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Space Nuclear Thermal Propulsion Test Facilities Subpanel Final Report

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FOREWORD

In December 1990, the Space Nuclear Propulsion Test Facilities Panel was established to assess test facilities needed to support development of nuclear propulsion (NP) for the Space Exploration Initiative (SEI). The Panel was charged to identify facility requirements and needs and to evaluate existing facilities and their capabilities to satisfy projected requirements and needs as well as defining any new facilities capabilities that were required. The scope of the assessment included both nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) facilities. The Panel made an early decision to establish two facilities Subpanels, one for NEP and one for NTP.

As noted in Appendix A, the Panel and Subpanels met monthly during most of FY 1991 at several different sites. Representatives from the Department of Energy (DOE), National Aeronautics and Space Administration (NASA), Department of Defense (DoD), DOE and DoD Laboratories, NASA Centers, and private industry participated in these meetings. In addition to the meetings, there were a limited number of visits to existing sites, presentations by representatives of several existing facilities, establishment of a significant facilities database by D. Baldwin, and written contributions submitted by Panel members and participants as well as by other technology panels.

With largely a volunteer group, the Subpanel delivered a very thorough and comprehensive report. The Subpanel defined top-level facility requirements and test objectives, matched facilities with projected needs, and identified key issues and facility funding priorities. Prototypic fuel element test reactor and reactor/engine test facilities were identified as top priority facilities that were needed but not currently existing and which should be started now.

This report represents the work and results of the Nuclear Thermal Propulsion Test Facilities Subpanel. Appreciation is expressed to the primary contributors listed below who volunteered their time, wisdom, and

writing skills to the development of this report. Also special thanks to George Allen and the other co-authors for providing major contributions to this Subpanel effort.

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This report represents a consensus opinion of the NTP Test Facilities Subpanel members and should not be construed to represent the official views of DOE, NASA or DoD, individually or collectively. No inferences should be drawn form this report regarding official funding commitments or policy decisions.

John W. Warren, Chairman
NP Test Facility Panel

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Executive Summary

From December 1990 through the summer of 1991, the Space Nuclear Propulsion Test Facilities Panel evaluated facility issues related to supporting nuclear propulsion development. Volunteer representatives from the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), the Department of Defense (DoD), NASA Centers, DOE and DoD Laboratories, and private industry participated in monthly meetings to evaluate facility requirements and strategies for both nuclear thermal and nuclear electric propulsion systems. This report represents the work of the Nuclear Thermal Propulsion (NTP) subpanel.

The objectives of the NTP Facilities Subpanel were to:

(1) Define NTP test facility requirements.
(2) Evaluate existing facility capabilities to 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.
(6) Comment on frequently asked questions related to NTP facilities.

The subpanel met all of these objectives, although it should be noted that as a volunteer organization there was no work funded to conduct detailed analyses of some of the information presented. Based upon inputs from other panels and its own expertise, the NTP Facilities Subpanel developed the summary test logic for nuclear thermal propulsion development that is shown in Figure ES-1. In order to collect data on testing locations and evaluate capabilities, nineteen facility categories were established. The categories are:

Fuel Fabrication Facilities
Test Facilities for Unirradiated Fuel Materials
Test Facilities for Unirradiated Materials
Hot Hydrogen Flow Test Facilities
Fuel Irradiation Test Facilities
Material Irradiation Test Facilities
Fuel Element Loops in Existing Reactors
Low-Power Critical Facilities

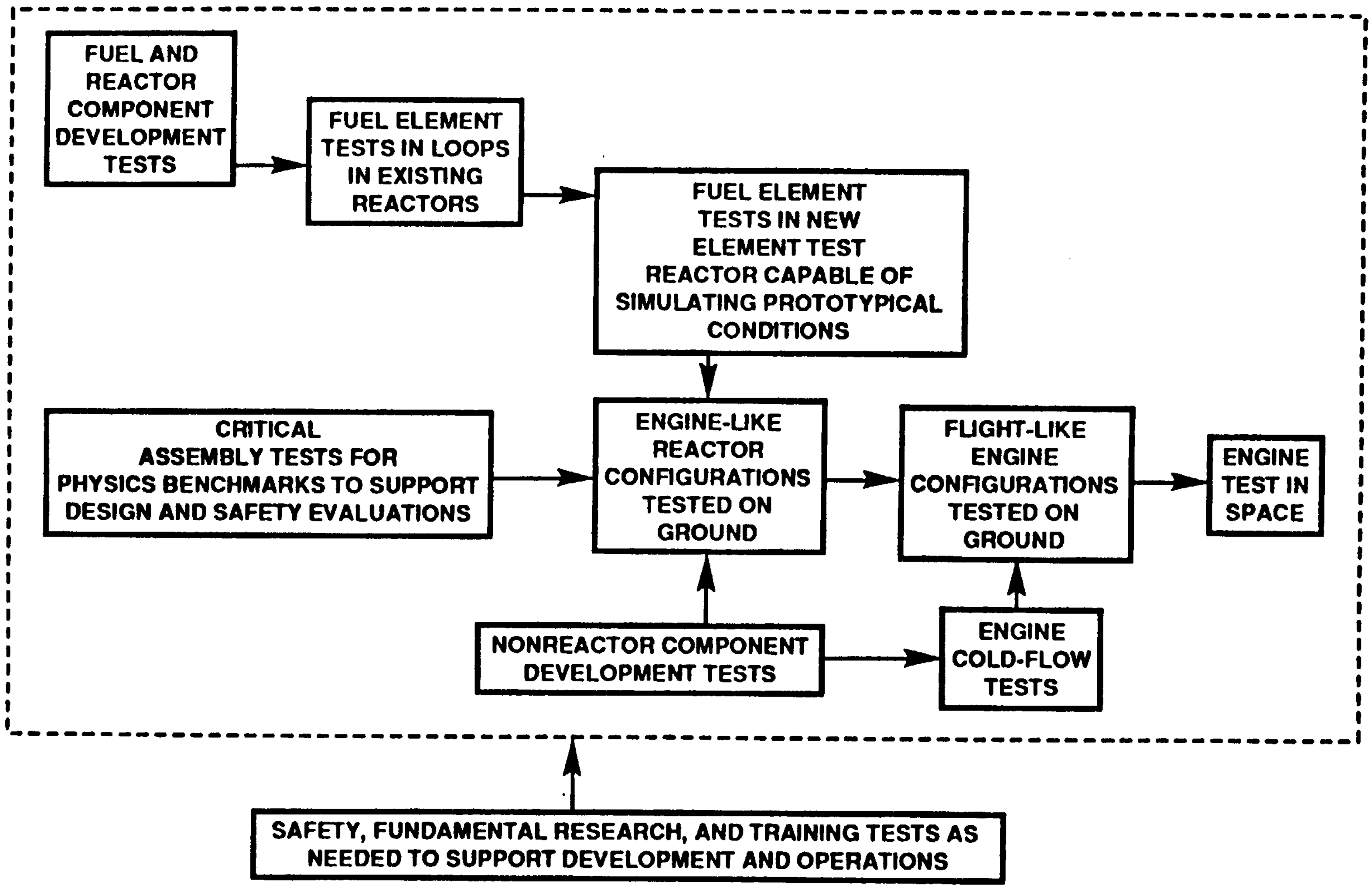

Figure ES-1. Summary Test Logic for NTP Development

Prototypic Fuel Element Test Reactor
Reactor Test Cell
Engine Ground Test Cell
Remote Inspection/PIE Facilities
Component Test Facilities without Hot Hydrogen or Irradiation Environment
Control System Test Facilities
Component Safety Test Facilities
Training and Simulator Test Facilities
Engine Integration Test Facility
Flight Test Facilities
System-Level Safety Test Facilities

The hot hydrogen flow test facility category is so large that it was further divided in groups: (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 Full Scale Nozzle Demonstration. While the Reactor Test Cell and Engine Test Cell are listed in separate categories, the Subpanel recommends co-location and considered them to be part of a single reactor/engine test facility.

Test facility requirements were compiled on each facility category. A considerable amount of information was collected on existing facilities. The course of this study revealed that the United States has a wealth of test facilities available for supporting NTP development. While some modifications will be required to support specific NTP development actions, there is a solid base of existing facilities available to satisfy a large majority of the test needs. Of the six test categories where no existing facilities were clearly identified, three are anticipated to either not be needed (e.g., system-level safety test facilities) or could be incorporated into other categories, or modifications to existing facilities (e.g., flight test support facilities or training and simulator test facilities could be made. This leaves the prototypic fuel element test reactor, reactor test cell, and engine test cell as the only facilities definitely unavailable. As stated earlier, the reactor test cell and engine test cell are expected to be co-located on a single reactor/engine test facility. Later deliberations by the subpanel resulted in the conclusion that the element test reactor should also be co-located on the same site as the reactor/engine test facility

The summary effect of this is that while upgrades and modifications may be made to many existing sites to support NTP development, only one new site needs to be developed from the ground up. However, this positive finding needs to be tempered with the realization that a significant amount of program funding resources will still be required for existing facility modifications, element/reactor/engine test facility development, and test operations. Based upon its reviews and assessment of NTP development requirements, the subpanel recommends the funding priority for facility development shown in Table ES-1 for the present. Certainly as NTP development activities evolve, the 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 Reactor/Engine test facility.

Safety and protection of the environment are the highest priority of nuclear thermal propulsion development. While always considering safety goals, the NTP subpanel recommends that NASA, DOE, and DoD:

(1) Focus first on facilities needed for fuel development and new facilities with long lead times.

(2) Start now on some essential near-term activities.

(3) Develop facilities intelligently and modestly.

(4) Use existing facilities and related program resources wisely.

(5) Develop only a minimum number of facilities/sites where capabilities do not presently exist.

Table ES-1. Present Facility Development Funding Priority

New	Priority	Existing
	Highest	
Prototypic Element Test Reactor		Fuel Fabrication Facilities
		Unirradiated Fuel Test Facilities
Reactor/Engine Test Facility		Hot H_2 Test Facilities
		Fuel Element Test Loops
		Post-Irradiation Examination Facilities
		Low Power Critical 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-H_2 Component Test Facilities
System-Level Safety Test Facilities		

SECTION 1
INTRODUCTION

1.1 Objectives

The objectives of the Nuclear Thermal Propulsion (NTP) Facilities Subpanel were to:

(1) Define NTP test facility requirements.

(2) Evaluate existing facility capabilities to meet these requirements.

(3) Identify new facilities required or existing facility modification needs.

(4) Identify critical path facility development requirements.

(5) Recommend facility development strategies.

(6) Comment on frequently asked questions related to NTP facilities.

It should be noted that environment, safety, and health considerations were frequently discussed during subpanel meetings. The subpanel considered no facility activity more important than public health and safety, and the protection of the environment. It should further be noted that the subpanel developed a number of working assumptions during its deliberations. In order to better understand the conclusions and recommendations of the NTP Facilities subpanel, these working assumptions are listed in Table 1-1.

The first objective was met by soliciting and receiving input from the other NASA/DOE/DoD panels addressing nuclear thermal propulsion. Specifically, inputs from the NTP Technology, Fuel and Materials, and Safety panels were key in developing facility requirements. Based on inputs from the other panels and the experience base of NTP subpanel members, the facility requirements were prepared and are summarized in Section 3.

The second objective was met by soliciting information from owners of existing facilities and comparing these capabilities against the facility requirements. Data on more than 200 facilities were compiled by Sverdrup, Inc. for the National Aeronautics and Space Administration/Lewis Research Center (NASA/LeRC). Several site visits and presentations were made. The information compiled by Sverdrup is presented in a companion report of this document entitled, "Candidate Nuclear Propulsion Test Facilities". A listing of individual facilities by category group is included in Appendix B. The summary evaluation of existing facilities is included in Section 3.

The third objective was met by comparing facility requirements against capabilities of existing facilities. In some cases, no existing facility is

Table 1-1. Major Working Assumptions

by

The NTP Facilities Subpanel

- A NASA/DOE/DoD Memoranda of Agreement will exist for coordination of nuclear propulsion activities.
- Safety is an overriding consideration for public acceptance, protection against accidents, and both ground testing and space operations.
- The ultimate safety objective is to minimize risk to the public and crew in normal and abnormal operations.
- Technical feasibility, schedule times, and cost envelopes were success-oriented.
- Concept and technology development should be focused toward meeting the Piloted Mars Vehicle Application.
- Integrated system demonstration/validation in a simulated environment (commonly referred to as "technology readiness level 6") by 2006.
    - First human Mars flight by 2014
    - Several demonstration flights between 2006 and 2014
- Evolving technologies such as open cycle gas core could not compete in the near term with mainline solid core concepts. Consequently solid core concepts are the baseline for achieving a technology readiness level (TRL) 6 by 2006.
- The current environment, safety, and health requirements may evolve but will not undergo quantum changes.
- Nuclear tests will be conducted at DOE facilities.

Table 1-1. Major Working Assumptions (Concluded)

- The major nuclear facility milestone assumptions are as follows:

DATE	MILESTONE
1997	Nuclear furnace type facility fully constructed
1998	Nuclear furnace tests completed
2000	Reactor system facility fully constructed
2001	First NTP reactor tests completed
2006	Full-size NTP ground engine system tests completed verifying technology readiness level (TRL) 6

- An open-cycle effluent treatment system will work and be accepted.
- Full-scale reactor/engine tests to failure will not be required on the ground.
- Engines will be not be required to be tested in clusters on the ground.
- Full expansion-ratio nozzle tests will not be required to be tested on the ground.
- Neither reactor assembly nor low-power critical tests will be required on the ground at the launch site.
- An unmanned demonstration flight would be conducted in space prior to manned flight.

available, and consequently a new facility was determined to be needed. In other cases, some or no modifications to existing facilities were identified as necessary. These evaluations resulted from a combination of panel discussions and individual written contributions and are also included in Section 3.

The fourth and fifth objectives were met by subpanel discussions on the development strategy and critical paths. Frequently, a particular point of view would have a champion who would submit or propose a particular approach. These would be discussed or reviewed by the subpanel prior to being included in Section V.

The sixth objective covers a number of issues that are frequently raised on facilities for NTP development. The subpanel discussed these issues and prepared a recommendation. These recommendations are summarized in Section IV.

1.2 Scope

The NTP Facilities Subpanel focused on facilities for developing both nuclear and nonnuclear components and systems for the mainline solid core concepts. These include:

(1) NERVA Derivatives
(2) Particle Bed
(3) Wire Core
(4) Cermet
(5) Pellet Bed
(6) Dumbo
(7) Low-pressure solid core

The baseline is a high-pressure system with low-pressure concepts treated as an alternative. The high-pressure systems were the only concepts judged to be capable of reaching a technical readiness level of six (TRL-6) by 2006. However, the major impacts of including low-pressure concepts in the facility requirements are discussed.

Facilities for liquid or gas core systems were not specifically discussed by the subpanel. However, it may be possible to conduct "proof-of-concept" tests for those currently listed as "innovative" (e.g., Nuclear Light Bulb) in some of the facilities covered in this report. A table of facility requirements for "proof-of-principle" tests on innovative concepts is provided in Section 2.2 of this report.

Since the subpanel was comprised of volunteers donating time to this effort, no detailed analyses were performed to verify subpanel positions. The input information provided by individual contributors was evaluated for reasonableness, but no independent analytical verification was possible. Consequently, the subpanel report shows enveloping ranges rather than specific values.

1.3 Test Facility Categories and Groups

One early activity of the subpanel was to categorize the facilities needed for NTP development by function. Nineteen facility categories and their expected relationships are shown in Figure 1-1. A brief definition of each of the facility categories is given in Table 1-2.

The nineteen facility categories were later put into five groups described in Table 1-3. There are two groups for facilities that do not currently exist and three groups of existing facilities.

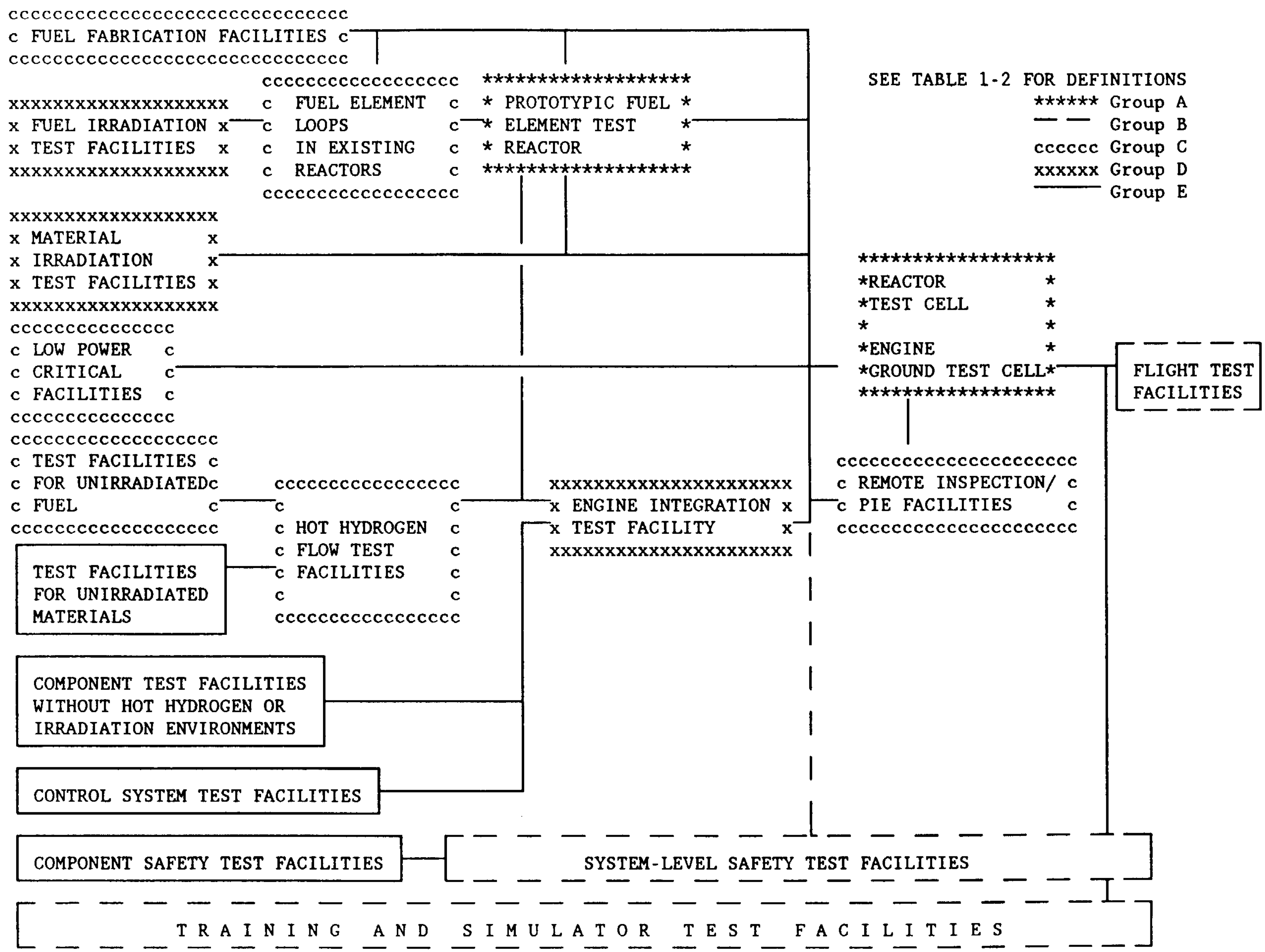

Figure 1-1. NTP Test Facilities

Table 1-2. Definitions of NTP Facility Categories

Facility Category	Definition
Fuel Fabrication Facilities	Facilities for development and eventual production of enriched uranium nuclear fuel materials and fuel elements
Test Facilities for Unirradiated Fuel Materials	Material testing and characterization laboratories capable of handling unirradiated, uranium fuel materials
Test Facilities for Unirradiated Materials	Material testing and characterization laboratories for nonradioactive materials proposed for structural components such as tie-rods, frits, pressure vessels, etc.
Hot Hydrogen Flow Test Facilities	Facilities featuring materials or subsystems in a flowing hot hydrogen environment without nuclear heating. Potential radioactive material inventory would be limited to unirradiated uranium in any fuel/elements tested. Hot hydrogen flow test facilities include the following two types: (1) Fuels and Materials/Low flowrate - Primarily uses pure H_2 for material and fuel tests (2) Equipment Development/High flowrate - H_2/O_2 gas generator or electrically heated H_2 used for turbopump, nozzle, and propellant management system testing
Fuel Irradiation Test Facilities	Reactor or radiation source facilities that provide a gamma or neutron fluence to a test specimen of uranium fuel material
Material Irradiation Test Facilities	Reactor or radiation source facilities that provide a gamma or neutron fluence to a test specimen of structural or non fuel-bearing material
Fuel Element Loops in Existing Reactors	Test loops for nuclear-heated fuel-element experiments in existing reactors

Table 1-2. Definitions of NTP Facility Categories (Continued)

Facility Category	Definition
Low Power Critical-Assembly Test Facilities	Low power, flexible geometry, variable material volume fraction reactor facility for physics benchmark, design confirmation, and safety tests.
Prototypic Fuel Element Test Reactor	Test reactor in which all desired performance parameters (time, temperature, power density, etc.) can be achieved together for experiments on one or more prototypic fuel elements. It is often called the "Nuclear Furnace" because the fundamental test objectives are the same as those for the Nuclear Furnace operated in the early seventies.
Reactor Test Cell	Portion of a Reactor/Engine Test Facility where early "engine-like" reactors would be tested at high powers on the ground
Engine Test Cell	Portion of a Reactor/Engine Test Facility where "flight-like" nuclear rocket engines would be tested at high powers on the ground
Remote Inspection/Post-Irradiation Examination Facilities	Hot cell facilities where post-test examinations of radioactive fuel, reactor, and engine components will be conducted
Component Test Facilities Without Hot Hydrogen or Irradiation Environment	Facilities that can simulate structural, thermal, and cycling environments during startup, continuous lifetime operation, and shutdown on system components. However, environments would not include irradiation or hot hydrogen.
Control System Test Facilities	Simulation laboratory to develop and test engine/system control system
Component Safety Test Facilities	Test facilities that can simulate on system components all realistic malfunctions and severe or accident environments

Table 1-2. Definitions of NTP Facility Categories (Concluded)

Facility Category	Definition
System-Level Safety Test Facilities	Test facilities that can simulate on the complete engine all realistic malfunctions and severe or accident environments
Training and Simulator Test Facilities	Facilities for operator/astronaut training. Emergency sequences would be simulated for training.
Engine Integration Test Facility	Cold flow test facility for complete engine system. Facility would use hot gas (H_2/O_2 gas generated) to simulate reaction and to evaluate potential pre-flight and flight problems. No nuclear critical operations or nuclear heating would occur.
Flight Test Facilities	Ground facilities at launch site or operations control center required for launch support or operations specifically as a result of having nuclear propulsion systems

Table 1-3. Groupings of Facility Categories

Group	Group Definition	Facility Categories Included in Group
A	No facilities currently exist. Development work should start now since these are long-lead-time facilities that probably fall on the NTP critical path.	Prototypic Fuel Element Test Reactor Reactor Test Cell Engine Ground Test Cell
B	No facilities currently exist. Development work should be deferred until requirements or need is clearly defined. The facilities do not presently fall on the NTP critical path, and their development could be delayed for a few years or their functions could be included in another facility.	Flight Test Facilities System-Level Safety Test Facilities Training and Simulator Test Facilities
C	Facilities currently exist, but some modifications may be required. These are the highest priority of the existing facilities, and needed modifications should be started on them first since they are the most likely to fall on the NTP development critical path.	Fuel Fabrication Facilities Test facilities for Unirradiated Fuel Hot Hydrogen Flow Test Facilities Fuel Element Loops in Existing Reactors Remote Inspection/ PIE Facilities Low-Power Critical Assembly Test Facilities
D	Facilities currently exist, but some modifications may be required in the longer term. Use of these facilities without modification should be adequate for the near term. Any modifications can probably be delayed for several years without affecting the NTP development critical path. Consequently, modifications for these facilities are a lower priority than those for Group C.	Fuel Irradiation Test Facilities Material Irradiation Test Facilities Engine Integration Test Facilities

Table 1-3. Groupings of Facility Categories (Concluded)

Group	Group Definition	Facility Categories Included in Group
E	Facilities currently exist and no large DOE/NASA/DoD funding is anticipated for development or modifications.	Test facilities for unirradiated materials Component test facilities without hot hydrogen or irradiation environments Control System Test Facilities Component Safety Test Facilities

SECTION 2

NTP DEVELOPMENT AND TESTING NEEDS

2.1 Summary Test Logic

The NTP Facilities Subpanel used much more than its own expertise to define testing needs and facility requirements. Figure 2-1 shows the interactions between the NTP Facilities Subpanel and the other NASA/DOE/DoD panels that were meeting during the same time period. The NTP Technology, Fuels and Materials, and Safety Panels provided considerable information and comments. There was very limited direct communication with the Mission Panel and essentially no interaction with the NEP Technology Panel. Interactions with the NEP Facilities Subpanel were primarily limited to full Nuclear Propulsion Test Facilities panel meeting discussions.

A summary test logic was developed based upon subpanel discussions and input from the other panels. This summary test logic is shown in Figure 2-2.

2.2 Input from the NTP Technology Panel

Detailed inputs on testing needs and facility requirements received from the NTP Technology Panel are shown in Table 2-1. Because of the importance of the Reactor/Engine ground test facility to NTP development, the engine test facility requirements are shown in the separate Table 2-2. The nominal value shown in Table 2-2 is the baseline requirement. The range would be evaluated by the design contractor for impact on the facility performance and cost during initial development/modification studies. Depending on results from these initial design studies, the baseline requirements would be changed. The Innovative Concepts Subpanel of the NTP Technology Panel provided input on facilities needed for "proof-of-concept" tests on gas core reactors. This information is summarized in Table 2-3. Wise use of existing facilities and development of new facilities would allow evolutionary growth of facility capabilities to enable testing of advanced designs and concepts.

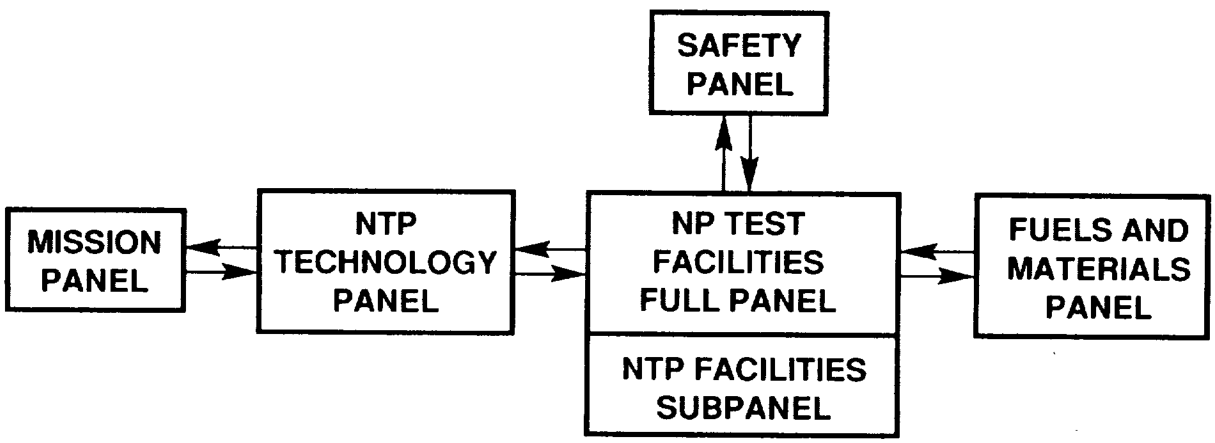

Figure 2-1. NTP Facilities Subpanel Interactions with Other NASA/DOE/DoD Panels

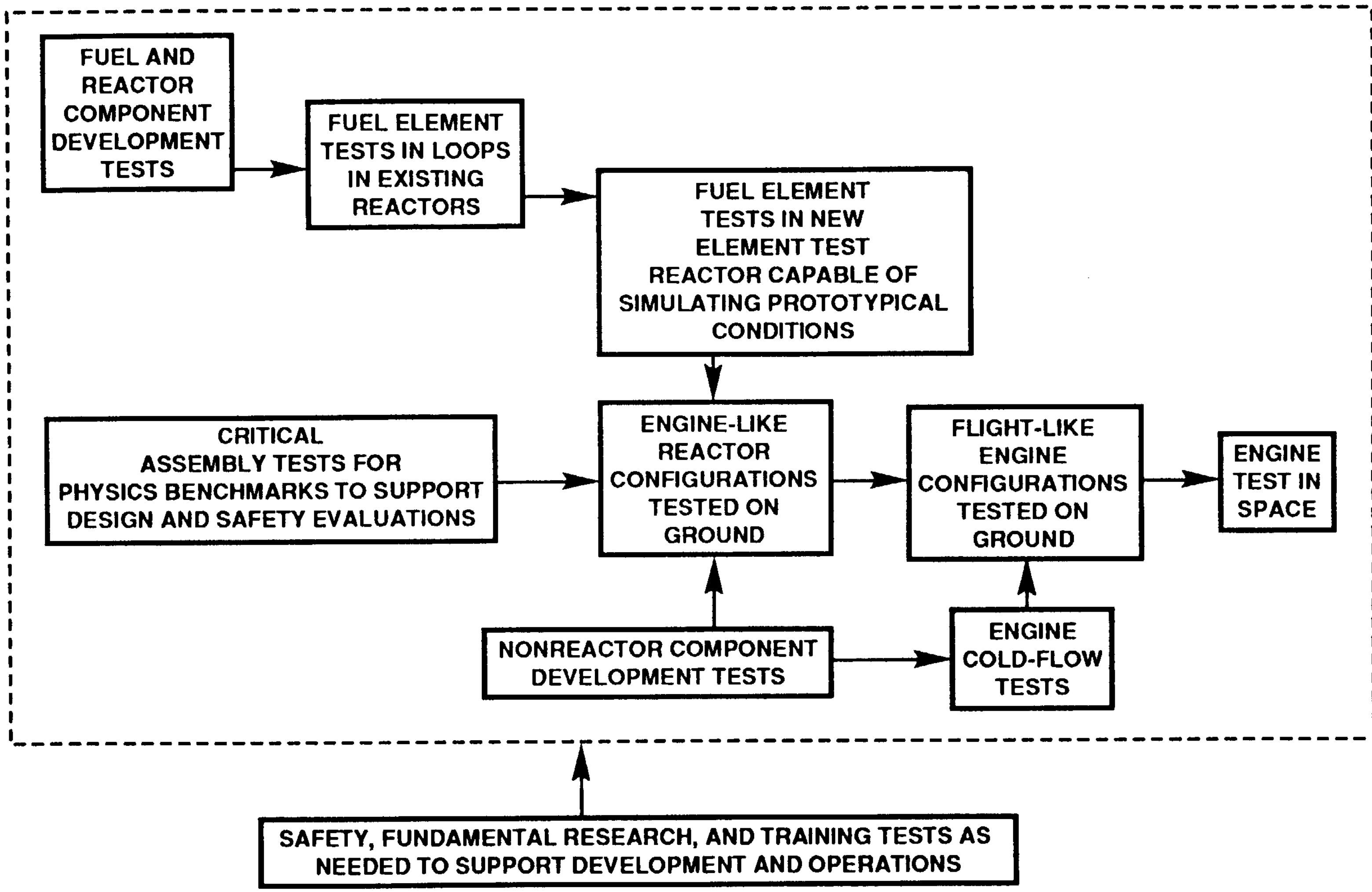

Figure 2-2. Summary Test Logic for NTP Development

Table 2-1. NTP Technology Panel Input to Facility Requirement

Facility	Test Requirements
Fuel Fabrication Facilities	No specific comment. NTP Technology Panel stated that input should come from Fuels and Materials Panel
Test Facilities for Fuels Not Subjected to Irradiation for Test Evaluations	No specific comment. NTP Technology Panel stated that input should come from Fuels and Materials Panel
Test Facilities for Materials Not Subjected to Irradiation for Test Evaluations	No specific comment. NTP Technology Panel stated that input should come from Fuels and Materials Panel
Test Facilities for Fuel Irradiation	No specific comment. NTP Technology Panel stated that input should come from Fuels and Materials Panel
Facilities for Material Irradiation and Testing	Ability to irradiate materials and evaluate (1) Embrittlement in H_2/radiation environment (2) Material physical property changes from irradiation (3) Moderator/shield dimension changes because of irradiation (4) Electronics/sensor damage because of irradiation (5) Material compatibility with working fluids in radiation environment (6) Bearing surface coating deterioration from irradiation (7) Fiber/composite material degradation in a radiation field

Table 2-1. NTP Technology Panel Input to Facility Requirement (Continued)

Facility	Test Requirements
Low Power Critical Test Facilities	Ability to conduct zero or low power critical reactor experiments to benchmark neutronics codes, to confirm nuclear design and safety assessment, and evaluate (1) Power distribution and criticality (2) Material reactivities (3) Doppler and temperature coefficients (4) Coolant density variation reactivity coefficients (5) Delayed neutron fraction and neutron lifetime (6) Control element worths (7) Engine clustering effects (8) Disturbed core configuration effects for safety studies
Test facilities for components not subjected to irradiation or hot H_2 for test evaluations	Ability to simulate structural loading, pressure, vacuum, shock, vibration, thermal behavior, thermal stress, cycling environments during startup, continuous lifetime operation, and shutdown on system components. These components include but are not limited to (1) Valves, seals, bearings (2) Sensors and instrumentation (3) Nozzle (4) Turbopump (5) Pressure vessels and piping (6) Control rod drives
Facilities to test unirradiated materials and components in flowing hot H_2 outside a radiation field	Ability to test the following in flowing hot H_2: (1) Fuel/elements - Input from Fuels and Materials Panel (2) Materials - Input from Fuels and Materials Panel (3) Nozzles - Erosion and performance over full operating range (life, cycles, etc.) (4) Turbopump - Demonstrate TPA performance including startup, throttling, shutdown, cooldown, and soakback (5) Other - Evaluation of throttle valves, mixers, sensors, and ducting

Table 2-1. NTP Technology Panel Input to Facility Requirement (Continued)

Facility	Test Requirements
Control System Test Facilities	A simulation laboratory to develop the engine/system control systems. Initial facility will focus on software and benchtop electronics development. Later requirements are expected to be integrated into adverse environment hardware evaluations and early element test reactor/reactor/engine configuration tests.
Existing Facilities for Fuel Element Testing	Ability to test full-length or part-length elements and evaluate (1) Performance at prototypical temperatures and run-times (2) Irradiation damage (3) Transient/Cycling Performance (4) Fission product release (5) Data requirements for engine safety tests
Prototypical Fuel Element Test Reactor Facility	A simple, potentially stand-alone, reusable facility capable of fast turnaround of fuel element tests. The facility should be available throughout the entire ground test and development program to provide a test capability for future fuel performance improvements. The facility should include: (1) Effluent Cleanup System - H_2 and water - Pilot for full-size test facility (2) Post-Irradiation Examination Capability (3) Capability to test elements to failure (4) Capability to provide prototypic environment for nonfuel components (e.g., electronics, valves, etc.) (5) Capability to evaluate alternate fuels (6) Ability to envelope the following nominal operating range: Total Power: 50-100 MW Fuel Element Power Density: 2-20 MW/ℓ Exhaust temperature: 3000-3500 K Pressure: 500-1500 psia Duration/Cycles: Sufficient to test elements beyond their design basis. (7) Infrastructure to support operations

Table 2-1. NTP Technology Panel Input to Facility Requirement (Concluded)

Facility	Test Requirements
Facilities for Component Safety Tests	Ability to simulate all realistic malfunctions and severe or accident environments. This includes but is not limited to (1) Launch pad fires (2) Re-entry (3) Land or water impact (4) End of flight disposal
Facilities for System-level Safety Tests	No requirements identified at this time.
Training and Simulator Test Facilities	No requirements identified at this time. Seems to be a natural expansion of requirements for control system and engine ground testing facilities.
Engine Integration Test Facility	Ability to perform complete system checkout without reactor startup. This includes but is not limited to the following: (1) Startup sequencing (2) Cold flow tests (3) Dynamic performance measurements (4) System interface, handling, and transport checkouts (5) Post-test purge procedures LH_2 and LO_2 are expected to be available for tests. (Including slush H_2).
Reactor Test Cell	Ability to accommodate SEI Reactor/Engine Ground Test Facility requirements shown in Table 2-2.
Engine Test Cell	Ability to accommodate SEI Reactor/Engine Ground Test Facility requirements shown in Table 2-2.
Remote Inspection/PIE Facilities	Ability to accommodate SEI Reactor/Engine Ground Test Facility requirements shown in Table 2-2.
Flight Test Facilities	Ability to perform pre-flight check-out and zero-power criticality tests.

Table 2-2. NTP Technology Panel Input - REQUIREMENTS FOR SEI REACTOR/ENGINE GROUND TEST FACILITY

Requirement	Nominal Value	Range
ENGINE		
Thrust:	75,000 lbs	30,000-250,000
Configuration:	Single engine Topping or Bleed Cycle	1 - 3 engines
Nozzle:	Two-piece, 10:1 for ground tests	Altitude simulation for Low-Pressure Concept (TBD)
Exhaust Chamber Pressure:	1000 psia	500-1500 psia
Mixed Mean Exhaust Temperature:	3000 K	2500-3600 K
Coolant Supply:	Liquid H_2 25 K 50 psia	Slush H_2 20-40 K 25-100 psia
Thrust Vector Control:	± 5°	0–5°
Dual Mode:	No dual mode	50 kW max. Steady-state
Maximum Single Burn:	1 hour	1 to 2 hours
Total Run Time/Engine:	4.5 hours	1.5 to 4.5 hours
Restarts:	24	1,4,24
Engine Control:	Redundant systems	-
Throttling Capability	100%	50-100% full power at full operating temperature

Table 2-2. NTP Technology Panel Input - REQUIREMENTS FOR SEI REACTOR/ENGINE GROUND TEST FACILITY (Concluded)

Requirement	Nominal Value	Range
Facility		
Heat Source for Turbopump:	100 MW	35-250 MW
Facility Control:	Robust	-
Data Acquisition:	Extensive	-
Post-Test Inspection:	Remote Inspection Post-Irradiation and Examination Capability	-
Engine Configurations:	Ability to test various high-pressure solid core concepts	Low Pressure and Contained Gas Core (e.g., Nuclear Light Bulb) Concepts
Fission Fragment Release Limits:	Within regulatory limits and as-low-as-reasonably-achievable (ALARA)	
Hydrogen Disposal:	Flare	Closed Cycle, Reuse

Table 2-3. Major Facilities Needed for "Proof-of-Concept" Tests Required to Support Gas Core Development

Facility	Mission/Objective	Requirements
Plasma Jet Facility	Use RF Heated Plasma Jets to evaluate both fundamental physics and systems components.	Initially 50-250 kW, 10,000 K chamber, low H_2 flow rate for radiation transfer, fluid mixing, opacity measurements, and diagnostics development. 1-5 MW facility, perhaps to 40,000 K, high H_2 flow for computer code benchmarking, radiation transport nozzle materials testing, and transpiration cooling development. Eventually a multisource/multiuser facility—perhaps one source of 10-15 MW with several lower sources for component development.
Test Loops in Existing Reactors	Perform in-pile tests of full and subscale gas core elements for reactivity of both open- and closed-cycle concepts. Includes hot element, cold moderator neutronics tests.	Driver core with cavity large enough for test capsule and neutron spectrum and flux sufficient for experiments.
High-Power Density Test Reactors	Conduct element/critical assembly tests at conditions more closely approaching prototypical.	High power density test reactor capable of driving gas core test capsules.

2.3 Input from the Fuels and Materials Panel

Inputs on testing needs and facility requirements received from the Fuels and Materials Panel are shown in Tables 2-4 and 2-5. It should be noted that there is an ongoing discussion in the Fuels and Materials Panel about the optimal fuels test strategy given anticipated budget constraints. The input provided here is for an "ideal" approach that includes capsule testing followed by loop testing followed by fully prototypic element testing. A more limited approach may be required depending on funds available and technical risks accepted.

2.4 Input from the Safety Panel

Control of hazards associated with NTP Systems will require safety test information to validate analysis and to support both establishing and demonstrating the satisfaction of safety requirements. Initial guidance to permit identification of the scope of test facility requirements for evaluating flight system safety features and the type of testing needed to support flight system safety are listed in Table 2-6.

It should be noted that the safety panel made the following recommendations which indicate system level safety test facilities will not be required:

(1) It is likely that no full reactor safety testing beyond that planned for design validation is required.
(2) It is likely that no large scale reactor destruction testing is required.
(3) Reliability testing should focus on demonstrating a lack of failure mechanism.

Propulsion systems technology varies over a broad range and the design definition associated with the many candidate concepts is also quite varied. Options based on solid fuel designs are reasonably definitive in their features, while other designs employing innovative liquid and gaseous fuel forms are only concepts with little design and performance data available. Recommendations based on current information of necessity rely heavily on

Table 2-4. Facilities Requirements for NTP Fuels and Core Materials

FACILITY REQUIREMENTS	MISSION GOAL/OBJECTIVES
Fuel Fabrication and Assembly Category 1 SNM Facility capable of processing 200 kg U and 1000 fuel elements per year: feedstock preparation; powder preparation; sphere fabrication; sintering, CVD coating; extrusion; hot pressing; graphitizing; brazing; electron beam; laser, and GTA welding; assembly lines; inspections; quality assurance; scrap recovery; and waste treatment.	• Recapture fabrication procedures • Determine phase equilibrium and melting points • Develop new fuels and fuel forms • Develop new Fabrication procedures • Fabricate test fuels and fuel elements • Develop fuel element joining techniques • Pilot plant fabrication of test cores • Develop spent fuel recovery procedures • Demonstrate quality-assured procedures
Ex-Pile Testing and Characterization Lab Adjunct to the Fuel Fabrication facility: analytical chemistry, ceramography, NDE, mechanical testing, high temperature testing, H2 testing, compatibility testing, and kinetic, physical, and thermodynamic properties	**Quantitatively understand:** • Thermal transport of material • Thermal stability of fuels and coatings • Chemical stability of fuels and coatings • Thermal stress resistance • Thermal properties for design • Component compatibility • Mass-loss and degradation caused by H2 reactions. • Thermal transient response
Hot Gas Testing Lab Capable of heating unirradiated NTP fuel elements to 3500 K in flowing hydrogen, with data collection and analysis, post-test characterization, hydrogen and SNM containment	**Quantitatively understand:** • Corosion mechanics • Hydrogen compatibility at high gas flow rates • Coating integrity and stability at high gas flow rates • Fuel and coating mass loss at high gas flow rates

Table 2-4. Facilities Requirements for NTP Fuels and Core Materials (Concluded)

FACILITY REQUIREMENTS	MISSION GOAL/OBJECTIVES
Capsule Test Reactor Small test reactor with instrumented capsules, fuel temperatures to 3500 K for 10 hours, in hydrogen atmospheres, NDE equipment, data collection and analysis, in-line fission gas analysis	• Screening of solid solution fuel forms **Quantitatively understand:** • Fission product release • Hydrogen compatibility • Irradiation induced swelling • Compatibility with fission products
Transient Test Reactor Rapid thermal transient testing of fuel elements and assemblies	• Restart and cycling capability • Thermal stress resistance • Off-normal operation • Fission product release
Nuclear Furnace Able to duplicate operating conditions of a full scale NTP reactor with data collection and analysis, fission product containment, and prototype gas flow rate	• Restart and cycling capability • Element/element interactions • Corrosion mechanics • Statistical irradiation data
Hot Cells Burnup analysis, neutron radiography, profilometry, gamma scan, ceramography, fission gas analysis, SEM, microprobe, analytical chemistry.	• Postirradiation examination of tests for fission gas release, swelling, mass compatibility, etc.

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities

Description	Mission/Objective	Requirements	Status
1. Mechanical Properties Ultrahigh-vacuum, high-temperature creep machines	• Characterize the creep properties of candidate materials • Provide the data necessary to downselect candidate materials • Provide preliminary engineering data required for conceptual design • Yield data sufficient to down-or-out select concepts	• Needed during the first year of program • Test facility should have capability to: - >3000 K - 10^{-10} torr vacuum - facilitate automated data acquisition • Proven and reliable test methods used and QA practices followed	• Limited facilities - most committed to long-term SP-100 test - remaining have been inactive for many years • Test devices available commercially at about $250K each
Environmentally controlled high temperature tensile testing machines	• Characterize the tensile and fatigue properties of candidate materials in inert gas and hydrogen • Provide data necessary for downselection of materials • Provide preliminary engineering data required for conceptual design • Yield data sufficient to down-or-out select concepts	• Needed during the first year of program • Hydrogen facility for testing alloys and graphics for NTP application with capability to: - >3000 K - capability of a wide range of strain rates - perform both low- and high-cycle fatigue - hydrogen pressure to 10K • Vacuum facility for testing ceramic and ceramic composites with capability to: - >3000 K - perform both low-and high-cycle fatigue - vacuum to 10^{-5} torr - bending moment of less than 0.1%	• Limited numbers of qualified facilities • Twenty to thirty facilities available - Appear to be committed to NASP program • Limited facilities available

Table 2-5. **Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)**

Description	Mission/Objective	Requirements	Status
1. Mechanical Properties (Cont)			
Pressurized tube creep test	• Inexpensive method to obtain long-term creep performance data on candidate alloys • Provide data for preliminary system design • Yield data needed to optimize system life versus performance trades	• Needed by the first year of the program • Hydrogen test furnace capable of: - 1900 to >3000° - hydrogen pressures to 1000 psi - running uninterrupted for hundreds of hours • Proven and reliable test methods used and QA practices followed	• Availability is unknown
Mechanical properties testing capability under multiaxial loading	• Characterize the failure mechanisms of candidate materials under complex loading conditions • Yield engineering data required for concept design	• Needed during third year of program • Test facility with - capability for at least bi-axial loading - temperature capability to >3000 K for NTP - ability to perform both low- and high-cycle fatigue - vacuum to 10^{-5} torr or controlled environments of inert gas or hydrogen	• Limited machines available for this type of testing - Need for additional testing capability is anticipated

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
2. Compatibility			
Hydrogen compatibility test laboratory	• Characterize compatibility of candidate materials at high temperatures in inert gas environment - assess dissimilar metals - mass transfer phenomena - evaporation phenomena - ductility loss - low-temperature embrittlement - fatigue and creep property degradation • Provide data necessary for conceptualization through final design • Yield data for concept downselection and optimization	• Needed in the first year of program • Extensive experience with design and operation of high-temperature hydrogen test with a variety of materials • Demonstrated experience in the safe operation of high-temperature, high-hydrogen tests • Refractory and superalloy plus structural ceramic fabrication facilities • Test apparatus capable of: - temperatures to >3000 K - hydrogen pressure to 1000 psi	Availability unknown • Very specialized facilities • Should exist in support of: - coal gasification and liquefaction programs - NASP - chemical propulsion

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
2. Compatibility (Cont)			
High-temperature tribological test laboratory	• Characterize the wear and galling characteristics of moving and bearing surfaces operating at high temperatures • Provide data necessary to show that feasibility issues associated with gall and wear problems have been mitigated • Generate failure mode data and reliability statistics	• Needed by fourth or fifth year of program • Extensive experience with design and operation of high-temperature tribological facilities • Refractory alloys, superalloy, ceramic, and coating processing experience and capability • Test apparatus capability - temperatures to >3000 K - test environment may include • vacuum to 10^{-8} torr • hydrogen to 1000 psi - rotational and/or reciprocating motion - appropriate diagnostic methods	• Limited capability in place for SP-100 Project - temperature limited to 1350 K - vacuum environment only
Atomic oxygen	• Characterize and assess the degradation of candidate structural materials (particularly refractory alloys) to atomic oxygen - ductility loss - alkali attack • Provide data necessary for conceptual design • Yield data for materials and concept down-or-out selection	• Need cursory test ability in 2-year program • Test apparatus capable of simulating atomic oxygen environment	• Numerous facilities are thought to be available, i.e., LANL, NASA-LeRC

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
3. Irradiation Tolerance Material Test Reactor	• Provide a facility capable of exposing materials in materials test assemblies to prototypic irradiation environments for subsequent characterization of irradiation damage effects	• Must identify test reactor in the first year to allow completion of test and PIE to support downselections in year four or five of program • One or more separate reactors may be requried to simulate NEP and separately NTP in-core and outside of core environments. Specific requriements include: - fast spectrum (NEP) - thermal spectrum (NTP) - capable of maintaining material environments of alkali metals or inert gas - capable of maintaining a predetermined test material temperature that may cover NTP temperatures of interest - support the capability for an instrumented test	• Several candidate DOE reactors are available: - FFTF - EBR-II - ATR - HFIR - others
Material irradiation test fabrication and assembly	• This facility is an integral part of the materials irradiation test activity • This facility, including its staff, will design materials test, build and instrument the test vehicle, install test specimens, ship test vehicle to reactor, and oversee the installation into the test reactor	• Must identify material test and assembly in the first year to allow completion of test and PIE to support downselection in year four or five of program • Experience with design of experiments for reactor selected	• Capabilities exist at several DOE laboratories

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
3. Irradiation Tolerance (Cont)		• Experience in meeting quality assurance requirements for test design and assembly • Suitable fabrication, assembly, and inspection capability	
PIE/Hot cells	• This facility (or facilities) is an integral part of the materials irradiation test activity • One facility will disassemble the test vehicle after reactor exposure • One or more facilities will perform material characterizations and report on results	• Must identify PIE/hot cells in the first year to allow effective test design and implementation • Facility must have the following: - experience with testing the candidate materials - equipment necessary to perform needed tests • neutron radiograph • profilometry • metallography and ceramography • microanalysis and microanalytical equipment • mechanical properties tests—tensile, impact, and bend • Appropriate quality assurance and environmental, health, and safety experience • Ability to test irradiated samples with a hot hydrogen cover gas	• Capability exists at several DOE laboratories

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
4. Processing Refractory Alloy (Primarily directed toward NEP application but may have some NTP benefits)	• Recapture alloy fabrication practices where needed or develop practices for new materials • In the near term, fabricate the product needed for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities: - melting - ingot breakdown - secondary and final product fabrication capability for sheet, plate, and tubing - annealing - inspection • Facility must have refractory alloy fabrication experience • High level of quality assurance practice is essential	
		Laboratory Scale • The capability to produce small quantities of prototypic alloys in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible	• Limited qualified facilities available at DOE labs, government labs, or industry
		Commercial Scale • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed during the next five to fifteen years	• There will probably be limited qualified commercial manufacturers willing to commit the resources to produce hardware for the ground test portion of the program

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
4. Processing (Cont)			
Ceramic Matrix Composites	• Develop fabrication practices needed for new materials • In the near term, fabricate the product needed for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities: - perform preparation - matrix fabrication - sintering - machining - inspection • Facility must have previous ceramic matrix component fabrication experience • High level of quality assurance practice is essential	
		Laboratory Scale • The capability to produce small quantities of prototypic alloys in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible	• Limited qualified facilities available at DOE labs, government labs, or industry
		Commercial Scale • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed during the next five to fifteen years	• Limited qualified commercial manufacturers

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
4. Processing (Cont)			
Metal Matrix	• Develop fabrication practices where needed for new materials • In the near term, fabricate the product needs for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and systems demonstration tests	• Facilities will need the following fabrication capabilities: - melting and/or matrix deposition processes - secondary and final product fabrication capability for sheet, plate, and tubing - annealing - joining and machining - inspection • High level of quality assurance practice is essential	
		Laboratory Scale • The capability to produce small quantities of prototypic components in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible	• Limited qualified facilities available at DOE labs, government labs, or industry
		Commercial Scale • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed during the next five to fifteen years	• Probably no commercial manufacturers capable of making hardware needed for space nuclear propulsion activities

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
4. Processing (Cont)			
Carbon Composite	• Recapture past fabrication practices where needed or develop practices for new materials • In the near term, fabricate the product needed for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities: - preform layup and weaving - impregnation - secondary and final product fabrication capability for sheet, plate, and tubing - carbonization - joining and machining - inspection • Facility must have carbon/carbon fabrication experience • High level of quality assurance practice is essential	
		<u>Laboratory Scale</u> • The capability to produce small quantities of prototypic materials in needed product forms will pace initial material performance tests that must be initiated as soon as possible	• Limited qualified facilities available at DOE labs, government labs, or industry
		<u>Commercial Scale</u> • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed during the next five to fifteen years.	• Limited qualified commercial manufacturers

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Continued)

Description	Mission/Objective	Requirements	Status
4. Processing (Cont)			
Monolithic Ceramic	• Recapture previous fabrication practices where needed or develop practices for new materials • In the near term, fabricate the product needs for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities: - blending, pressing, and sintering - machining - fabrication capability for sheet, plate, and tubing - inspection • High level of quality assurance practice is essential	
		<u>Laboratory Scale</u> • The capability to produce small quantities of prototypic alloys in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible	• Several qualified facilities available at DOE labs, government labs, or industry
		<u>Commercial Scale</u> • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed during the next five to fifteen years	• Probably no commercial manufacturers prepared to support project; probably willing to scale up

Table 2-5. Facility Needs for Space Nuclear Thermal Propulsion Materials Activities (Concluded)

Description	Mission/Objective	Requirements	Status
4. Processing (Cont)			
Radiation Shield (Hydride)	• Recapture previous fabrication practices where needed or develop practices for new materials • In the near term, fabricate the product needs for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities: - blending, pressing, sintering, or melting - machining - encapsulation - inspection • Facility must be designed for safe operation when handling hydride materials or other toxic materials • High level of quality assurance practice is essential	
		Laboratory Scale • The capability to produce small quantities of prototypic alloys in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible	• Limited qualified facilities available at DOE labs, government labs, or industry
		Large Scale • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed during the next five to fifteen years.	• There will probably be limited qualified commercial manufacturers willing to commit the resources to produce hardware for the ground test portion of the program

Table 2-6. Safety Panel Input to the NTP Facilities Subpanel

Candidate Testing to Support Flight Safety Evaluations

Flight Event	Potential Safety Testing Required	Facility Category
Launch	1. Critical experiments for accident caused geometries or introduction of moderator or reflective material.	1. Low Power Critical Assembly Test Facilities
	2. Core material behavior for solid booster fire environments.	2. Component Safety Test Facilities
	3. Exposure of safety features to launch pad explosion and fire environments.	3. Component Safety Test Facilities
	4. Testing for toxic materials.	4. Test Facilities for Unirradiated Materials
Powered Flight	1. Measurement of inherent core reactivity mechanisms for assuring stable control.	1. Low Power Critical Assembly Test Facilities Reactor/Engine Test Facility
	2. Reliability of control, shutdown and shutdown cooling features.	2. Component Test Facilities Control System Test Facilities
	3. Demonstration of adequacy of flight system operator interfaces and operating procedures.	3. Training and Simulator Facilities
	4. Adequacy of instrumentation calibration, reliability and lifetime data.	4. Component Test Facilities Control System Test Facilities

Table 2-6. Safety Panel Input to the NTP Facilities Subpanel (Continued)

Candidate Testing to Support Flight Safety Evaluations

Flight Event	Potential Safety Testing Required	Facility Category
Powered Flight (cont'd)	5. Measurement of fission product release.	5. Fuel Irradiation Test Facilities Fuel Element Loops in Existing Reactors Prototypic Fuel Element Test Reactor Reactor/Engine Test Facility
	6. Transient testing of fuel under design basis and off-normal conditions.	6. Fuel Irradiation Test Facilities Fuel Element Loops in Existing Reactors Prototypic Fuel Element Test Reactor
	7. Demonstration of shielding performance including margin to lifetime.	7. Material Irradiation Test Facilities
	8. Ability to achieve some level of performance despite degraded engine.	8. Reactor/Engine Test Facility
Reentry and Earth Impact	1. Dynamic impact testing of core elements required to retain the function of assuring acceptable retention of radioactivity and permit appropriate emergency actions. This would include features that assure subcriticality on ground or water impact.	1. Component Safety Test Facilities

Table 2-6. Safety Panel Input to the NTP Facilities Subpanel (Concluded)

Candidate Testing to Support Flight Safety Evaluations

Flight Event	Potential Safety Testing Required	Facility Category
Reentry and Earth Impact (cont'd)	2. Testing of features required to assure success of planned mode of reentry.	2. Component Test Facilities Component Safety Test Facilities
	3. Testing of features that assure location and recovery of debris.	3. Component Safety Test Facilities
Disposal	1. Obtain performance and reliability data on features employed to implement disposal plan. Features may include systems for separation of disposable items or attachment of disposal devices.	1. Component Test Facilities Control System Test Facilities
	2. Reliability of reactor systems required to prepare core for disposal.	2. Component Test Facilities Control System Test Facilities

solid core design and the Rover Program experience. Although preliminary recommendations may provide useful reference for the innovative designers, further development of these design concepts must proceed before safety testing requirements unique to their characteristics can be developed. It appears reasonable, however, to proceed with recommendations recognizing the limitations. As the innovative concepts become more developed, the facility plans and safety testing issues can be reviewed for the impact, if appropriate.

The Safety Panel recommended that all activities in the SEI Program, including the nuclear propulsion activities, should be managed through a formal safety program. The safety program should include a task to definitize and assure completion of the testing required for flight system safety. This element of the safety program should focus on data required to assure the safety objectives, as they apply to the flight systems, will be achieved. These data would be deemed necessary to obtain flight approval. Some of the data identified may also be useful to other major tasks, such as development testing on the ground propulsion reactors. Care should be taken not to confuse safety requirements for ground testing with those for the flight system. Safety testing to support safety of ground tests of reactor propulsion systems should focus on three key functions:

(1) Reliability of safe reactor shutdown.
(2) Reliability of safe shutdown heat removal.
(3) Control and confinement of radioactive materials during operation and postulated accidents.

Specific test needs will be dependent on the details of the design features in each system. For the NTP system tests it will be necessary to have data on fission product release as a function of operating temperature and time. The safety and environmental constraints on ground testing of these reactors may demand greater retention of radioactivity than flight mission. Ground testing of space nuclear propulsion systems and components that include nuclear fuel and the potential for release of radioactive materials or exposure of personnel to direct radiation should, at a minimum, adhere to existing DOE orders related to siting and establishment of safety design requirements. The safety program will need to provide early focus on the demonstration of the reliability of shutdown and shutdown heat removal functions to support nuclear system level ground testing.

Demonstration of the reliability of functions could be demanding, depending on the extent to which components with demonstrated reliability are used. The reliability demonstration cannot be accomplished on the basis of large-sample statistics. It will require reliability modeling and systematic evaluation and demonstration of margins relative to identified failure mechanisms.

The issue of confinement/containment of severe accidents requires early attention and is closely coupled to program schedule and strategy. Large safety margins potentially provided by containment can be used to simplify and accelerate safety evaluations and reviews. Providing large margins for low probability severe accidents can be expensive and unnecessary if the timing and the physics of the accidents permit demonstration of adequate margins through experimentation and analysis. Although the program needs to evaluate such events, the short operating time and the assumed durability of the fuels used in nuclear propulsion reactors may not demand accident mitigation to achieve the safety objectives. This can only be determined with the knowledge of program specifics. The flight safety tasks can be logically separated into four groupings, related to mission phase: launch safety, powered flight safety, reentry safety and disposal safety. These are shown in Table 2-6. Potential safety testing that should be considered during facility planning is listed under these four groupings. The list represents candidate testing that should be considered for test facility planning purposes only. This does not represent a recommendation that the testing will actually be needed for flight approval. Clearly, more specific evaluation of specific designs is required to establish the safety testing requirements.

SECTION 3

FACILITY REQUIREMENTS AND CAPABILITY OF EXISTING FACILITIES TO MEET TESTING NEEDS

3.1 Facility Category Listing

As stated in the introduction, the NTP development and testing facilities were divided into nineteen categories by the subpanel. The test objectives, top-level and detail and facility requirements, and potentially applicable existing facilities to meet these needs are summarized here for each category. A qualitative position on the ability of the existing facilities to meet NTP development requirements or on the need for new facilities is also presented. Table 3-1 shows the facility categories covered in this section.

Table 3-1. NTP Facility Listing

Category	Requirements Summary Table	Section Reviewing Existing Facility Capabilities
Fuel Fabrication Facilities	3-2	3.2
Test Facilities for Unirradiated Fuel Materials	3-3	3.3
Test Facilities for Unirradiated Materials	3-4	3.4
Hot Hydrogen Flow Test Facilities	3-5	3.5
Fuel Irradiation Test Facilities	3-6	3.6
Material Irradiation Test Facilities	3-7	3.7
Fuel Element Loops in Existing Reactors	3-8	3.8
Low-Power Critical Facilities	3-9	3.9
Prototypic Fuel Element Test Reactor	3-10	3.10
Reactor Test Cell	3-11	3.11
Engine Ground Test Cell	3-12	3.12
Remote Inspection/Post-Irradiation Examination Facilities	3-13	3.13
Component Test Facilities without Hot Hydrogen or Irradiation Environment	3-14	3.14
Control System Test Facilities	3-15	3.15
Component Safety Test Facilities	3-16	3.16
Training and Simulator Test Facilities	3-17	3.17
Engine Integration Test Facility	3-18	3.18
Flight Test Facilities	3-19	3.19
System-Level Safety Test Facilities	-	3.20

3.2 Fuel Fabrication Facilities

Fuel Fabrication Facility requirements are summarized in Table 3-2. Several facilities exist that provide extensive capability. Babcock & Wilcox (B&W), Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory (ORNL), and Argonne National Laboratory (ANL) could establish pilot lines for producing the high-enriched carbide, nitride, and oxide fuel materials on relatively short notice. Other sites that have potentially usable facilities include Westinghouse Hanford Company (WHC). The Fuel Manufacturing and Evaluation Facility (FMEF) at WHC was developed for manufacturing liquid-metal fast breeder reactor (LMFBR) fuels. While the FMEF never became operational, it represents a significant resource. Fabrication of elements would take longer (up to a few years for some concepts) but could probably be accommodated in existing facilities.

Conclusion. Some equipment purchases and minor upgrades are anticipated, but no new facilities are required in the near term.

3.3 Test Facilities for Unirradiated Fuel Materials

Requirements for Test Facilities for Unirradiated Fuel Materials are summarized in Table 3-3. These facilities are typically an adjunct to the fuel fabrication facility. However, a number of facilities around the United States have the capabilities and licenses to test limited quantities of highly enriched uranium fuels even though they do not have the capability to produce original fuel forms. Consequently, there is an expanded market of available services for this category of facilities since fuels could be shipped off-site from the fabrication facility to separate test facilities.

Conclusion. Some equipment purchases and minor upgrades are anticipated, but no new facilities are required in the near term.

Table 3-2. Fuel Fabrication Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Fuel Fabrication Facilities	Recapture earlier NTP fuel fabrication procedures Develop new fuels and forms Develop improved fabrication procedures Fabricate test fuels and fuel elements Demonstrate quality assured procedures Pilot plant fabrication of test cores	Category I SNM facility capable of processing at least 200 kg of high-enriched uranium and 1,000 fuel elements per year while fully complying with all environmental, safety, and health requirements. Able to establish pilot production lines of a variety of fuel forms (prismatic, particles, pellets, wire, cermet, etc.). Able to measure and evaluate production parameters to define their effect on product. Able to implement detailed QA program.

Table 3-2. Fuel Fabrication Facility Requirements (Continued)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Fuel Fabrication Facilities	Feedstock preparation	Los Alamos National Laboratories	Up to tens of millions of dollars	Not anticipated to be needed
	Powder preparation	B&W Lynchburg Facility	Less than one year for some fuel forms and up to two years for others	
	Fuel form fabrication	Argonne National Laboratory - West		
	Sol-gel and/or cryochemical sphere forming	Oak Ridge National Laboratory		
	Extrusion	Westinghouse Hanford Co.		
	Hot pressing	Nuclear Fuel Sevices, Inc.		
	Graphitizing			
	Sintering			
	Coating			
	Brazing			
	Welding			
	Production assembly lines			
	Fuel element assembly			

Table 3-2. Fuel Fabrication Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Cost Range and Time Required for Modifications to Existing Facility	Cost Range and Time Required for a New Facility
Fuel Fabrication Facilities	Fuel element production Waste treatment and disposal Reactor Assembly Component Characterization QA			

Table 3-3. Requirements for Test Facilities for Unirradiated Fuel Materials

Facility	Test Objectives	Top-Level Facility Requirements
Test Facilities for Unirradiated Fuel Materials	To characterize unirradiated fuel for its chemical, thermal and structural properties and for evaluations needed to improve performance and provide design data. To provide baseline information on fuels prior to irradiation testing. To evaluate fuels subjected to nonnuclear test environments (e.g., hot hydrogen cover gas). To assist in defining performance limits and provide data for early selection.	Material evaluation facility capable of complying with all safeguards, safety, and environmental requirements. Ability to obtain data to improve fabrication techniques and product quality.

Table 3-3. Requirements for Test Facilities for Unirradiated Fuel Materials (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Test Facilities for Unirradiated Fuel Materials	Measure thermal stability of fuels & coatings	LANL	Up to ten of million of dollars	Not anticipated to be needed
		B&W Lynchburg/Alliance	Approximately one year	
	Measure thermal stress resistance	UNC Naval Products		
		ANL		
	Measure thermal properties for design	SNL		
		ORNL		
	Measure component compatibility	INEL		
	Evaluate mass loss due to H_2 reactions	WHC		
	Analytical chemistry, ceramography, NDE, mechanical testing, high temperature testing, H_2 testing, compatibility testing, kinetic, thermodynamic, and physical properties			

3.4 Test Facilities for Unirradiated Materials

Requirements for Test Facilities for Unirradiated Materials are summarized in Table 3-4. Basically, these require a high-quality, specialty materials laboratory. There are anticipated to be multiple potential sites for conducting this work around the United States. The major constraint on getting these tests done will probably not be existing facility limitations but rather the availability and coordination of expert staffs to conduct the work.

Conclusion. Because of the potentially competitive marketplace for these tests, large dollar sums for facility development will probably not be required. Some limited funding may be required for specialized test equipment.

3.5 Hot Hydrogen Flow Test Facilities

Hot hydrogen test facilities are required to provide an early capability to perform significant materials and component testing in relevant NTP environments. Any facility would also prove useful throughout the program as an inexpensive way of screening candidate components by testing them in a nonnuclear environment before expensive nuclear testing.

Hot hydrogen test facilities should be constructed to be as versatile as possible. In reality, because of the wide range of tests to be performed on a variety of components, several facilities may be required. Nozzle testing and component flow characterization testing could be performed. Components and materials could be tested for their corrosion resistance and thermal stress characteristics. Relatively lower flowrates are required for fuel, fuel element, and materials tests. High flowrates are required for nozzle and turbopump tests. The requirements for hot hydrogen flow test facilities are summarized in Table 3-5. In some cases it should be noted that liquid O_2 is required for combusting the H_2 and providing the power of thermal energy needed for testing purposes.

Conclusion. As noted in Table 3-5, there are many potential facilities for hot hydrogen testing. A primary limitation on these existing facilities

Table 3-4. Requirements for Test Facilities for Unirradiated Materials

Facility	Test Objectives	Top-Level Facility Requirements
Test Facilities for Unirradiated Materials	To conduct material assessments needed to support NTP system design and development activities	Able to conduct extensive range of material evaluation tests on unirradiated samples of NTP components and hardware. Able to develop material property data base on specialty alloys, composites, ceramics, and coatings.

Table 3-4. Requirements for Test Facilities for Unirradiated Materials (Continued)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Test Facilities for Unirradiated Materials	High-quality specialty materials laboratory Ability to handle radioactive materials is <u>not</u> required Ultra-high vacuum, high-temperature creep machines High-vacuum, high-temperature vacuum tensile machine Pressurized tube creep test facilities capable of testing in alkali metal, vacuum, and hydrogen High-temperature, environmental control mechanical property test units	Multiple	Time should generally be less than one to two years. However, some pieces of specialized materials test equipment may have a longer lead time for procurement.	Not anticipated to be needed

Table 3-4. Requirements for Test Facilities for Unirradiated Materials (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Test Facilities for Unirradiated Materials	Specialized thermal properties test facilities for measuring hydride materials			

Table 3-5. Hot Hydrogen Flow Test Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Fuels & Materials Hot Hydrogen Flow Test Facilities	To evaluate fuels, materials, and fuel element performance in relevant hydrogen temperature and flow environment	Facility should be able to meet all operational safety (particularly hydrogen) requirements. Able to deliver hydrogen at temperature, pressure and flowrates required Temperature: Up to 3000 K Baseline (3500 K Range) Pressure: Up to 1500 psia Flowrates: 1 to 10 lbm/s Able to meet SNM and security requirements. Able to accommodate all data acquisition needs. Able to test a variety of fuels and materials.

Table 3-5. Hot Hydrogen Flow Test Facility Requirements (Continued)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Fuels and Materials Hot Hydrogen Flow Test Facilities	Ability to meet desired hydrogen flow parameters Ability to conduct blowdown, or closed loop experiments	B&W/Alliance BCL Cortest Labs NASA/LeRC NASA/MSFC Materials Engineering Assoc. LANL ORNL SNL Southwest Research Inst. NASA/Ames Arnold	One to three years	Three to five years

Table 3-5. Hot Hydrogen Flow Test Facility Requirements (Continued)

Facility	Test Objectives	Top-Level Facility Requirements
Hot Hydrogen Flow Test Facilities for Turbo-pump Development	Simulate range of engine operations on turbopump components Demonstrate turbopump life Demonstrate turbopump performance including startup, throttling, shutdown, cooldown, and soakback	Ability to provide electric drives for spin tests. Ability to provide high RPM dynamometer. Ability to provide sufficient liquid hydrogen for tests. Ability to provide O_2/H_2 required for either expander or hot bleed tests. Able to meet all operational safety requirements. Able to accommodate data acquisition needs. Able to test multiple designs.

Table 3-5. Hot Hydrogen Flow Test Facility Requirements (Continued)

Facility	Details of Capability Needs*	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Hot Hydrogen Flow Test Facilities for Turbo-pump Development	Minimum of 8000 HP Drive with 40,000 RPM output Large liquid hydrogen supply (~3 × 10^6 gallons) capable of providing 100 lb/s of LH_2 Minimun of 8000 HP dynamometer with 40,000 RPM input O_2/H_2 system capable of delivering 40 lbm/s at 500°F for expander cycle and 5 lbm/s at 1200°F for hot bleed cycle	Rocketdyne (cells 3B & 4B) Aerojet Arnold Engineering Center Garrett/Allied Signal NASA/LeRC NASA/MSFC NASA/Ames Pratt & Whitney	Zero to two years	Two to four years

*Details supplied by Rocketdyne for requirements of a NERVA-like engine of 75,000 lb thrust.

Table 3-5. Hot Hydrogen Flow Test Facility Requirements (Continued)

Facility	Test Objectives	Top-Level Facility Requirements
Hot Hydrogen Flow Test Facilities for Nozzle Development	To evaluate nozzle erosion and performance over full operating range (life, cycles, etc.) To evaluate nozzle joints To evaluate nozzle regen sections To evaluate radiatively cooled nozzle sections	Facility should be able to meet all operational safety requirements. Able to meet data acquisition Able to deliver hydrogen or hydrogen rich steam or hot air at temperature, pressure and flow rates required Temperature: Up to 3000 K baseline (3500 K maximum range) Pressure: Up to 1500 psia Flowrates: Up to 100 lbm/s

Table 3-5. Hot Hydrogen Flow Test Facility Requirements (Continued)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Hot Hydrogen Flow Test Facilities for Nozzle Development		Rocketdyne Engineering Development Laboratory Rocketdyne Advanced Propulsion Test Facility Aerojet Arnold Engineering Center NASA/LeRC NASA/MSFC NAAO Thermal Lab	Zero to a few years	A few years

Table 3-5. Hot Hydrogen Flow Test Facility Requirements (Continued)

Facility	Test Objectives	Top-Level Facility Requirements
Hot Hydrogen Flow Altitude Simulation Facility for Full-Scale Nozzle Demonstration	For full scale nozzle throat region, tube wall nozzle, and radiatively cooled nozzle, verify the performance of the nozzle and the structural integrity of the materials, nozzle joints, and structure under hot-fire test conditions in an altitude test facility	Nozzle exhaust pressure of proposed SEI design Altitude of 110,000 feet Nonnuclear testing using a hydrogen and oxygen test bed Cryogenic hydrogen and oxygen Reduction of blowback at shutdown Data recording requirements and sufficient propellant storage capacity to accumulate NTR mission time

Table 3-5. Hot Hydrogen Flow Test Facility Requirements (Continued)

Facility	Details of Capability Needs*	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Hot Hydrogen Flow Altitude Simulation Facility for Full-Scale Nozzle Demonstration	Nozzle exhaust pressure of 0.11 psia (based on a 500:1 expansion ratio) Chamber pressure = 1000 psia Altitude of 110,000 feet Non-nuclear testing using a hydrogen and oxygen test bed Cryogenic hydrogen and oxygen Reduction of blow-back at shutdown Data recording requirements and sufficient propellant storage capacity to accumulate NTR mission time	NASA Lewis Research Center Plumbrook: SPRF (B-2 site), HHTF Arnold Engineering Development Center: Rocket Development Cell (J-3), Rocket Test Cell (J-6), Rocket Test Cell (J-4).	Not determined	Not determined

*Details supplied by Rocketdyne for estimated needs of a NERVA-like engine

Table 3-5. Hot Hydrogen Flow Test Facility Requirements (Continued)

Facility	Test Objectives	Top-Level Facility Requirements
Hydrogen Flow Test Facilities for Technology Validation and Propellent Management	Simulate range of engine operations on propellant management systems Demonstrate control systems Evaluate throttle values, mixers, sensors, and ducting Demonstrate system lifetimes Evaluate pump performance versus saturation tank pressure Evaluate effects heating addition on system components	Facility should be able to conduct hydrogen operations safely. Able to provide required hydrogen flows at desired conditions. Able to simulate nuclear heating effects through appropriate use of electrical heating. Able to handle slush H_2.

Table 3-5. **Hot Hydrogen Flow Test Facility Requirements (Concluded)**

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Hydrogen Flow Test Facilities for Technology Validation and Propellent Management	Vertical overhead LH_2 tank Saturation LH_2 tank pressure up to 40 psia Liquid hydrogen flowrates up to 100 lbm/s Megawatt level tank and piping heating systems Large LH_2 supply tanks (up to 10^6 gal)	Rocketdyne (cell 1) NASA/LeRC NASA/MSFC NASA/JSC Arnold Engineering Development Center Aerojet	Zero to a few years	A few years

is that most were not developed for the temperatures and flowrates required for NTP applications. Where the facilities were developed for NTP applications (e.g., NASA/LeRC/Plumbrook Station), modifications would still be required to make the facility operational today. In a number of cases, these facilities do not have all the appropriate safety and environmental permits in place to support NTP testing. Given the high priority needs for hot hydrogen testing, facility upgrades are anticipated. Early upgrades are anticipated to focus on capabilities for fuels and materials tests. These should be followed with upgrades for nozzle and turbopump tests.

3.6 Fuel Irradiation Test Facilities

Capsules of fuel will be irradiated in reactors to evaluate their performance with nuclear heating. Requirements for Fuel Irradiation Test Facilities are summarized in Table 3-6. There are six (ACRR, ATR, EBR-II, FFTF, HFIR, and TREAT) DOE reactors currently operating that could be used for capsule fuel tests.

Conclusion. Since fuel irradiation typically falls within their standard operating envelope, no major facility modifications are anticipated for contained fuel capsules. Two of the reactors (ACRR and TREAT) are primarily pulse-type reactors that could be used for short duration, high-power-density experiments.

3.7 Material Irradiation Test Facilities

Material coupons and system components will need to be subjected in reactors, gamma source facilities, or accelerators to prototypic irradiation environments for subsequent characterization of radiation damage effects. Requirements for Material Irradiation Test Facilities are shown in Table 3-7.

Conclusion. A number of existing facilities could be used for these tests. Consequently, no major facility modifications are anticipated to support material irradiation tests. Equipment purchases and minor upgrades that are typically required to support any new test campaign are anticipated.

Table 3-6. Fuel Irradiation Test Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Fuel Irradiation Test Facilities	To determine the effect of irradiation on candidate NTP fuels	Ability to test NTP fuels in environments needed within safety envelope established for continued reactor operations.
	To evaluate steady-state and transient performance data	Ability to accommodate prototypical physical size of test specimen in a contained capsule.
	To obtain safety data (e.g., fission gas release) on candidate fuels	Ability to provide irradiation history (ramp rates and operating conditions) needed for evaluations.
		Ability to insert and remove samples at minimum cost.
		Ability to test fuel to failure
		Ability to support data collection needs such as real-time or post-test measurements of flux exposure, pressure, temperature, and flow rates.
		Ability to test with flowing hydrogen gas surrounding the fuel sample. Measurements of flow rates are required.
		Ability to sample cover gas for fission product release measurements.
		Ability to prepare samples for transportation to hot cells for post-irradiation examination (PIE). PIE will include wet chemistry, scanning electron microscopy, mass spectrometry, and many other measurements

Table 3-6. Fuel Irradiation Test Facility Requirements (Continued)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Fuel Irradiation Test Facilities	Thermal spectrum with a desired maximum thermal neutron flux of $10^{15} n/cm^2$-s. A minimum of axial variation is desirable. Test time and test specimen configuration can be adjusted to characteristics of the reactor. The specimens will be in a hydrogen environment. In some cases, the hydrogen will not be changed during the test, and in others it will be purged, with measurements periodically required to check for gaseous fission products or other evidence of	ACRR ATR EBR-II FFTF HFIR TREAT	Capsule tests are not anticipated to require significant facility modifications, so time should be short	Not anticipated to be needed

Table 3-6. Fuel Irradiation Test Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
	deterioration. The test specimen pressure can be maintained at the required value with the temperature varied from room temperature to >300 K. Externally controlled temperature or pressure variations during any single test are not anticipated.			

Table 3-7. Material Irradiation Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Material Irradiation Test Facility	To determine the effect of irradiation on candidate materials and components that would be placed in the radiation field of an operating NTP engine	Ability to simulate the desired radiation environment within the safety envelope established for continued facility operations. Ability to irradiate materials and evaluate: (1) Embrittlement in H_2/radiation environment. (2) Material physical property changes from irradiation. (3) Moderator/shield dimension changes due to irradiation. (4) Electronics/sensor damage due to irradiation. (5) Material compatibility with working fluids in radiation environment. (6) Bearing surface coating deterioration from irradiation. (7) Fiber/composite material degradation in a radiation field. Ability to insert and remove samples at minimum cost. Ability to support data collection needs and post-test examinations. Ability to test with hydrogen gas surrounding material test coupons.

Table 3-7. Material Irradiation Test Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities*	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Material Irradiation Test Facility	Wide range of radiation environments needed	ATR	Significant facility modifications are not anticipated, so times should be short.	Not anticipated to be needed.
		EBR-II		
	Radiation source	FFTF		
	Radioactive material handling capability	HFIR		
		HFBR		
	Data acquisition	ACRR		
	Post-irradiation examination capability or ability to transport to offsite facility for post-test evaluations	TREAT		
		MITR-II		
		Univ. of Mo Reactor		
		SNL/GIF		
		SNL/MERMES		
		SNL/SATURN		
		BNL/REF		

*See Appendix B

3.8 Fuel Element Loops in Existing Reactors

The fastest way to obtain data on fuel element performance is to put a flowing hydrogen test loop in an existing test reactor. The limitation of using existing reactors is that fully prototypic normal operation and accident conditions cannot be simulated for all concepts or test conditions. Peak power densities are limited to several MW/ℓ for any significant time periods. The requirements for fuel element loops in existing reactors are summarized in Table 3-8. There are four primary candidate facilities for these tests. Each has particular strengths and weaknesses.

Conclusion. Once test plans have been developed for the fuel element concepts to be supported, a decision on the most cost-effective facility to be used can be made. The cost to insert test loops in existing reactors extends over a very broad range that depends on the specific reactor and particular test proposed. No new facilities are required and the amount of modification depends on the facility selected.

3.9 Low-Power Critical Facilities

Low-power critical facilities having flexible geometries and variable material volume fractions provide physics benchmark data to support concept development and data to confirm reactor design. The more complex and unusual the reactor engine design coupled with the need for high performance, the greater is the requirement to conduct critical experiments at low power that mockup or simulate, as closely as possible, the actual reactor engine for design confirmation data. The requirements for these facilities are shown in Table 3-9.

Although critical facilities have been operated at many DOE sites, their use has declined because of the trend toward standardization of commercial power reactors, and improvement of evaluated cross section data and reactor physics computer codes. Another factor has been the increasing cost of operating critical facilities as compared to the decreasing cost of accurate design computations for conventional reactor designs.

Table 3-8. Requirements for Fuel Element Loops in Existing Reactors

Facility	Test Objectives	Top-Level Facility Requirements
Fuel Element Test Loops in Existing Reactors	Determine performance of candidate fuel elements in conditions simulating the reactor environment of an NTP engine as well as can be achieved in an existing reactor under anticipated operating and transient conditions. Obtain performance data to support both design and safety studies.	Ability to conduct required tests in a safe and environmentally sound manner Ability to test full or part-length elements in a hydrogen flow loop and evaluate (1) Performance at prototypical temperatures and run times (2) Irradiation damage (3) transient/cycling performance (4) fission product release (5) Data requirements for engine safety tests Ability to support test data acquisition needs. The test modules will include extensive instrumentation to assist in the analysis of the anomalies, which are anticipated during the early development testing of candidate fuels. Instrumentation will also be required to diagnose the onset of failure during the reliability testing. The retention system, formulation, structural characteristics, and dimensional configuration of the test element or module will be as close as possible to the intended reactor configuration. The flow loop environment and the operating procedures will be as close as possible to those anticipated in the reactor during an actual mission. A thermal spectrum flux will be needed with the main requirement being the power generated in the fuel. NERVA concept fuel will require

Table 3-8. **Requirements for Fuel Element Loops in Existing Reactor (Continued)**

Facility	Test Objectives	Top-Level Facility Requirements
Fuel Element Test Loops in Existing Reactors		an average power density of 3-4 MWW/ℓ in a chopped cosine. The PBR concept requires a higher power density which is not feasible in any existing test reactor. Experiments that achieve prototypic power density and temperature or temperature and run time will be conducted when all prototypic operating conditions cannot be achieved. A continuous measurement of inlet (~280 K) and outlet temperature (~1000 to >3000 K) will be required. Pressure measurements will be required (15-30 psia for the LPNTR, 1000-1200 psia for high pressure tests and 500-600 psia for intermediate pressure tests). Temperature measurements at various element and coolant locations will also be required. Flow rate and power measurements required. Ability to accommodate different fuel element concepts. Ability to conduct tests in a cost-effective manner. Ability to prepare test samples for transportation to hot cells for PIE. The hot cells can be at the facility or in remote locations. PIE requirements include wet chemistry, scanning electron microscopy, mass spectrometry, and other measurements.

Table 3-8 Requirements for Fuel Element Loops in Existing Reactors (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Fuel Element Test Loops in Existing Reactors	Test reactor with ability to accept a flowing pressurized hydrogen loop Support infrastructure to conduct tests •Experiment preparations •Post-test handling •Data acquisition •Waste management	Steady-state/long duration tests: ATR FFTF EBR-II HFIR Transient/short duration tests: ACRR TREAT	One to three years would be required from decision to proceed	By definition of this category a new facility is not applicable

Table 3-9. Low Power Critical Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Low Power Critical Facilities	To obtain benchmark physics and design confirmation on specific concept designs	Ability to conduct operations in a safe and environmentally sound manner. Ability to conduct critical experiments to benchmark reactor physics codes, experimentally confirm reactor design, and evaluate the following: (1) Power distribution and criticality (2) Material reactivities (3) Doppler and temperature coefficients (4) Coolant density variation reactivity coefficients (5) Delayed neutron fraction and neutron lifetime (6) Control element worths (7) Engine clustering effects (8) Disturbed core configurations for safety studies

Table 3-9. Low Power Critical Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Low Power Critical Facilities	Reactor operations	ANL/ZPPR	Materials needed to simulate NTP reactor configurations may need to be designed and purchased. Unconventional materials in large quantities may require significant funding resources and time for fabrication.	New facilities are not anticipated
	Safety and accident mitigation systems	SNL/SPR		
		PNL		
	Inventory of material to simulate reactor engine configuration	LACEF		
	Ability to simulate low and high temperature effects in a portion of the facility		One to three years from decision to go ahead	
	Ability to introduce liquid and gaseous hydrogen into portions of the facility			
	Experiment data measurement techniques and data evaluation support infrastructure			
	Availability of expert operations experiment, and analysis crew			

Conclusion. There are currently a few operating critical facilities such as the Zero Power Physics Reactor (ZPPR) at Argonne-West at INEL, SPR at SNL, and LACEF at Los Alamos which could be used for the NTP reactor design process. An expert operations and analysis staff is essential for effective operation of these facilities.

3.10 Prototypic Fuel Element Test Reactor

The Prototypic Fuel Element Test Reactor is frequently referred to as the "nuclear furnace," based upon its similarity of purpose with the reactor of that name which operated in the early seventies. The requirements for the prototypic fuel element test reactor are summarized in Table 3-10.

Conclusion. No facility currently exists, and a new one will need to be developed. Given the long lead time to have an operational element test reactor, the development of this facility is on the NTP program critical path.

3.11 NTP Reactor Test Cell

The NTP Reactor Test Cell is anticipated to be part of a Reactor/Engine Test Facility. Requirements for the NTP Reactor Test Cell are shown in Table 3-11. No adequate existing facilities are available. The Nuclear Rocket Development Station (now called the Nevada Research and Development Area) on the Nevada Test Site is discussed further in Section 4.9. Like the Prototypic Fuel Element Test Reactor, this is part of a long lead-time facility for development.

Conclusion. An NTP Reactor Test Cell needs to be included in a new Reactor/Engine Test Facility. Cost ranges are large, depending on assumptions for multi-facility colocation, initial facility capabilities, and how environmental and safety review costs are taken into account.

Table 3-10. Prototypic Fuel Element Test Reactor Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Prototypic Fuel Element Test Reactor	1. Obtain performance data on several types of fuel elements under prototypical NTP operating conditions including: - power density - run time - temperatures - coolant type, pressure, temperature, flow rate, and contaminant level - cycle behavior 2. Obtain data on design margins by testing fuel elements up to and through failure thresholds 3. Obtain safety performance data including: - fission product release under both normal prototypic and greater severity environments - failure mode data 4. Perform technology validation of fuel elements	1. Test reactor configuration capable of simulating desired prototypical operating and transient conditions to fuel element(s) being tested. <u>Operating Assumptions</u> 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. Fast turnaround of element tests possible. 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. Process fluids supplied as required for both operations and post-test decay heat removal according to specification.

Table 3-10. Prototypic Fuel Element Test Reactor Requirements (Continued)

Facility	Test Objectives	Top-Level Facility Requirements
Prototypic Fuel Element Test Reactor		6. Effluent releases within regulatory limits and as-low-as reasonably achievable. 7. Robust instrumentation capability provided for meeting both operational requirements and experiment data acquisition needs. 8. Capability to test nonfuel components (e.g., electronics, valves, etc.) in NTP environment (i.e., radiation, hot H_2, etc.) 9. On-site post-test examination and handling capability is the baseline with off-site inspection/examination capabilities an option, provided the associated handling, packaging, transportation, and post-test 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 sufficient for the entire NTP ground test program. 11. Facility kept as simple as possible to reduce test costs. 12. Interim storage of test articles accommodated. 13. Facility accommodates efficient decontamination, decommissioning, and waste disposal. 14. Facility complies with applicable security and safeguards requirements. 15. Ability for recovery and reuse after major fuel element failure event.

Table 3-10. Prototypic Fuel Element Test Reactor Requirements (Concluded)

Facility	Details of Capability Needs	Potential Sites	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Prototypic Fuel Element Test Reactor	1. Assembly and Experiment Preparation Area 2. Reactor Cell/ Building 3. Process Fluids Supply 4. Effluent Treatment System 5. Disassembly and Inspection Facility 6. Reactor/Site Control Complex 7. Administrative Center 8. Safeguards and Security System 9. Waste Management Facility	1. Nevada Test Site 2. Idaho National Engineering Laboratory 3. Hanford Reservation 4. Savannah River Site	NOT APPLICABLE for new reactor sites	Up to seven years

Table 3-11. NTP Reactor Test Cell Requirements

Facility	Test Objectives	Top-Level Facility Requirements
NTP Reactor Test Facility	1. Obtain performance data on complete reactor configuration(s) operating under prototypical conditions 2. Obtain safety performance data from normal operating conditions, including fission product release rates, reactivity coefficients, and flow stability 3. Obtain information on off-normal operations and operations at the qualification level 4. Verify control algorithms and statistical data on component and hardware performance	1. NTP Reactor Test Facility will be colocated on same site or facility as Engine Test Facility with maximum efficient use of same support infrastructure. Multiple test cells are anticipated for redundancy and to prevent scheduling conflicts. 2. Test cells capable of supporting operations meeting requirements for reactor system verification. Operating Assumptions Total Power: Up to 2000 MW Exhaust Chamber Pressure: 15 to 1500 psia Mixed Mean Exhaust Temperature Range: 1000 to 3500 K Coolant Supply: Liquid or slush H_2 20-40 K 25-100 psia delivered to turbopump Maximum Single Burn: 1-2 h Cumulative Reactor Run Time: 1.5 to 4.5 h Restarts/Cycles: Up to 24 3. Test cell has capability to test alternative solid core concepts. 4. Capability available to use either a facility or test article turbopump for high pressure fluid supply. Test complex can supply necessary power required to operate turbopump that is not integral with reactor being tested. Nominal power requirements range from 35 to 350 MW. 5. Reactor complex will comply with all environmental and safety regulations.

Table 3-11. NTP Reactor Test Cell Requirements (Continued)

Facility	Test Objectives	Top-Level Facility Requirements
NTP Reactor Test Facility		6. Process fluids supplied as required for both operations and post-test decay heat removal according to specification. 7. Effluent releases within regulatory limits and as-low-as reasonably achievable. Flaring of exhaust hydrogen is baseline. 8. Robust instrumentation capability provided for meeting both operational requirements as well as experiment data acquisition needs (~1000 channels of experimental data anticipated). 9. On-site post-test examination and handling capability is the baseline with off-site inspection/examination capabilities an option, provided the associated handling, packaging, transportation, and post-test examination can be accomplished effectively and in a manner which does not perturb the test articles/assemblies or invalidate the test results. 10. Interim storage of test articles accommodated. 11. Facility accommodates efficient decontamination, decommissioning, and waste disposal. 12. Facility complies with applicable security and safeguards requirements. 13. Ability for recovery and reuse after major fuel element failure event.

Table 3-11. **NTP Reactor Test Cell Requirements (Concluded)**

Facility	Details of Capability Needs	Potential Sites	Time to Modify Existing Facility	Time Required for a New Facility
NTP Reactor Test Facility	1. Assembly and Experiment Preparation Area 2. Reactor Test Cell(s)/Bldg. 3. Process Fluids Supply 4. Effluent Treatment System 5. Turbopump Power Supply 6. Disassembly and Inspection Facility 7. Reactor/Site Control Complex 8. Administrative Center 9. Safeguards and Security System 10. Waste Management Facility Note: It is anticipated that some of these facility elements would be in common use with the NTP engine test facility.	Nevada Test Site Idaho National Engineering Laboratory Hanford Reservation Savannah River Site	Modifications to NRDA would be equivalent to a new facility	Time required is up to ten years.

3.12 NTP Engine Ground Test Cell

The NTP Engine Ground Test Cell is anticipated to be part of a Reactor/Engine Test Facility. Requirements for the NTP Engine Ground Test Cell are shown in Table 3-12. Like the NTP Reactor Test Cell, no adequate existing facilities are available. The use of the NRDA is further discussed in Section 4.9. This is part of a long-lead-time facility for development.

Conclusion. An NTP Engine Test Cell needs to be included in a new Reactor/Engine Test Facility.

3.13 Remote Inspection/Post-Irradiation Examination Facilities

Requirements for Remote Inspection/Post-Irradiation Examination Facilities are shown in Table 3.13.

Conclusion. A number of existing facilities could meet the requirements. Some funding would be required for equipment purchases and upgrades, but no major new facilities are needed.

3.14 Component Test Facilities Without Hot Hydrogen or Irradiation Environments

The requirements for Component Test Facilities without hot hydrogen or irradiation environments are summarized in Table 3-14. These facilities do not have to address hydrogen or irradiated materials safety issues.

Conclusion. It is anticipated that there will be a competitive market for supply of these services and so no new facilities should be required. New test equipment costs should be modest.

Table 3-12. NTP Engine Ground Test Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
NTP Engine Ground Test Facility	1. Obtain performance data on complete engine configuration(s) operating as close to flight conditions as can be reasonably achieved on the ground 2. Obtain safety performance data from normal operations conditions 3. Obtain information on off-normal operations and operations at the qualification level 4. Verify control algorithms and statistical data on component and hardware performance.	1. NTP Engine Test Facility will be colocated on same site or facility as Reactor Test Facility with maximum efficient use of same support infrastructure. Multiple test cells are anticipated for redundancy and to prevent scheduling conflicts. 2. Test cells capable of supporting operations meeting capability requirements for engine system verification and engine flight qualification. Operating Assumptions Single Engine Tests with a Total Power up to 2000 MW Maximum Allowable Normal Operating Exhaust Pressure at Nozzle Exit: TBD Thrust Vector Control Operation: 0 to 5% Exhaust Chamber Pressure: 15 to 1500 psia Mixed Mean Exhaust Temperature Range: 1000 to 3500 K Coolant Supply: Liquid or slush H_2 20 - 40 K 25 to 100 psia Topping or Bleed Cycle for Turbopump Maximum Single Burn: 1-2 h Cumulative Reactor Run Times: 1.5 to 4.5 h. Restarts/Cycles: Up to 24 3. Test cells can test alternative solid-core concepts. 4. Test cells can simulate or accommodate close coupling of lower portion of propellant tank. 5. Test complex will comply with all environmental and safety regulations.

Table 3-12. NTP Engine Ground Test Facility Requirements (Continued)

Facility	Test Objectives	Top-Level Facility Requirements
NTP Engine Ground Test Facility		6. Process fluids supplied as required for both operations and post-test decay heat removal according to specification. Ability to handle slush hydrogen included. 7. Effluent releases within regulatory limits and as-low-as reasonably achievable. Flaring of exhaust hydrogen is baseline. 8. Robust instrumentation capability provided for meeting both operational requirements as well as experiment data acquisition needs. (~1000 channels of experimental data anticipated). 9. On-site post-test examination and handling capability is the baseline with off-site inspection/examination capabilities an option, provided the associated handling, packaging, transportation, and post-test examination can be accomplished effectively and in a manner which does not perturb the test articles/assemblies or invalidate the test results. 10. Interim storage of test articles accommodated. 11. Facility accommodates efficient decontamination, decommissioning, and waste disposal. 12. Facility complies with applicable security and safeguards requirements. 13. Ability for recovery and reuse after major fuel element failure event.

Table 3-12. **NTP Engine Ground Test Facility Requirements (Concluded)**

Facility	Details of Capability Needs	Potential Sites	Time Required for Modifications to Existing Facility	Time Required for a New Facility
NTP Engine Ground Test Facility	1. Assembly and Experiment Preparation Area 2. Reactor Test Cell(s)/Bldg. 3. Process Fluids Supply 4. Effluent Treatment System 5. Disassembly and Inspection Facility 6. Reactor/Site Control Complex 7. Administrative Center 8. Safeguards and Security System 9. Waste Management Facility Note: It is anticipated that some of these facility elements would be in common use with the NTP reactor test facility.	Nevada Test Site Idaho National Engineering Laboratory Hanford Reservation Savannah River Site	Modifications to NRDA would be equivalent to a new facility.	See Table 3-11 for current estimate.

Table 3-13. Remote Inspection/PIE Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Remote Inspection/Post-Irradiation Examination (PIE) Facilities for NTP Development	1. Conduct post-irradiation inspection, evaluations, and examination of test components and fuel to evaluate performance during tests 2. Fuel examinations include evaluations of fission gas release, swelling, mass loss, compatibility, etc.	1. Facility shall be capable of visual and dimensional inspection of all irradiated test components. 2. Facility shall be capable of nondestructive examination, analytical chemistry, and mechanical testing of irradiated structural components. 3. Facility shall be capable of evaluating irradiated fuels. This includes burnup analysis, neutron radiography, profilometry, gamma scan, metallography, ceramography, fission gas analysis, scanning electron microscropy (SEM) microprobe, physical property measurements, and analytical chemistry. 4. Facility has efficient interface to get articles from test location to examination/inspection location. 5. Facility accommodates efficient decontamination, decommissioning, and waste disposal.

Table 3-13. Remote Inspection/PIE Facilities Requirements (Continued)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Remote Inspection/ Post-Irradiation Examination Facilities for NTP Development		1. ANL - Hot Fuel Examination Facility	Currently Operating	Up to seven years
		2. ANL - Alpha/Gamma Hot Cell Facility	Currently Operating	
		3. B&W Lynchburg Hot Cell Facility	Currently Operating	
		4. EG&G - Test Area North Hot Shop	Standby	
		5. EG&G TRA Hot Cells	Currently Operating	
		6. EG&G ARA-1 Cells	Standby	
		7. SNL- Hot Cell Facility	Currently Operating	
		8. W-Hanford - Hot Cell Examination Facility	Currently Operating	
		9. ORNL - High Radiation Level Examination Facility	Last operated in 1990 No modifications req'd	
		10. LANL - CMR Hot Cell Facility	Last Operated in 1986	
		11. NRDA - Engine Maintenance and Disassembly (EMAD) Facility	Last operated in 1980's. Facility was recently committed to other uses.	

Table 3-13. Remote Inspection/PIE Facilities Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Cost Range and Time Required for a New Facility
Remote Inspection/ PIE Facilities		12. W-Hanford - FMEF	One to three years	

Table 3-14. Requirements for Component Test Facilities Without Hot Hydrogen or Irradiation Environments

Facility	Test Objectives	Top-Level Facility Requirements
Component Test Facilities without hot hydrogen or irradiation environments	To test fabrication and assembly of system components To obtain performance data on components subjected to operating and accident environments with the exception of hot hydrogen and radiation sources	Ability to test fabrication, assembly, and function of system components. Ability to simulate structural loading, pressure, vacuum, shock, vibration, thermal behavior, thermal stress, cycling environments during startup, continuous lifetime operation, and shutdown on system components. These components include but are not limited to the following: (1) valves, seals, bearings (2) sensors and instrumentation (3) nozzle (4) turbopump (5) pressure vessels and piping (6) control rod drives

Table 3-14. **Requirements for Component Test Facilities Without Hot Hydrogen or Irradiation Environments (Concluded)**

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Component Test Facilities without hot hydrogen or irradiation environments		Many sites; see Appendix B for detailed list	A few years at most	New facilities are not anticipated to be needed.

3.15 Control System Test Facility

Aerospace and electronic industries have extensive experience with control systems and test facilities. It is believed that there will be sufficient competition in this market so that it will not be necessary to develop additional government facilities. Most of the control system/health monitoring designers set up very complex test facilities if for no other reason than to ensure a good product prior to delivery.

Conclusion. Resource requirements for these types of facilities will be modest additions to control system design and production.

3.16 Component Safety Test Facilities

It is anticipated that an extensive amount of safety testing will be conducted at all facilities used for concept development tests. For example, fuel tests in existing or new reactors, to evaluate design performance, will also generate data essential to safety analyses. Sometimes a specific extension of normal development tests will be performed to gather needed safety data (e.g., taking test conditions beyond normal design operating parameters). Fission-product release information will be obtained from many of the fuel/element/reactor tests planned to support concept development. Disturbed-core configurations will be evaluated using the same low-power critical assembly facilities used to evaluate reactor physics issues on an intact core. Consequently, many of the facilities covered in the other categories will be used to perform safety testing. The component safety test facilities covered in this section are intended to include only those test environments that cannot be simulated in the other test categories. Requirements for Component Safety Test Facilities are shown in Table 3-16.

Conclusion. There are a number of existing facilities that could be used for component safety tests. Costs for needed new equipment or facility modifications are anticipated to be modest, in the few millions of dollar range.

Table 3-15. Control System Test Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Control System Test Facility	To support the development and ground test validation of the NTP engine control system (also applicable to NEP systems)	A simulation laboratory to develop the engine/ system control systems. Initial facilities will focus on software and benchtop electronics development. Later requirements are expected to be integrated into adverse environment hardware evaluations and early element test reactor/ reactor configuration tests.

Table 3-15. Control System Test Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Control System Test Facility	Extensive computer simulation capability with interfaces to components as they become available. Requires massively parallel computing capability.	1. LeRC Simulation and Control Facility (Rm 112 IRL) 2. MSFC SSME Control System Simulation Test Facility 3. ORNL See Appendix B	A few years at most	Not anticipated to be needed

Table 3-16. Component Safety Test Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Component Safety Test Facilities	To obtain performance data on system components subjected to severe environments for use as benchmarks in safety analyses	Ability to simulate realistic malfunctions and severe or accident environments on reactor/engine components. The environments to be simulated on the components include but are not limited to: (1) launch pad explosions and fires (2) re-entry (3) land or water impact (4) end of flight disposal Ability to safely handle nuclear or appropriate surrogate material in severe accident tests. Ability to support extensive instrumentation and data reduction required for tests.

Table 3-16. Component Safety Test Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Component Safety Test Facilities	High-speed impact test facilities with rigid, soil and water targets Explosive test facilities Thermal and fuel fire test facilities Temperature, humidity, shock, vibration test facilities Water immersion test facility	Multiple sites available; see listing in Appendix B.	Zero to a few years at most.	None anticipated to be necessary.

3.17 Training and Simulator Test Facilities

Testing and operations relative to a nuclear rocket engine should not vary unnecessarily from the successful methods developed during the last 40+ years of operating chemical rocket engines. The basic concepts must be the same. Variations unique to the nuclear portion of the operation must be smoothly incorporated into the existing proven methodology. The key to this methodology is that all operations are conducted in a very disciplined format using proven or validated procedures operated by well trained and qualified personnel. No operation should be conducted for the first time on "flight" hardware and no "hot" testing should be conducted without well-validated procedures. Facilities required for these training and procedure validation operations must be located separate from the operational facilities as much as possible to ensure safety and flexibility. An added and very valuable bonus received by keeping these facilities separate is the capability to duplicate anomalies that may occur during a "hot" operation in a benign environment. Once an anomaly is duplicated, a safe and efficient solution can be developed and validated and the necessary training or practice can be conducted as many times as necessary. This will be even more important with a nuclear operation.

If the system and the facilities are designed with this in mind at the beginning of the program, a major portion of these training and validation facilities can be incorporated with the Engine Integration Test Facility (Section 3.18). These two operations are naturally compatible. The requirements for Training and Simular Test Facilities are shown in Table 3-17.

Conclusion. With proper planning, special facilities for training and validation can be integrated into other program required facilities and will not require any major additional schedule or fiscal resources.

3.18 Engine Integration Test Facility

An Engine Integration Test Facility is required to investigate the interactions between the various components in an NTP system and to characterize system performance before the reactor is integrated into the system. Intimate knowledge of any system or subsystem is mandatory prior to

Table 3-17. Training and Simulator Test Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Training and Simulator Test Facilities	To simulate operations to determine robustness of procedures and equipment To train operating personnel and enhance their effectiveness in normal and emergency situations To evaluate human factors at the man-machine interface	1. The ability to simulate actual operations and system response as closely as possible. 2. The ability to simulate a variety of off-normal or faulted conditions.

Table 3-17. Training and Simulator Test Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Training and Simulator Test Facilities	Not defined	See Appendix B	Not estimated	Not estimated

progressing to the next more expensive or possibly hazardous operation. Physical and operational interfaces, functional capability and interrelated transients must be verified at the lowest possible step in a building block method.

Turbopumps, valves, hydrogen tanks, and associated components can be mounted on the facility in a manner similar to the way they would be configured in an actual NTP system. The arrangement should be versatile enough that different engine cycle configurations could be studied with a minimum of effort in reconfiguring the test stand and training/simulation/validation objectives could be incorporated. Requirements for an Engine Integration Test Facility are summarized in Table 3-18.

Conclusion. Several existing sites could be modified to perform this function, or a test cell could potentially be added to the Reactor/Engine Test Complex to perform these tests.

3.19 Flight Test Facilities

Special safety precautions must be established and facilities provided to ensure that fabrication, assembly, storage, checkout, testing, and integration of nuclear propulsion system flight hardware will not pose a safety hazard to the public, workers, property, or the environment at the launch site. Prior to operational start-up and use in space, nuclear propulsion flight hardware must be safely fabricated, assembled, stored, checked-out, tested, and integrated. During fabrication, assembly, storage, checkout, and integration, physical security must be provided and ensured. If fabrication/assembly, storage, checkout, testing, or integration of flight hardware occurs just prior to launch (virtually a certainty), then a specially designed facility may be required at the launch site.

A special facility exists at KSC, FL, for RTG storage, checkout, testing, and integration. Appropriate physical security and shielding are provided for this facility. Similarly, a special facility was provided at Vandenberg AFB, CA for storage, checkout, testing (limited), and integration of the SNAP-10A flight reactor power system. No such facility was ever begun under the NERVA program, primarily because the program was terminated during

Table 3-18. Engine Integration Test Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Engine Integration Test Facility	To characterize and demonstrate the performance, operating modes, and interactions of the various components and sub-systems of an NTRR system at relevant flow and thermal conditions	Ability to handle the fluid supply and exhaust products from cold testing a 75,000 lb_f class NTP engine. Ability to supply significant electrical power or utilities for a gas turbine Located in a secure area Ability to mount components in a high fidelity configuration Ability to perform complete system checkout without reactor startup. This includes but is not limited to the following: (1) startup sequencing (2) cold flow tests (3) dynamic performance measurements (4) system interface, handling, and transport checkouts (5) post-test purge procedures LH_2 and LO_2 are expected to be available for tests Ability to handle slush H_2

Table 3-18. Engine Integration Test Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Engine Integration Test Facility	Should be able to test the interaction of the various components in an NTR system at prototypical temperature, and flow rates Facility should allow for the engine configuration to be modified easily	NASA/Lewis NASA/Marshall NASA/Stennis Arnold Pratt & Whitney Aerojet Rocketdyne	Up to three years to perform modifications	Several years

development before the flight demonstration phase was initiated. However, the need for such a facility was recognized. Precedents have, therefore, been established for such a facility. The requirements for Flight Test Facilities are summarized in Table 3-19. It should be noted that the subpanel recommends that reactor assembly and low-power nuclear critical tests not be performed at the launch site.

Conclusion. Although design and construction of such a facility can probably be completed within two to three years, required facility safety reviews, environmental documentation, and certification will extend the total time considerably. Because of the uncertainties about what needs to be performed at this facility (and under some use scenarios it could become a long-lead facility) the requirements for this facility need attention early in the development program.

3.20 System-Level Safety Test Facility

No requirements have been identified for a system-level safety test facility.

Table 3-19. Flight Test Facility Requirements

Facility	Test Objectives	Top-Level Facility Requirements
Flight Test Facilities	To support specialized activities on the ground at the launch site and operations center created as a result of the NTP engine	Ability to conduct turbo-pump spin test Ability to check-out valves and actuators Ability to check-out control system

Table 3-19. Flight Test Facility Requirements (Concluded)

Facility	Details of Capability Needs	Potential Existing Facilities	Time Required for Modifications to Existing Facility	Time Required for a New Facility
Flight Test Facilities	Not defined	KSC WSMC	No existing support infrastructure specifically for NTP systems at launch sites	To be determined

SECTION 4

NTP FACILITIES SUBPANEL EVALUATION

4.1 Position Development Method

During its meetings, the Nuclear Thermal Propulsion (NTP) Facilities Subpanel had the opportunity to discuss a number of issues that affect facility development. The panel's positions on these issues are presented in this section. It should be noted that the discussions sometimes overlapped with topics being considered by the NTP Technology or Fuels and Materials Panels. This was to be expected given the composition of the facilities subpanel. The personnel were a cross-section of people and organizations knowledgeable of both facilities and nuclear thermal propulsion. Consequently, the subpanel included both its own experience base as well as the "customer requirements" as provided by the other panels in developing positions on topical issues.

4.2 Facility Requirements

The NTP Facilities Subpanel generally concurs with the testing needs as presented by the other panels. Again, it should be noted that environment, safety, and health considerations were a top priority in subpanel discussions. There were some modifications and additions to the inputs from other panels in Section 2 as they evolved into the proposed facility requirements in Section 3. However, there are no major philosophical differences. Basically, the requirements for each facility are an envelope of the capabilities one needs if there are sufficient funds to use, modify, or construct such facilities.

4.3 Facility Development Priority

The highest priority facilities for receiving design or modification funds are listed in order in Table 4-1. Facilities required for fuel development are first, followed by hot hydrogen flow test facilities, and then low power critical facilities. The other categories of facilities (mainly in Groups B, D, and E) are lower priority for construction and

Table 4-1. Highest Priority Facilities for Receiving Development or Modification Funds to Support Nuclear Thermal Propulsion

1. Facilities Required for Fuel Development

Development of New	Modification of Existing
• Element Test Reactor	• Fuel Fabrication Facilities
• Reactor/Engine Test Facility	• Hot Hydrogen Flow Test Facilities for Fuels and Materials
	• Fuel Element Loops in Existing Reactors
	• Remote Inspection/PIE Facilities

2. Hot Hydrogen Flow Test Facilities for Equipment Development

3. Low Power Critical Facilities

upgrades. The element test reactor and Reactor/Engine test facility are high on the priority list, not because they would be used first, but because they are long-lead-time items for design, construction, and operational approval. The subpanel considered colocation of the element test reactor and reactor/engine test facility on the same site to be beneficial. The colocation issue is discussed more in Section 4.7. The facilities in Table 4-1 were sometimes referred to as "long poles in the tent." The facilities for fuel development were considered to be most important early in the program to initiate fuels development activities.

4.4 Baseline Approach for Determining Flexibility and Capacity of Facilities

Luxury cars cost more than economy cars, but both provide basic transportation. Two facilities could each provide a basic testing capability, but the amenities and capacities could be very different. The flexibility and capability in a facility to accommodate the needs for all concepts for all test conditions could be prohibitively expensive. Consequently, the subpanel adopted solid-core concepts as the baseline for new facilities to be developed. Systems that actively discharge large amounts of fission products into the effluent stream, such as open-cycle gas cores, were not included in the baseline requirements. A closed-cycle gas core, such as the Nuclear Light Bulb, was not actively discussed, but it might be enveloped by the baseline requirements with minor modifications. The Innovative Concepts Subpanel of the NTP Technology Panel developed a list of facilities (see Section 2.2) needed for "proof-of-concept" tests. The wise design of early facilities would allow evolutionary growth to enable testing of advanced engine designs and concepts.

At one subpanel meeting, the curve shown in Figure 4-1 was presented. It is indicative of the fact that for some of the facilities proposed for development, there are not favorable economies with increasing scale and neither is the scaling linear when one goes past a lower source term region where the state of knowledge is more defendable. At some point, adding an increment of capability can be increasingly expensive, depending upon the state of knowledge at the time the addition is proposed. Consequently, the subpanel felt that the facilities should accommodate the minimum to envelope the requirements of the mainline, high-pressure, solid-core concepts. The environmental and safety review process would be a prime determinant on just where the "knee of the curve" shown in Figure 4-1 is located. It was recognized by the committee that the NEPA process is a critical early step in implementing the eventual detailed strategy for testing.

4.5 Alternatives to High-Pressure, Solid-Core Baseline

A low-pressure NTP engine is one of the candidates presently being considered for development as a part of the Space Exploration Initiative. The low operating pressure of this concept could cause problems in the design of the facility pressure recovery system and potentially in the size of the required ducting. Trade studies are in progress on the concept, and until a final concept is defined, the total impact on facility design cannot be accurately determined. The following summarize some of the design considerations that will have an impact on the ground test facility.

The low-pressure engine will operate at a thrust chamber pressure in the range of one to two atmospheres, with a thrust in the range of 10,000-30,000 lbf. It will have a relatively short nozzle cooling section after the throat

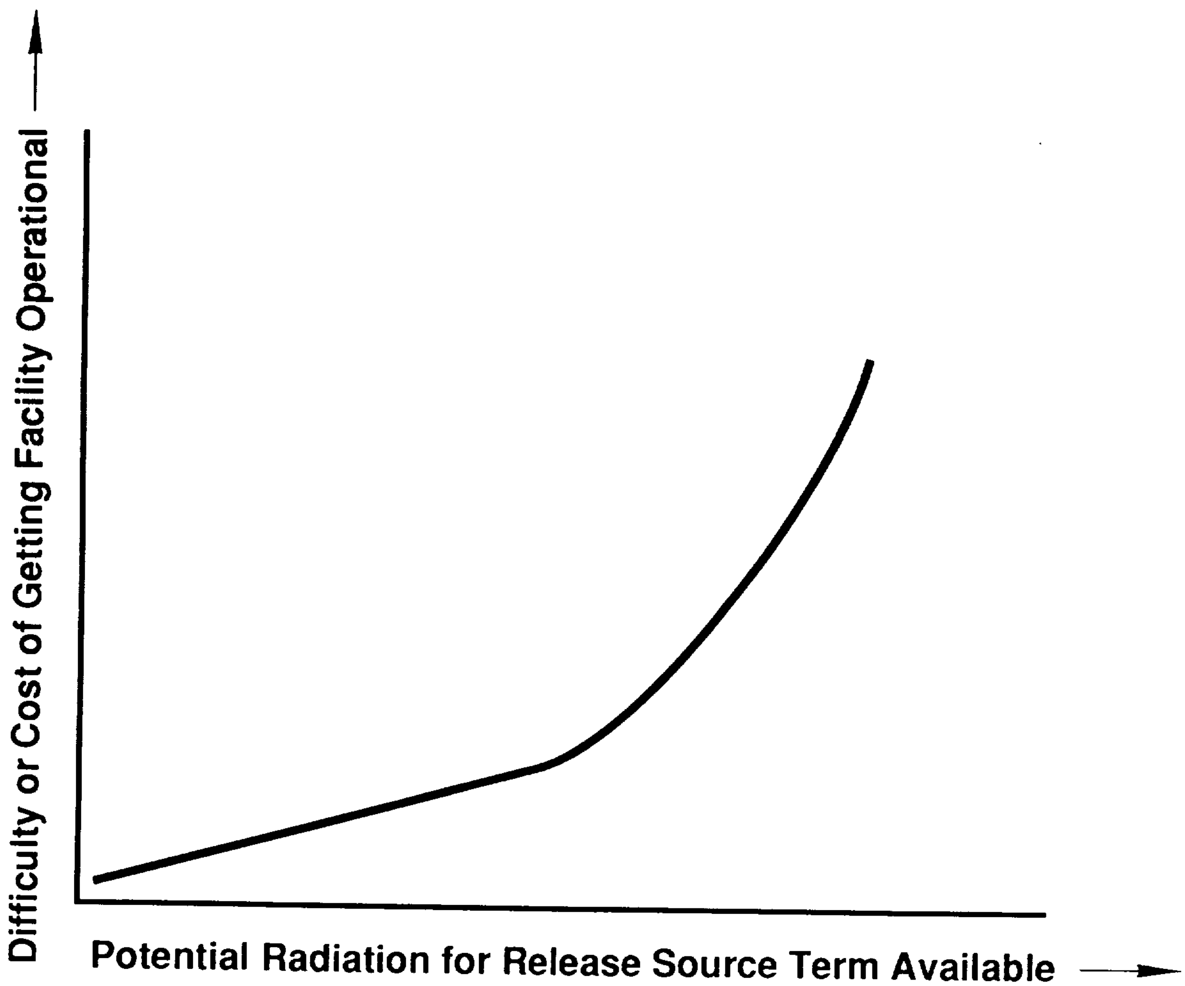

Figure 4-1. Cost Profile of Reactor/Engine Test Facility vs Source Term Available for Release

and will most likely have a requirement for extensive partial power operation, that is, extensive operation at pressures below the full power pressure of one to two atmospheres.

The net effect of these design considerations is that the ground test facility will have a much more difficult requirement for pressure recovery, and there could be a significant impact on the size of the ducting if large engines are required. A preliminary assessment of the net effect of the low pressure engine on facility design was made in the INEL study for the Air Force Phillips Laboratory.* Consideration was given to axial compressors and steam ejectors to obtain the needed duct pressure. It was concluded that a multistage ejector with a cooler/condenser after each stage looked promising. On the order of 150 MW of thermal power would be required for the ejectors. Additional study is required to evaluate the availability and feasibility of an axial compressor. If the low-pressure engine is to be carried as a viable alternative, each candidate test facility designer should provide an engineering study and cost estimates that include both high and low pressure concepts. The study and estimates would address facility modifications or cost needed to accommodate the low-pressure concept.

Because of the potential performance benefits of the low pressure NTP engine concept, it should be evaluated as an alternative until the actual facility cost differential and/or concept viability is determined. However, it should be noted that the subpanel in general took the position that all concepts should be evaluated against the same 75,000 lb thrust baseline. Consequently, the facility study should evaluate the impact of using a 75,000 lb_f low-pressure engine.

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*Whitbeck, Judson F. *Preliminary Study of Facility Requirements for Nuclear Thermal Rocket Ground Qualification*, Idaho National Engineering Laboratory Report EGG-NPD-9548, in preparation for the Air Force Phillips Laboratory, Astronautical Sciences Division.

4.6 Effect of First Space Use Timing on Ground Test Facility Development

Some of the facilities take significant time to develop and start up. An early use date may compress the facility development schedule to a point where we must bypass some testing and accept higher risk. While schedules can be accelerated, there are realistic minimum times for developing new facilities. For example, it is estimated that a new reactor facility could not be operational in less than five years from its initial funding approval or ten years from program start.

4.7 Test Facility Co-location

The subpanel was unanimous in the position that the reactor and engine test facilities generating neutrons and large amounts of energy should be colocated on the same site. Later discussions also indicated strong benefits for colocation of the prototype element test reactor at the same site/test complex as the reactor/engine test facilities. All would be located at an existing DOE site or reservation. They would use the existing permits, environmental assessments, infrastructure, and waste management/fuel processing facilities to the maximum extent feasible. In addition, the subpanel considered colocation of the new element/reactor/engine test facilities in one test complex as a prudent action to combine permit processes and reduce time, effort, and cost. Since the prototypic element test reactor would probably be sited first, one should give consideration to where the reactor/engine test cells would be colocated on the same site. Multiple cells and/or other physical separations should be included in the test complex to allow work on different elements, reactors, or engines to proceed in parallel.

4.8 Engine Cluster Tests

The Reactor/Engine Test Facility would be designed for single engine tests at power only. Multiple reactors would be tested only in clusters in low-power critical experiments.

4.9 Nevada Research and Development Area (NRDA) Use

The subpanel toured the NRDA on the Nevada Test Site. Using the existing rocket test cells on the NRDA is anticipated to cost as much as new facilities. In addition, the NRDA is within view of the proposed location of the Yucca Mountain nuclear waste repository. The Engine Maintenance and Disassembly (EMAD) Building is potentially usable. If NRDA is seriously considered for use, an authoritative study of the cost effectiveness of upgrading the existing test site, as opposed to the design and construction of an all-new facility, needs to be done. Although the existing reactor test cells and nuclear engine test stand, and their supporting material assembly and disassembly buildings were expressly constructed for Rover/NERVA test programs, evolving environmental constraints and cannibization of test facility equipment have reduced the existing utility of this test complex to meet the projected test requirements of the NTP program. A factor which may influence the results of this study is the governments' judgment of what constitutes the best utilization of the existing EMAD building.

4.10 Bypassing Element Test Reactor (Nuclear Furnace)

The prototypic element test reactor is an intermediate step between fuel tests in existing reactors and complete reactor/engine tests. Because it is an expensive facility, the question naturally arises as to whether it could be bypassed. After considerable discussion, the subpanel recommended that nuclear propulsion development not attempt to bypass the element test reactor. In addition to providing a test environment not achievable in existing reactors, the element test reactor is an intermediate test bed for the development of effluent treatment systems and other major systems that are anticipated to be needed for engine testing. It is also possible to perform element cluster tests in a new element test reactor and evaluate system interactions that may not occur in loop tests. This will allow evaluating failure mechanisms that would not occur in loop tests.

Existing reactors, such as the ATR or FFTF, can achieve power densities in experimental loops in the range achieved by the ROVER/NERVA program (up to 6 MW/ℓ). This power density is below the design value of some upgraded or proposed fuels. A goal of the element test reactor is to match prototypical conditions and to perform overtests to failure to allow evaluation of element design margins. Higher power densities than can be achieved in existing reactors are required to achieve all of these goals.

An important consideration in any decision about an element test reactor is the development path for large effluent treatment systems. If, as expected, the loop tests or prototypic element test reactor provide important development steps to the reactor/engine test facility, this greatly increases the need for that step.

4.11 Timing on Element Test Reactor

It is essential to have the element test reactor as early as possible. The NEPA process and development activities should be started now. It is estimated that about seven years will be required between project start and test operations.

4.12 Element Test Reactor - Driver vs Self-Driven Core

The prototypic element test reactor may be designed as either self-driven or with a driver core. With a self-driven concept, the experiment being tested itself forms a critical mass. When the experiment is removed, there is no reactor core. With a driver core, a ring or similar configuration of fuel elements would always be resident in the core. These "driver elements" would probably compose a critical reactor by itself and would have a coolant system that was physically separated from the experimental section. These would be high integrity elements that would not be expected to fail during test operations. A driver-core would have a separate central loop where the elements being tested would be located.

The subpanel reached no consensus on which approach would be better because detailed design studies are needed. The choice should be left to the designer, who could evaluate safety, ability to meet required fuel test conditions, life-cycle cost, potential for testing multiple fuel concepts, etc. The advantages of each approach are listed in Table 4-2.

Table 4-2. Driver Core vs Self-Driven Core

Advantages of Driver Core	Advantages of Self-Driven Core
More certainty in integrity of large portion of core	No separate element development needed for driver fuel
Experiment coolant can be separated from driver elements and potentially result in a smaller effluent treatment system	No reactor to maintain when experiment is removed
Once driver core exists, test operation costs may be lower	No large permanent build-up of long-lived fission products in core
	More experimental elements tested at the same time
	Not having a fixed driver core configuration yields more flexibility in establishing test core arrangements

4.13 Ability of Element Test Reactor to Evaluate Different Fuel Concepts

Given the potential expense of an element test reactor, the question naturally arose about its general applicability for testing fuels for a variety of engine concepts (i.e., ability to match various prototypic power densities, neutron energy spectra, etc.). Building a number of element test reactors at various sites around the country would be prohibitively expensive, and it is planned that the facility will be as "general purpose" as economically reasonable.

Most of the infrastructure at the element test reactor should be usable for tests on any of the baseline fuels. This reusable infrastructure includes the process fluid supply systems, effluent treatment, reactor control rooms, assembly/disassembly areas, waste management, shielding and confinement structures, and security systems. If the fuel test region is developed as a module that can be plugged into this infrastructure, the overall facility can be usable for a variety of fuel concept tests. An approach should be followed in which as much of the element test reactor facility as possible is reusable for testing multiple fuels. The fuel test region, which is specific to a given engine concept, should be as limited and easy to change as possible.

4.14 Reactor/Engine Test Facility Timing

This is the long-lead-time facility. Start the NEPA and development process now. During discussions of NTP development strategies, there were proponents of several near-term options (e.g., do loop testing in existing reactors and bypass the prototypic element test reactor or do hot H_2 testing and bypass loop tests) but the one point of universal consensus was that one could not bypass reactor/engine testing on the ground.

4.15 Engine Test Facility - Engine Only vs Complete Stage

The question arose as to whether one needed to test a complete rocket stage (engine, full-size propellant tanks, etc.) on the ground. The subpanel took the position that only close-coupling of a representative section of the tank bottom would be required. Any portion of this nozzle that is regeneratively cooled should be included in the ground test unit.

4.16 Safety Testing at System Level

No specialized facility for safety testing at the full systems level was identified. This is consistent with input from the Safety Panel.

4.17 How Much Testing Is Required?

A key question to scope the ground test facilities will be the flight qualification criteria that will be imposed. For traditional chemical liquid rockets, a series of tests is typically performed on "developed" hardware to validate the flight qualification of the hardware. These tests usually involve several engine units operated for several times their nominal mission operating times. The rationale is that certain levels of demonstrated robustness (4 to 10 times the nominal operating time) that is experimentally verified in a limited number (3 to 6) engines will provide reasonable confidence in flight reliability and safety. The experimental data demonstrate the adequacy of analytical models, control of hardware manufacture and assembly processes, operability margins, and any engine integration issues. It is reasonable to expect similar flight qualification requirements being imposed on nuclear thermal propulsion.

The ability of nuclear propulsion to operate for several times nominal operating times is questionable. This is due in part to the probable relationship between fission fragment migration to time at temperature that will directly affect quantity of fission products released from cores. Typical engine flight qualification programs would require a significant growth in the number of engines ground tested for only nominal operating times (10 to 30 engines) before flight qualification is validated. The only option remaining to decrease the number of engines tested and the duration that they are fired is to rely much more heavily on component development data and analytical models. This will likely require more extensive test instrumentation, longer build-up times, and tighter acceptance criteria for integrated engine tests.

The issue can thus be summarized as a need to quantify the number of engines to be tested, the length of time each engine is to be tested, and the scope of any component, subscale, or development testing that will be used to support ultimate engine flight qualification. The answer to these questions will be needed to estimate the individual test cell turnaround time, the number of test cells required, the inventory of fission fragments that are present at the test facility, and the quantity of fission fragment that could be expected to be released from individual engines. When this information is fully developed, then high quality environmental impacts can be estimated, facility development costs estimated, and realistic test site operating plans established.

4.18 Facility for Post-Test Hardware Storage

In the development and flight qualification process, nuclear testing of fuel, fuel elements, reactors, and engines will create a quantity of residual hardware that will have varying degrees of radioactivity. The hardware is much more than hot waste, however. It is design-relevant hardware that directly applies to the understanding of propulsion system operating materials and environments. In the event of later development, qualification, and flight operational anomalies, historical development hardware provides a database for evaluating cause, determining precursor indicators, and helps suggest subsequent design or process changes.

Due to the very high program value of historical development hardware, one needs a rigorous, well-controlled, residual hardware warehousing and storage capability. The identification of existing facilities that are currently capable of these requirements has not yet been performed. A new facility would need to have safeguard controls, high-quality ventilation capability, and power and fluid-system capability as needed for safe storage. All articles may need to be accessible for subsequent examination. Colocation at the site of the element test reactor/reactor/engine test facility is recommended.

4.19 Waste Disposal

Wastes will accumulate from three principal sources during the ground testing of nuclear thermal propulsion engines: the filters used for exhaust cleanup systems, the radioactive fuel from various tests, and the nonnuclear hardware used for test assemblies, in reactors, and in engines. In addition, at the conclusion of the program, all hardware and the test site will have to be decontaminated and decommissioned (D&D). Colocation of the prototypic element/reactor/engine test facilities on sites that have low-level waste disposal capabilities will be beneficial and desirable. The nuclear thermal propulsion program will take the approach of waste minimization when comparing options for disposal of the wastes.

The following paragraphs summarize plans for disposing of the various wastes.

Nuclear Fuel

Test fuel will nominally be stored for five or more years to assist in post-test analysis of any anomalies that arise during the test program. After completion of the test program, the fuel will be reprocessed to recover the unburned uranium. The spent fuel from the Rover/NERVA program was successfully reprocessed at the Chemical Reprocessing Plant at the Idaho National Laboratory (INEL). The graphite/carbide fuel reprocessing facility could be refurbished and operated as needed to dispose of fuel that has passed the nominal storage date. Recovered uranium will be added to the government stockpile or used for the fabrication of additional NTP fuel as required. Fission products will be processed to a form suitable for actinide burning or included in high-level waste disposal operations from DOE reactors.

Nonnuclear Components

Nonnuclear components will be stored for a number of years to assist in post-test analysis similar to the nuclear fuel. After this post-test evaluation period, the material will be disposed of as required by DOE order 5820.2a. This order classifies material by its activity. Category 1, 2, and 3 material will be sent to the appropriate facilities being prepared for permanent disposal. These include a treatment and size reduction facility and a facility which prepares them for permanent shallow disposal.

Until detailed design work is completed, the relative amounts of the various categories of waste, which will be produced by the NTP program, cannot be determined. However, facilities will be available to process both types of waste and the program should not have to pay for the facilities. Some preprocessing will be necessary and the NTP program will have to supply these facilities. This most likely will be accomplished in the hot cells that do the post-test analysis of engine tests. It will be necessary for the NTP program to maintain a liaison with the waste process management groups to ensure the facilities are properly designed to handle NTP wastes.

Contaminated Filter Materials

All materials will be disposed of as required by DOE order 5820.2a. While the volumes of low-level waste to be disposed of are anticipated to be reasonable, there will be significant volumes.

Final Decontamination and Decommissioning (D&D) of facilities

It is anticipated that all ground test facilities will be designed for a life of 30 years. The facilities will be designed and operated per the requirements of Chapter 5 of DOE order 5820.2a, which defines D&D requirements. This order requires that all drawings, including as built, updates and modifications be retained along with records of leaks, accidents, etc. Based on these data, the facility is characterized and a D&D plan is written. Final disposal will be based on requirements that exist when the facilities are ready for D&D.

4.20 Qualification Testing of Nozzles

Some nuclear thermal propulsion concepts propose using nozzles with expansion ratios as much as 500 to 1. Consequently the question arose as to what the ground test qualification requirements for such a nozzle would be. Would altitude simulation be required? The subpanel recommended that only components with smaller expansion ratios be tested on the ground or that subscale models be used for full expansion ratios. More study of this issue may be required.

4.21 Vibration Flight Simulation Testing of Critical Reactors

The question arose about the potential requirement to simulate launch vibration and acceleration loads on a reactor or engine operating on the ground. The subpanel took the position that these types of dynamic tests should only be conducted on subcritical systems. Further study may be required.

4.22 Fuel Loading and Zero-Power Testing at Flight Test/Launch Facilities

Fuel loading and zero-power critical testing of space reactors needs to be conducted at facilities qualified for nuclear operations. The question arose as to whether the flight test or launch facility needs to plan on conducting such operations. The NTP facility subpanel took the position that procedures should be established that would preclude the need to load fuel or conduct critical reactor operations at the launch site. Fuel loading and zero-power testing would be conducted at the reactor manufacturing/assembly location. The unit would be shipped as an assembled unit to the launch site. This would follow similar precedents used for naval propulsion units. Further study of this issue is recommended by this subpanel.

SECTION 5
FACILITY DEVELOPMENT STRATEGY

5.1 Recommendations

Safety, both nuclear and nonnuclear, is the highest SEI program priority. A clear philosophy of indoctrination and implementation of environmental, safety, and health standards must be evident. We must build safe facilities and space reactors. The differences between NTP systems and ground or space-based power systems need to be recognized.

NTP reactors run at high powers for short periods of time, and generate large number of predominantly short-lived fission products. Because of this relatively short operating history, NTP reactors accumulate only gram quantities of fission products in the core compared with tonne quantities in land-based power reactors. In addition, because of the use of highly enriched uranium fuels and short operating times, NTP systems generate little transuranic material. However, because hydrogen is the optimal propellant, hydrogen safety issues are a significant concern. While considering nuclear safety, we must not overlook hydrogen safety concerns.

To ensure that appropriate facilities are available to support NTP development and testing, the Nuclear Thermal Propulsion Facilities Subpanel recommends the following:

(1) Focus First on Facilities Needed for Fuel Development and New Facilities with Long-Lead Times

Most experts, panel members, and knowledgeable individuals seem to agree that a high-integrity, high-temperature fuel is the critical component that will determine the success of solid-core nuclear thermal rockets. Since fuel development, fabrication, and testing appear to sit squarely on the critical path, facilities to support these activities should be the first priority. The subpanel's prioritization for all facility categories is listed later in this section.

The ability to (1) do fuel element testing under fully prototypical conditions and to (2) evaluate reactor/engine systems on the ground is also anticipated to fall on the NTP development critical path. Because an NTP element test reactor (nuclear furnace) and a reactor/engine test facility do not currently exist, they will have to be planned, designed, constructed, and approved for operation. A major new nuclear facility of this type will probably take seven to ten years to develop. A typical development schedule listing some of the major activities is shown in Figure 5-1. Because of these long lead times, development of these essential new facilities should be started now.

Facilities supporting fuel development and new element/reactor/engine test sites with long lead-times should receive nearly all the early facility funds. All facilities should be included in the planning and requirements development activities, but significant funding commitments for lower priority facilities should wait until later when additional funds are available or until they have the potential for being on the critical path.

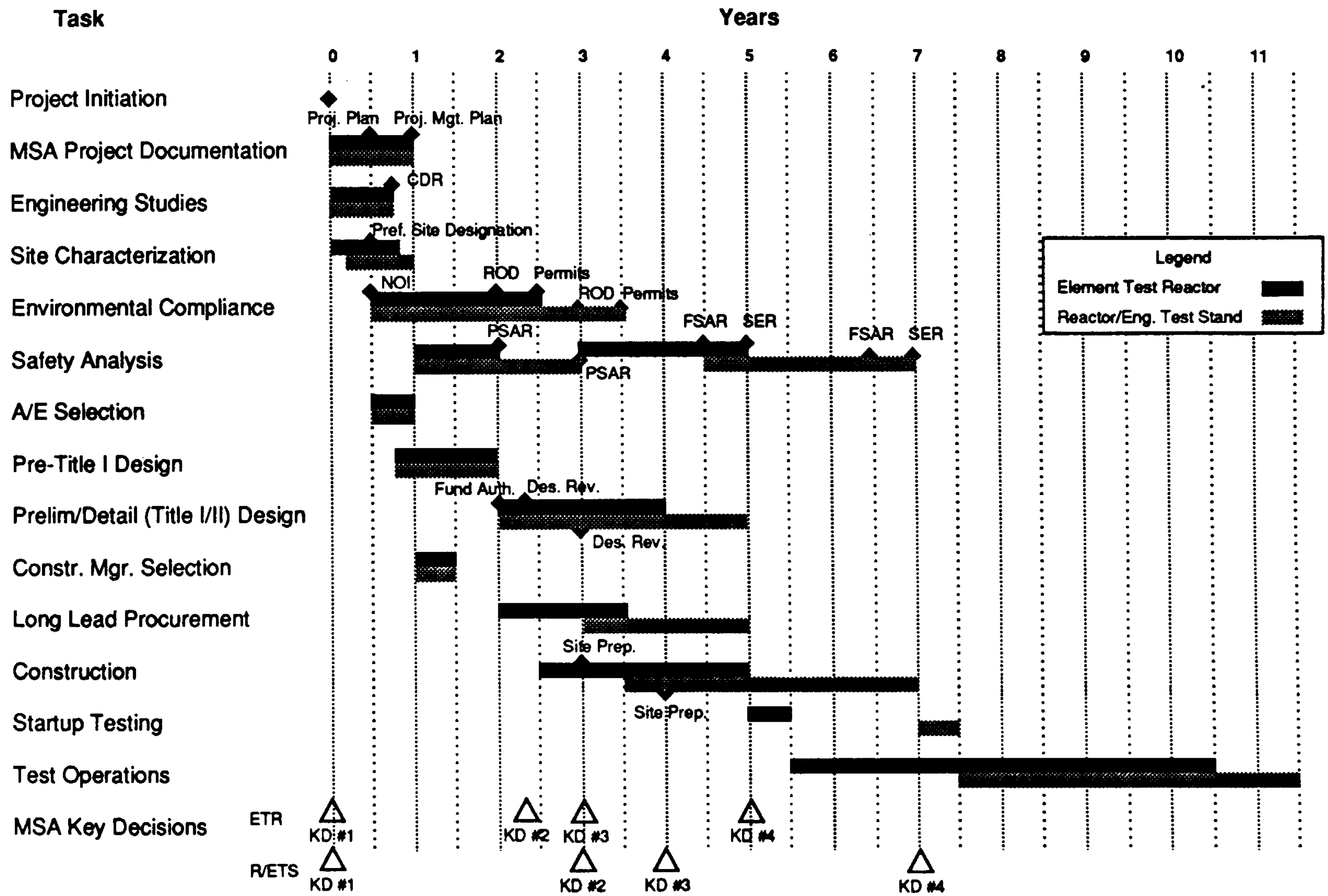
(2) Start Now on Some Essential Near-Term Activities

NASA/DOE/DoD should immediately start on the following near-term tasks needed to expedite facility development and assist the overall NTP program:

(1) NEPA process for:
- (a) The program.
- (b) Prototypic element test reactor.
- (c) Reactor/Engine Test Facility.

(2) Requirements management process for SEI that includes:
- (a) NTP Development test plan.
- (b) SEI Facility Development plan.

(3) Conceptual Design Studies for:
- (a) Fuel fabrication facility modifications.
- (b) Hot H_2 material test facility modifications.
- (c) Loop tests in existing reactors.
- (d) Prototypic element test reactor.
- (e) Reactor/Engine test facility.



Note: ◆ Milestone Indicator

Construction of both facilities at one site may delay the ETS by 6 Mo. and shorten the R/ETS by 6 Mo.

Figure 5-1. Hypothetical Development Schedule for an Element Test Reactor or Reactor/Engine Test Facility

(4) Formal site and facility evaluations effort using a select team of site/facility representatives chartered by the program senior officials (PSO) responsible for SEI nuclear propulsion. The results of this effort should provide:
   (a) Site and facility evaluation criteria for approval by the PSO.
   (b) Evaluation of the candidate sites and facilities against the approved evaluation criteria.
   (c) Recommended facilities for modification and/or construction.

(5) Evaluation of impacts of testing different fuel forms in key facilities (e.g., loop tests in existing reactors and prototypic element test reactor).

(6) Major systems acquisition/construction project documentation.

(7) Modifications to existing fuel fabrication/production facilities that will be used to get high-priority early data.

The NEPA process is probably on the critical path for many near-term activities. Support for the programmatic environmental process (either/both SEI or nuclear propulsion) is essential. The NEPA Compliance Plan and Description of Proposed Actions and Alternatives for proposed new facilities and modifications should be prepared.

Since the government facility funding cycle is formalized and takes years between an idea and funding, Major System Acquisition/Construction Planning documents to authorize capital projects and support budget submissions need to be prepared. Funding requests for facilities need to be processed.

Since high priority fuels test data is essential early for both programmatic decisions and to show visible progress, limited modifications to existing facilities deemed necessary should be supported immediately to permit generation of such data.

(3) Develop Facilities Intelligently and Modestly

Many facility cost estimates were presented to the NTP Facilities Subpanel, as well as other panels, during several meetings. The amount that could be spent on facilities clearly is large. Consequently, NASA/DOE/DoD need a well-planned and intelligent approach to facility development. A volunteer committee such as the NTP Facilities Subpanel cannot make the hard choices required of the Federal agency decision-makers, but the following guidelines should be considered:

1. Use existing facilities as extensively as appropriate.

2. Separate facility needs from wants and only buy the needs initially.

3. Start with a minimum facility first and plan modular expansion capability.

4. Emphasize multi-user/multi-use facilities with applications beyond initial NTP activities.

A task force should be funded by NASA/DOE/DoD to establish detail facility development plans. Separating needs from wants will clearly be a difficult task. Every researcher clearly wants the capability and flexibility to handle all potential test requirements, but trying to accommodate all potential requirements in the first stage would be prohibitively expensive. Similarly, scientists may have to select a few key pieces of equipment initially rather than whole new laboratories.

(4) Use Existing Facilities and Related Program Resources Wisely

A brief review of Appendix B, which lists more than a hundred facilities, shows that the United States has an extensive capability and investment in existing test facilities. Most facility categories required to support NTP development have several existing facilities that are options for use. These existing facilities should be used if they meet essential test needs and if they are truly the lowest cost option. Decisions on facilities (either modifications or new developments) should be based on the most effective way of meeting future program requirements (cost, schedule, and performance). Previously invested or sunk costs should not be a determining factor. Given the many existing facilities proposed for use in NTP development, facility-use decisions should be as market-based as possible. Competition for a number of services should be possible and would be beneficial.

A number of on-going programs, both nuclear and nonnuclear, are developing and/or using test facilities for reactor and advanced propulsion projects. SP-100 and the National Aerospace Plane (NASP) are two examples of programs that will have some synergy with NTP development. Multiple use of facilities being developed by related or parallel programs has major benefits.

(5) Develop Only a Minimum Number of New NTP Facilities and Modify Existing Facilities/Site Capabilities for the Remaining Needs

Despite the fact that there were nineteen facility categories identified as needed for NTP development, only a few major new facilities should be needed. Unfortunately, these new facilities can be very expensive. In order of need, the new facilities are: (1) Prototypic Element Test Reactor; (2) Reactor/Engine Test Facility; and (3) Flight-Test Support Facilities. Existing facilities or site capabilities should be modified or upgraded to provide the remaining test capabilities needed.

5.2 Facility Development Priority

The current facility development priority for use of near-term funding is shown in Table 5-1. This is the priority list at the present time that would be used for applying available funds to facility modifications and development. This priority list will change as years pass.

Table 5-1. Present Facility Development Funding Priority

New	Priority	Existing
	Highest	
Prototypic Element Test Reactor		Fuel Fabrication Facilities
Reactor/Engine Test Facility		Unirradiated Fuel Test Facilities
		Hot H_2 Test Facilities
		Fuel Element Test Loops
		Post-Irradiation Examination Facilities
		Low Power Critical 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		
Training and Simulator Facilities		Control System Test Facilities
System-Level Safety Test Facilities		Non-Irradiation/Non-H_2 Component Test Facilities

5.3 Facility Development Activities

Facility development activities are summarized in Figure 5-2. Considerably more detail would be put into the facility acquisition strategy prepared by the Nuclear Propulsion Project Office.

5.4 Facility Evaluation/Selection Process

As a preface to the modification of existing facilities or the construction of new facilities, the subpanel recommends that a formal site evaluation effort be performed by a select team of facility representatives. The group would be chartered, for example, by senior DOE/NASA/DoD Designated Officials having the lead for the SEI. The FET would undertake two principal tasks:

(1) Propose and submit site evaluation criteria for approval by the Designated Officials.

(2) Evaluate the candidate facilities against the site evaluation criteria as approved, and recommend facilities for modification and/or construction.

This process would be accomplished using the following methodology:

- The FET would meet initially to establish and confirm the criteria to be used during the evaluations.

- The criteria would be provided to the facilities and sites under consideration for preparation of presentations on capability.

- The FET would visit the facilities and sites under consideration and receive a presentation by the facilities and sites on their capability to fulfill the identified mission against the criteria.

- The FET would rank the facilities and sites against the criteria for the intended mission.

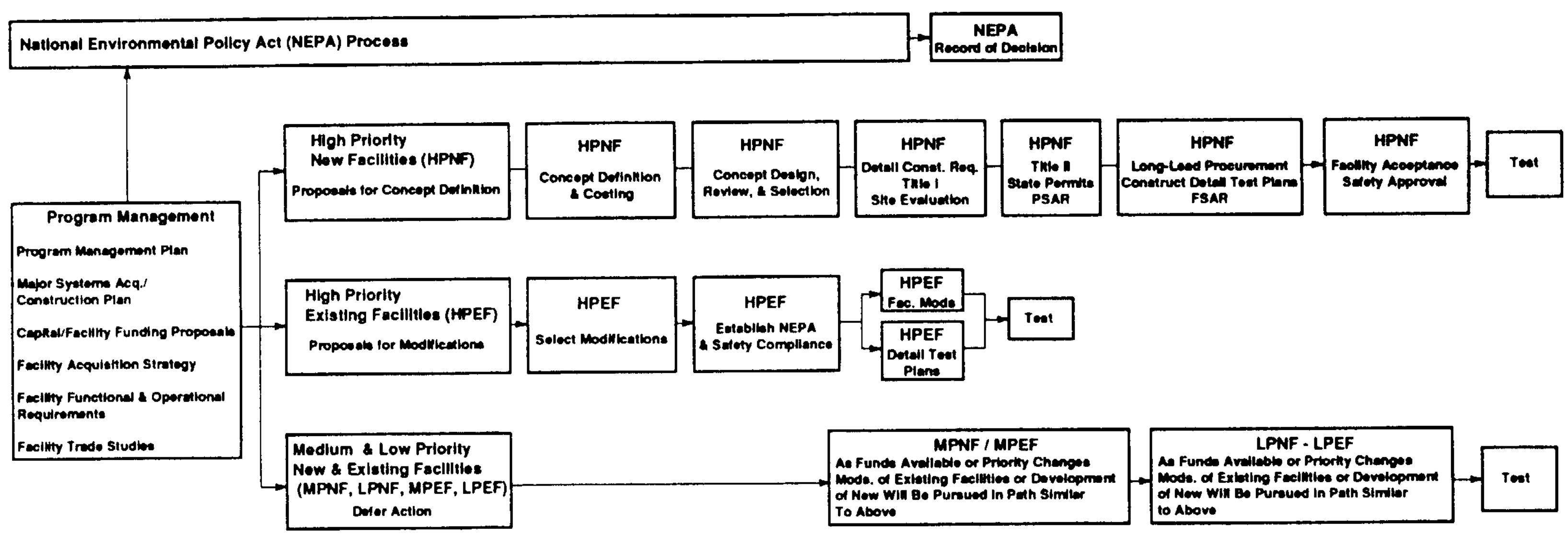


Figure 5-2. Facility Development Activities

- The FET would rank the facilities and sites against the criteria for the intended mission.

- The results of the FET would be submitted to the Designated Officials for final approval.

Typical criteria used for these types of evaluations are summarized below:

A. Experience Base

1. Capability to design, modify, construct, and operate the selected facilities in accordance with their intended mission.

2. Capability to effectively administer the selected facility acquisition and procurement activities per the applicable orders and regulations.

3. Capability to complete the licensing or permitting processes necessary to construct and operate the selected facilities.

4. Capability to conduct the necessary NEPA process.

5. Capability to comply with the safety analysis processes.

6. Capability to transport materials needed for construction and operation of the selected facilities.

B. Site Support Facilities

1. Adequacy and availability of site services for waste handling and treatment (nuclear, chemical, and mixed).

2. Adequacy and availability of general site support services required for any operating facility.

3. Research, development, and demonstration facilities available to support the facilities being considered.

C. Environmental, Safety, and Health

1. Ability to meet the criteria established for a nuclear facility.

2. Ability to comply with applicable federal, state and local environmental, safety, and health requirements within reasonable bounds of time and cost.

3. Ability to mitigate potential environmental, safety, and health impacts within reasonable bounds of time and cost.

4. Local and regional geology considerations that may effect the construction and operation of the selected facilities.

5. Meteorologic conditions which may affect the construction and operation of the selected facilities.

6. Public and worker health impacts under routine and accident conditions.

D. Transportation

1. Projected availability of adequate transportation during construction and operation of the selected facilities.

2. Projected off-site and on-site impacts associated with the movement of materials related to construction and operation of the selected facilities.

E. Cost and Schedule

1. Site conditions that would have a significant impact on cost and schedule for constructing and operating the selected facilities.

2. Impact on the cost of providing adequate support facilities for the life of the test program.

3. Project availability of adequate labor pool and stability of labor rates, work rules, and labor productivity for construction and operations.

F. Safeguards and Security

1. Existing and project safeguards and security at the selected facility.

2. Extent of additional safeguards and security resources that would be required to protect the selected facility.

G. Utilities

1. Projected availability of reliable power to support the selected facility.

2. Projected availability of adequate and reliable supply of water for the selected facility.

H. Socio-Economic

1. Projected availability of adequate public facilities, local services, and infrastructure to support the construction of the selected facilities.

APPENDIX A

SUBPANEL MEMBERS,
MEETINGS, AND SITE VISITS

APPENDIX A

Subpanel Members, Meetings, and Site Visits

Subpanel Members

Facilities Panel Chairman	J. Warren, DOE
Facilities Panel Vice Chairman	J. Martinell, INEL
NTP Facilities Subpanel Chairman	G. Allen, SNL
Subpanel Members:	J. Clark, NASA/LeRC
	T. Byrd, NASA/MSFC
	D. Evans, NASA/JSC
	S. Bhattacharyya, ANL
	W. Kirk, LANL
	W. Kato, BNL
	D. Perkins, DoD/PL
	T. Lawrence, DoD/PL
	R. Pressentin, DOE
	K. Freese, AEDC

Meetings

Location	Date	Sites Visited
Sandia National Laboratories Albuquerque, N. Mex.	December 7, 1990	
Space Power Symposium Albuquerque, N. Mex.	January 9, 1991	
Schaeffer Assoc. Rosalyn, Va.	February 6, 1991	
Las Vegas, Nev.	March 5-7, 1991	Nevada Test Site
NASA/Johnson Houston, Texas	April 11-12, 1991	
Richland, Wash.	May 6-8, 1991	Hanford Reservation
Idaho Falls, Idaho	June 11-13, 1991	Idaho National Engineering Laboratory
Oak Ridge, Tenn.	July 15-17, 1991	Oak Ridge National Laboratory

SPACE NUCLEAR PROPULSION
TEST FACILITIES PANEL

PANEL MEMBERS

Chairman:	J. Warren (DOE-HQ)
Vice-Chairman:	J. Martinell (INEL)
NTP Subpanel Chairman:	G. Allen (SNLA)
NEP Subpanel Chairman:	D. Dutt (WHC)
NASA	J. Clark (LeRC)
	T. Byrd (MSFC)
	D. Evans (JSC)
DOE	S. Bhattacharyya (ANL)
	R. Bohl (LANL)
	A. Roberts (NV)
	M. Fontana (ORNL)
	W. Kato (BNL)
	K. Thommason (LLNL)
DOD	D. Perkins (USAF/Phillips Lab)
	M. Schuller (USAF/Phillips Lab)

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Aerojet	W. Dahl
Babcock and Wilcox	D. Roy
Bechtel	J. Cunliffe
INSPI	I. Maya
Lockheed	E. Laursen
NJG, Inc.	N. Gerstein
Pratt & Whitney	B. Rowe
Rocketdyne	B. Brengle
Westinghouse	J. Livingston

APPENDIX B

DATA SHEETS ON EXISTING FACILITIES WITH POTENTIAL APPLICATION TO NTP TESTING

APPENDIX B

Data Sheets on Existing Facilities With Potential Application to NTP Testing

B-1 Listing of Facilities by Category

Fuel Fabrication

Test Facilities for Unirradiated Fuel Materials

- Materials and Structures Laboratory 200
  Location: United Technologies Pratt & Whitney

- Gas and Materials Analysis Laboratory 154
  Location: Stennis

- Rocketdyne Materials Laboratory 194
  Location: Rocketdyne/Canoga Park

Hot Hydrogen Flow Test Facilities

<u>Hot Hydrogen Flow Test Facilities -
Equipment Development/High Flow Rate</u>

Hot Hydrogen Flow Testing

Fuel Irradiation Test Facilities

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- High Flux Isotope Reactor (HFIR) Location: Oak Ridge	39
- Advanced Test Reactor (ATR) Location: INEL	49
- Power Burst Facility (PBF) Location: INEL	50
- Annular Core Research Reactor (ACRR) Location: Sandia	51
- Experimental Breeder Reactor II Location: Argonne	97
- Transient Reactor (TREAT) Location: Argonne	99
- Fast Flux Test Facility (FFTF) Location: Hanford	104

Material Irradiation Test Facilities

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- Plum Brook Reactor Facility Location: Lewis - Plum Brook	5
- High Flux Isotope Reactor Location: Oak Ridge	39
- Tower Shielding Facility Location: Oak Ridge	40
- Experimental Gas Cooled Reactor Location: Oak Ridge	41
- Advanced Test Reactor Location: INEL	49
- Power Burst Facility Location: INEL	50
- Annular Core Research Reactor Location: Sandia	51
- Gamma Irradiation Facility Location: Sandia	53
- Hermes III Gamma Flux Irradiator Location: Sandia	55
- Saturn X-Ray Irradiator Location: Sandia	56
- LICA (Co-60) Irradiator Location: Sandia	69
- X-Ray Irradiator Facility (Photo II) Location: Sandia	73

Fuel Element Loops in Existing Reactors

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- Advanced Test Reactor Location: INEL	49
- Annular Core Research Reactor Location: Sandia	51
- EBR-II Location: Argonne	97
- TREAT Location: Argonne	99
- FFTF Location: Hanford	104
- HFIR Location: Oak Ridge	39

Low Power Critical Assembly Test Facilities

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- Critical Mass Laboratory Location: Hanford	108
- Zero Power Physics Reactor Location: Argonne	101
- Sandia Pulse Reactor Facility Location: Sandia	52
- INEL	-
- Los Alamos Critical Experiments Facility (LACEF) Location: Los Alamos	35

Prototypic Fuel Element Test Reactor
Reactor Test Cell
Engine Test Cell

Candidate Locations:
- Nevada Test Site
- Idaho National Engineering Laboratory
- Hanford Reservation
- Savannah River Site

Remote Inspection/Post-Irradiation Examination Facilities

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- Fuels Research Facility (TA-55) Location: Los Alamos	29
- CMR Hot Cell (TA-3) Location: Los Alamos	31
- High Radiation Level Examination Facility Location: Oak Ridge	43
- Hot Cell Facility Location: Sandia	71
- Alpha/Gamma Hot Cell Facility Location: Argonne	98
- Hot Fuel Examination Facility Location: Argonne	100
- Hot Cell Examination Facilities Location: Hanford	106
- UFTR Hot Cell Location: University of Florida	164
- MIT Research Reactor Location: Massachusetts Institute of Technology	169
- Engine Maintenance and Disassembly Building Location: NTS	160
- Hot Cell Facility Location: B&W Lynchburg Research Center	178
- INEL	

Component Test Facilities Without Hot Hydrogen or Irradiation Environment

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- Heat Source Technology Location: Los Alamos	34
- Cryogenic Propellant Tank Research Facility Location: Lewis - Plum Brook	2
- Environmental Testing Facility - Standard Machines Location: Los Alamos	18
- Environmental Testing Facility - High Capacity Machine Location: Los Alamos	19
- Centrifuge Facility Location: Sandia	64
- Vibration and Modal Testing Facilities Location: Sandia	67
- Electromagnetic Environments Simulator Location: Sandia	63
- Radiant Heat Facility Location: Sandia	54
- Climatic Test Facilities Location: Sandia	60
- DOE Measurement Standards Facility Location: Sandia	74
- Horizontal Actuator - Shock Loading Location: Sandia	76
- Dynamic Structural Test Facility Location: Marshall	138

Control System Test Facilities

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- Cryogenic Instrumentation Laboratory Location: Marshall	128
- Nuclear Instrumentation Laboratory Location: Marshall	129
- Shuttle Main Engine Simulation Laboratory Location: Marshall	136
- Thermal Instrumentation Development Laboratory Location: Marshall	137
- Electronic System Manufacturing Facility Location: Aerojet	189

Component Safety Test Facilities

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- Thermal Hydraulic Out of Reactor Safety Facility Location: Oak Ridge	37
- Radiation Effects Facility Location: Brookhaven	110
- Water Impact Facility Location: Sandia	57
- Rocket Sled Facility Location: Sandia	58
- Aerial Cable Facility Location: Sandia	59
- Lurance Canyon Burn Site (Fuel Fire Facility) Location: Sandia	61
- Explosive Testing Facility Location: Sandia	62
- Sandia Lightning Simulator Facility Location: Sandia	68
- Kauai Rocket Launch Facility Location: Sandia	75
- Severe Accident Test Facility (Remote Site 9939) Location: Sandia	77
- Severe Accident Test Facility (Remote Site 9940) Location: Sandia	78
- Electromagnetic Earth-to-Orbit Launcher Location: Sandia	80

Training and Simulator Test Facilities

Facility
No facilities listed

Engine Integration Test Facility

Facility	Candidate Nuclear Propulsion Test Facilities Report Page Number
- Rocket Engine Test Facility Location: Lewis	8
- Spacecraft Propulsion Research Facility (B-2) Location: Lewis - Plum Brook	3
- Rocket Development Test Cell (J-3) Location: Arnold (AEDC)	92
- Rocket Development Test Cell (J-6) Location: Arnold (AEDC)	93
- Hydrogen Flow Through Test Cell (C-1) Location: Arnold (AEDC)	95
- LOX/Hydrogen Rocket Engine Component Test Facility Location: Edwards (Phillips Laboratory)	116
- FI Engine Static Test Stand (EP4696) Location: Marshall	119
- Hydrogen Flow Facility (EPHF) Location: Marshall	123
- Propulsion Component Test Facility (EP4548.1) Location: Marshall	126
- Hydrogen Propellant Test Facility (Stand 115) Location: Marshall	130
- Space Propulsion Test Facility (Area E) Location: United Technology Pratt & Whitney	199
- Rocket Engine Test Facility (Test Area E) Location: Aerojet Propulsion Division	185
- B-1 Test Position Location: Stennis	149

APPENDIX C

MEMO ESTABLISHING NP TEST FACILITIES PANEL

DOE F 1325.8
(8-89)

United States Government Department of Energy

memorandum

DATE: December 6, 1990

REPLY TO ATTN OF: NE-50

SUBJECT: Establishment of Test Facilities Technical Panel for Space Nuclear Propulsion

TO: Gary Bennett, NASA
Roger Lenard, DOD

At the recent meeting of the ad hoc Space Nuclear Propulsion Steering Committee meeting at NASA Lewis Research Center in Cleveland, Ohio, I accepted for DOE the action to establish a technical panel to assess test facilities for the SEI Space Nuclear Propulsion Program. These assessments will help determine the capabilities of the existing test facilities and what test facilities requirements and test philosophies are needed for this program.

By copy of this memorandum, the individuals listed below are being invited to serve on the Nuclear Propulsion Test Facilities technical panel.

Chairman: John Warren (DOE/HQ)
Vice Chairman: John Martinell (INEL)
Members:
- NASA
  - John Clark (LeRC)
  - Bob Richmond (MSFC)
- DOE
  - George Allen (SNLA)
  - Samit Bhattacharyya (ANL)
  - Dick Bohl (LANL)
  - Dale Dutt (WHC)
  - Allen Roberts (NV)
  - H. Fontana (ORNL)
- DOD
  - Dave Perkins (USAF, Astronautics Lab.)
  - Mike Schuller (AFWL)

This Test Facilities technical panel is chartered to assess test facilities for the SEI Space Nuclear Propulsion Program and to deliver by June 1991 a test facilities assessment report. The assessment should evaluate both existing facilities and their capability to satisfy projected requirements as well as defining future facilities that would need to be constructed or modified. The assessment should consider the impact on test facility requirements of various development and system qualification approaches and technology options. The assessment should emphasize engine system testing but should also consider reactor fuel, fuel element, or other component testing.

Since providing test facilities has been identified during the nuclear propulsion workshops as a critical path development activity which needs to be started as soon as possible, completion of this technical panel's effort will be an important step toward getting the overall space nuclear propulsion program well underway.

Earl J. Wahlquist
Acting Associate Deputy Assistant Secretary
for Space and Defense Power Systems

cc:
Test Facilities Panel
Chairman and Members
Tom Miller, NASA
Steve Lanes, NE-50
Wade Carroll, NE-52

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13. ABSTRACT ***(Maximum 200 words)***

On July 20, 1989, in commemoration of the 20th anniversary of the Apollo 11 lunar landing, President George Bush proclaimed his vision for manned space exploration. He stated, "First for the coming decade, for the 1990s, Space Station Freedom, the next critical step in our space endeavors. And next, for the new century, back to the Moon. Back to the future. And this time, back to stay. And then, a journey into tomorrow, a journey to another planet, a manned mission to Mars." On November 2, 1989, the President approved a national space policy reaffirming the long range goal of the civil space program: to "expand human presence and activity beyond Earth orbit into the solar system." And on May 11, 1990, he specified the goal of landing astronauts on Mars by 2019, the 50th anniversary of man's first steps on the Moon. To safely and ever permanently venture beyond near Earth environment as charged by the President, mankind must bring to bear extensive new technologies. These include heavy lift launch capability from Earth to low-Earth orbit, automated space rendezvous and docking of large masses, zero gravity countermeasures, and closed loop life support systems. One technology enhancing, and perhaps enabling, for piloted Mars missions is nuclear propulsion, with great benefits over chemical propulsion. Asserting the potential benefits of nuclear propulsion, NASA has sponsored workshops in Nuclear Electric Propulsion and Nuclear Thermal Propulsion and has initiated a tri-agency planning process to ensure that appropriate resources are engaged to meet this exciting technical challenge. At the core of this planning process, NASA, DOE, and DOD established six Nuclear Propulsion Technical Panels in 1991 to provide groundwork for a possible tri-agency Nuclear Propulsion Program and to address the President's vision by advocating an aggressive program in nuclear propulsion. To this end the Nuclear Electric Propulsion Technology Panel has focused its energies; this final report summarizes its endeavor and conclusions. Note: This report represents a consensus opinion of the panel members and does not necessarily represent the official views of NASA, DOE, or DOD. No inferences should be drawn from this report regarding funding commitments or policy decisions.

14. SUBJECT TERMS
Nuclear propulsion; NTP; SEI facilities

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National Aeronautics and
Space Administration

Lewis Research Center
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