also agreed that the Element Test Reactor could be located with the Reactor Test Cell and Engine Ground Test Cell, forming a single element/reactor/engine test site. This test complex would be located on an existing DOE site or reservation and could use the existing permits, environmental assessments, infrastructure, and waste management/fuel processing facilities as much as possible. Such an approach would save time, effort, and cost. Multiple cells and/or other physical separations should be included in the test site complex to allow work on different test articles to proceed in parallel.

Nevada Research and Development Area (NRDA)

During the early 1960s, NASA tested a nuclear thermal propulsion reactor and engine system (NERVA) at the Nuclear Reactor Development Station in Nevada. The project was stopped, but the facilities still remain in a test complex renamed as the Nevada Research and Development Area (NRDA). The NTP Facilities Subpanel visited the NRDA to determine if the site could be reused for current NTP development. The NRDA test cell facilities would require extensive refurbishment and modification to be useful for current nuclear rocket development. The effects of long dormancy coupled with the requirements of much more restrictive environmental standards probably makes the existing NRDA facilities unviable. Additionally, much of the equipment at NRDA has been scavenged and some of it is currently being used by other programs.

TABLE 2. Example of Top-Level Facility Requirements - Prototypic Fuel Element Test Reactor.

1. Test reactor configuration capable of simulating desired prototypical operating and transient conditions to fuel element(s) being tested.

Operating Assumptions

Total Power: >50MW

Power Density: Prototypic value for given concept (2 to 20 MW/l)

Test Environment: Hydrogen

Exhaust temperature: 1000-3500 K

Pressure: 15-1500 psia

Duration/Cycles: Sufficient to test elements beyond design basis of engine test article (up to 2 h single burn, 4.5 h cumulative burn, up to 24 cycles).

2. Reactor has capability to test alternate fuel concepts with maximum reuse of components feasible.
3. Facility is capable of fast turnaround of element tests.
4. Reactor complex will comply with all environmental and safety regulations. This includes being able to subject fuel to be tested up to and through failure thresholds as a planned, normal operational event.
5. Facility can supply process fluids as required for both operations and posttest decay heat removal according to specification.
6. Facility can maintain effluent releases within regulatory limits and as-low-as reasonably achievable.

7. Facility has robust instrumentation capability for meeting both operational requirements and experiment data acquisition needs.

8. Facility has capability to test nonfuel components (for example, electronics, valves) in NTP environment (that is, radiation, hot H₂)

9. On-site posttest examination and handling capability is the baseline with off-site inspection/examination capabilities an option, provided the associated handling, packaging, transportation, and posttest examination can be accomplished effectively and in a manner which does not perturb the test articles/assemblies or invalidate the test results.

10. Facility lifetime and reusability should be sufficient for the entire NTP ground test program.

11. Facility should be kept as simple as possible to reduce test costs.

12. Facility accommodates interim storage of test articles.

13. Facility accommodates efficient decontamination, decommissioning, and disposal of waste.

14. Facility complies with applicable security and safeguards requirements.

15. Facility has capability for recovery and reuse after major fuel element failure event.

RECOMMENDATIONS AND CONCLUSIONS

The subpanel concluded that while upgrades and modifications may be made to many existing facilities to support NTP development, only the prototypic element test reactor and the reactor/engine test facilities need to be constructed from the ground up. However, this positive finding must be tempered with the realization that a significant amount of program funding will still be required for new facility development, existing facility modifications, and test operations.

Safety and protection of the environment will be the highest priority of nuclear thermal propulsion technology development. These issues were foremost in the subpanel's considerations. While always considering safety goals, the NTP Facilities Subpanel recommended that NASA, DOE, and DoD:

1. Focus first on facilities needed for fuel development and new facilities with long lead-times. The need to perform fuel element testing under fully prototypical conditions and to evaluate reactor/engine systems on the ground is anticipated to make the prototypic element test reactor and the reactor/engine test facilities fall on the NTP critical path. Major new test facilities of these types will probably take seven to ten years to develop and, therefore, development of these facilities and high-priority facility modifications should receive high funding priority.

Based upon its reviews and its assessment of NTP development requirements, the subpanel presently recommends the funding priority for facility development shown in Table 4. Facilities required for fuel development have highest priority, followed by hot-hydrogen flow test facilities, and then low power critical facilities. The prototypic element test reactor and reactor/engine facilities are high on the list, not because they would be used first, but because they are long-lead-time items.

TABLE 4. Present Facility Development Funding Priority.

Priority	New	Existing	
Highest	Prototypic Element Test Reactor	Fuel Fabrication Facilities	Unirradiated Fuel Test Facilities
	Reactor/Engine Ground Test Facility	Hot-hydrogen Test Facilities Fuel Element Test Loops	Low power Critical Facilities Post-irradiation Examination Facilities
Medium		Fuel Irradiation Test Facilities Material Irradiation Test Facilities Engine Integration Test Facility	Unirradiated Material Test Facilities Component Safety Test Facilities
Low	Flight Test Support Facility	Control System Test Facilities	
	Training and Simulator Facilities	Non-irradiation/Non-hydrogen Component Test Facilities	
	System-level Safety Test Facilities		

Certainly, as NTP development activities evolve, this priority list will change. But, at the present time, funding emphasis should be on facilities required to support nuclear fuel development and long lead-time facilities such as the prototypic element test reactor and reactor/engine test facilities.

The approach suggested by the NTP Facilities Subpanel will make maximum use of the many existing facilities in the United States and the facilities' experienced staffs in developing space nuclear thermal propulsion. At the same time, our approach requires a minimum of new construction. Wise choices, careful planning, and sufficient funding will ensure that the NTP program attains its goal of completing full system ground testing by 2006.

Only

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