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Summary and Recommendations on Nuclear Electric Propulsion Technology for the Space Exploration Initiative

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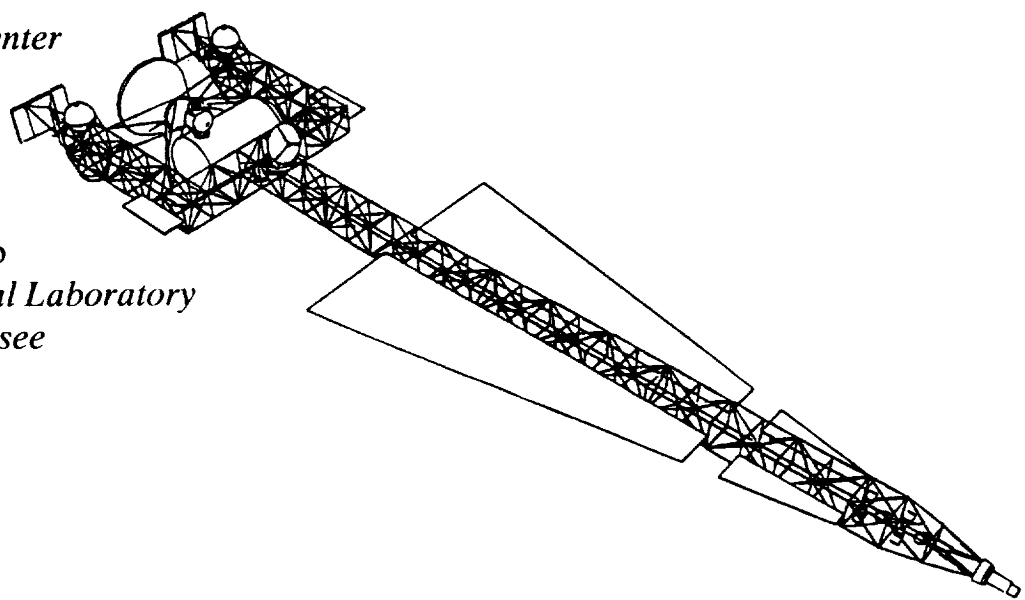

April 1993

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Contents

1.0 FOREWORD

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.◆

2.0 EXECUTIVE RECOMMENDATIONS

The Stafford "Synthesis Committee" has identified a number of possible mission architectures for the exploration of the Moon and Mars under the Space Exploration Initiative (SEI)[1]. All of these architectures imply some form of more permanent human presence in space. New technologies will be important in all of these architectures, to provide the tools necessary for the safe and cost effective exploration of the Moon and Mars.

2.1 WHY "NUCLEAR" PROPULSION?

Safe and affordable exploration of the Moon and Mars requires the development of nuclear propuls on systems and technologies. Personnel, equipment, and supplies will have to be moved from the surface of the Earth, to low Earth orbit, and on to the Moon and Mars. For transfer of personnel from Earth orbit to Mars orbit, transit times must be made as short as possible to minimize the time that flight crews are exposed to the potential hazards of galactic cosmic radiation and zero-gravity[2]. Vehicle mass, including the propellant needed for the round trip, must also be minimized in order that space vehicle systems may be delivered to Earth orbit with as few launch vehicle launches as possible.

The combined requirements of high performance and low mass necessitate consideration of advanced propulsion concepts such as nuclear propulsion. Compared to chemical propulsion systems, nuclear propulsion, both nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP), promises significantly greater performance and reduced vehicle mass. This is because both forms of nuclear propulsion inherently offer a significantly higher specific impulse - a key measure of a propulsion system's efficiency in utilizing it's propellant - than that offered by chemical propulsion. The resulting nuclear propulsion system(s) will greatly enhance the nation's capability to travel back to the Moon to stay, to Mars, and beyond.

2.2 WHY NUCLEAR "ELECTRIC" PROPULSION?

In addition to reduced transit time for Mars piloted missions, NEP has attractive characteristics which enhance mission safety and flexibility for megawatt-class missions to the Moon and Mars. Because an NEP propulsion system operates for periods of time approaching the duration of transit time, almost continual abort modes are possible for a piloted mission to Mars, insuring the safe return of crew to Earth in the event of a partial power loss or other non-propulsive event which requires the mission to be altered[3]. NEP, having specific impulses an order of magnitude higher than NTP, is much more tolerant of variations in launch date, stay time, and opportunity than NTP, as well as other forms of ballistic propulsion. This same figure of merit, specific impulse, implies low resupply propellant masses, making extremely attractive the idea of a reusable interplanetary space vehicle.

Many of the advanced robotic science missions contemplated by NASA's Office of Space Science and Applications (OSSA) are in need of non-conventional delivery systems, such as NEP[4]. Recent missions such as Galileo (Jupiter Orbiter with Probe), CRAF (Comet Rendezvous/Asteroid Flyby), and Cassini (Saturn Orbiter with Titan Probe), using conventional chemical rockets, have been made possible with clever applications of gravity assists, but at the expense of longer flight times. A flight time advantage of NEP over ballistic options is expected in most of these missions because time consuming gravity assists are unnecessary. In contrast to chemical options, the preclusion of gravity assists with NEP also means that launch opportunities occur with normal frequency (every synodic period for planets with low eccentricity)[5]. Once there, the NEP system can enable a rendezvous maneuver with the planetary system vice the high speed flyby that is characteristic of ballistic propulsion. The nuclear reactor can then be employed as a healthy on-board power resource for science and communications. For these reasons, kilowatt rated NEP systems have been shown capable of performing exotic science missions such as: comet nucleus sample return, multiple mainbelt asteroid encounter, observation of Pluto atmosphere collapse, and a multibody examination of the Jovian system.

2.3 EVOLUTIONARY DEVELOPMENT

NEP can be developed in an evolutionary manner, starting with less demanding applications such as the advanced robotic science missions, and proceeding to lunar and Mars cargo (unmanned) missions, before eventually being applied in Mars piloted missions. There are existing technology programs in the space nuclear power discipline as well as in the electric propulsion discipline that serve as appropriate starting points for system development. There are also candidate technologies whose solitary development appears to enable the next mission application. Thus, evolutionary development of NEP appears realistic because of the range of missions it can be applied to and to the interchangeability of applicable subsystem technologies. NEP might be initially demonstrated in a near-Earth mission to assure readiness for system development for the robotic science mission.

2.4 RECOMMENDATIONS

In view of the benefits of NEP for the Space Exploration Initiative, the following recommendations are made by the Nuclear Electric Propulsion Technology Panel concerning NEP and its technology development (these recommendations have been included in a summary statement of the results and recommendations of the six NASA/DOE/DOD Nuclear Propulsion Technicial Panels[6]):

- The United States should plan and implement an evolutionary technology development project in NEP, a project directed toward providing the technologies for a piloted mission to Mars, while also including interim project milestones which yield NEP technologies for near Earth, interplanetary robotic, as well as lunar and Mars cargo missions;

- From the project outset, efforts should be initiated to (1) determine performance and life limits of kilowatt-class and megawatt-class electric thrusters, (2) determine efficiencies, lifetimes, and radiation tolerance of high-temperature power electronics, and (3) address fundamental technology issues associated with lightweight heat rejection systems;

- Accelerate the schedule for a ground test demonstration of the SP-100 space reactor and power conversion technologies in the late 1990s;

- Perform a systems/ subsystems trade study early in the NEP technology project to clarify critically needed NEP technologies and to specify detailed technology requirements for system safety and performance;

- Demonstrate high power, dynamic power conversion technologies;

- If justified by systems trade studies, develop and demonstrate a new reactor (non SP-100) technology;

- Demonstrate the SP-100 fuels technology at higher temperatures than the current SP-100 program calls for to identify technological feasibility and applicability to high performance NEP;

- Assess candidate facilities for NEP power subsystem and propulsion subsystem testing for their suitability to meet ground testing requirements; and

- Provide a forum for the continued involvement of experts in all technology areas of NEP as the project is implemented.

This report provides the rationale and basis for the above recommendations.◆

3.0 NEP TECHNOLOGY - STATUS, NEEDS, AND DEVELOPMENT

3.1 WHAT IS NUCLEAR ELECTRIC PROPULSION?

NEP is a propellant-efficient type of low thrust-to-weight propulsion for space-based propulsion applications. NEP systems employ a nuclear reactor as a thermal source in a closed heat transport system to generate electricity, which drives an electric thruster. The electric thruster uses the electrical energy to accelerate a propellant, producing mechanical energy or thrust.

Because low thrust is characteristic of electric propulsion, electric propulsion (EP) only realizes its usefulness in microgravity fields. Near planetary bodies, an EP spacecraft's flight is characterized by a spiral trajectory about the planet until escape is achieved. Once free of a planetary gravity well, the spacecraft trajectory is as direct as need be for target body intercept. Extremely high EP spacecraft velocities are achieved by continual thrusting over a period of time.

Five major subsystems comprise an NEP system: nuclear reactor, power conversion subsystem, thermal management or heat rejection subsystem, power management and distribution subsystem, and electric thruster (see Figure 3.1).

Based on system and vehicle studies to date, an NEP vehicle is characterized by a long truss to separate crew and/or payload from the nuclear reactor, sizeable radiator panels for waste heat rejection, and small propellant tanks (see Figure 3.2). Multireactor vehicle configurations to enhance piloted mission flexibility and safety are envisioned, comprised of deployable power modules to simplify in-space assembly (see Figure 3.3).

3.2 MISSION APPLICATIONS FOR NEP

NEP is useful to a wide range of propulsion needs: piloted Mars missions, unpiloted cargo missions to the Moon and Mars, interplanetary robotic missions, and near-Earth orbital transfer and stationkeeping applications. Going back four decades, the benefit of using NEP for these missions has been considered by many[1,2,3,4,5,6,7,8,9,10,11,12].

3.3 NEP TECHNICAL DEVELOPMENT

The basic elements of NEP technical development are: technology development, advanced development, and flight. Technology development precedes both advanced development and flight, being fundamental both to define the most beneficial technologies to develop (based on their suitability for a given application), and to test those technologies to validate their readiness for advanced development. Advanced development is the actual design, fabrication and qualification of flight hardware. The NEP Technology Panel was chartered to consider only technology development.

3.3.1 NEP Technology Status

NEP has a legacy associated with it. Basic feasibility issues for electric propulsion were identified back as early as the late 1940s. Undoubtedly encouraged by the birth of the space age, ion engine models were successfully operated in the laboratory setting by 1958, and by 1960, electric propulsion work had become a standard element in the research and development program of almost every aerospace company in the United States[13]. Flight tests of both EP and NEP occurred in the mid and late 1960s. In an historic flight in 1964, known as Space Electric Rocket Test #1 (SERT I), a mercury ion thruster was operated in space showing that remote neutralization of the ion beam was possible. The following year, a cesium ion thruster powered by a one-half kilowatt-electric (kWe) nuclear reactor (SNAP-10A), operated on orbit before the reactor ceased operation. In 1970, SERT II was launched into high satellite orbit. Powered by a 1 kWe solar electric power source, the mercury ion thrusters operated successfully for 6,750 hours over a period of eleven (11) years until the propellant supply was consumed. In the 1960s, a technology development program in potassium-Rankine power conversion existed[14].

Today, a number of existing power and propulsion technology programs provide a significant starting point for a program in NEP technology. A strong technology program in electric thrusters exists within NASA, involving the analysis, design, and testing of ion and magnetoplasmadynamic (MPD) thrusters from 10 - 250 kWe. A nuclear power source for space applications (SP-100) is being developed under a NASA/DOE/DOD co-sponsored arrangement. Under this program, lithium cooled nuclear reactor and thermoelectric power conversion technologies to produce one hundred (100) kWe of space electric power are to be validated. Technical issues for both high temperature heat rejection and high temperature semiconductor technology are being addressed under NASA's Civil Space Technology Initiative (CSTI).

The facility structures for the ground testing of all the major subsystems of an NEP system exist, although modification of facility equipment, in some part, will be required. Vacuum tanks, capable of being upgraded to provide the pumping speeds necessary for high power and long life electric thruster testing, are in existence at NASA and DOE laboratory sites. Thermal vacuum chambers, having the ability to provide a "cold sink" for the testing of high power heat rejection subsystems, are also in existence within both NASA and DOE. Finally, a number of existing DOE reactor test facilities appear quite able to host the testing of either liquid metal cooled or high temperature gas cooled reactors up to 50 megawatts thermal (MWt).

3.3.2 NEP Technology Needs

A key figure of merit for NEP is the propulsion system specific mass, which is the total propulsion system mass divided by the electrical power available to the thruster, usually measured in units of kilograms per kilowatt-electric. The lower the specific mass of an NEP system, the higher its performance. In general, NEP system performance is increased by lowering the specific mass of the subsystems which comprise it, taking particular regard for those sub-systems which provide the largest percentage of weight. Specific NEP technology needs are high power, long life nuclear reactors, high power, efficient power conversion, light weight heat rejection systems, high temperature, efficient power management and distribution (PMAD), and long life electric thrusters. High reliability is required for all subsystem technologies.

Technology readiness for a piloted Mars mission requires development and validation of both nuclear electric power and electric propulsion technologies. NASA's Office of Aeronautics and Space Technology (OAST), to more objectively quantify the readiness of any new technology for its application in space, provides a descriptive statement of technology readiness levels. This statement is shown in Table 3.1.

The panel recommends that NEP technology be validated at the subsystem level, or TRL-5, prior to a full system validation in space (TRL-7). In the case of NEP, TRL-5 might be achieved by independent validation of reactor, power conversion, heat rejection, PMAD, and thruster subsystems, or by simultaneous validation of more than one subsystem in a combined demonstration. A proposed summary test plan to validate MW-class NEP technology at a Technology Readiness Level 5 is shown in Figure 3.4. Reasons for not recommending a full system ground validation (TRL-6) for NEP include the prohibitively large size required of such a facility (for adequate separation of reactor and thrusters) and the superlative vacuum pumping required to prevent thruster effluent from contaminating the reactor, power conversion, and heat rejection subsystems. The major facility requirements for validating NEP technology to TRL-5 are presented in Table 3.2.

There are a number of subsystem technology options for reactor, power conversion, thermal management, power management and distribution (PMAD), and electric thruster. These options are shown in Table 3.3. This table includes all of the power and propulsion options presented at the June 1990 NEP Workshop[15,16]. The panel judged the NEP subsystem technology options according to their projected technology readiness. Table 3.4 displays the projected readiness of those options in Table 3.3 that would apply to megawatt-class SEI missions. Within Table 3.4, any of the options listed in the middle column could be ground tested in a relevant environment, or TRL-5, by the year 2005 (with adequate funding) and have been classified by the panel as "enabling" technologies. Those options not expected to reach TRL-5 by 2005 are listed in the right-hand column of this table, and have been classified by the panel as "innovative". The year 2005 was chosen so that the technologies would be available in time to be considered for the SEI missions.

3.3.3 NEP Technology Development

The panel recommends an accelerated schedule for SP-100, leading to the demonstration of the SP-100 space reactor and power conversion technologies by the late 1990s. This demonstration will yield the enabling nuclear electric power technologies needed for kilowatt-class NEP, and likewise provide a strong technology foundation in lithium liquid-metal-cooled reactor technology. Lithium liquid metal reactor technology appears to have good potential to meet the demands of the megawatt-class SEI missions, especially if SEI program and mission architectures require early technology readiness, fewer projected flights, and lower budgets[17].

The panel recommends that the nuclear fuels technology for SP-100 be tested at higher temperatures than what is established in the SP-100 program goals statement. SP-100 fuel technology (Uranium Nitride pellets enclosed in Niobium-1Zirconium clad tubing) may directly apply to fast piloted missions to Mars if the integrity of the nuclear fuel can be demonstrated at higher temperature (albeit with shorter lifetime).

The Nuclear Propulsion Technology Program has been established to develop the nuclear propulsion technologies (NEP and NTP) needed to satisfy SEI mission requirements. Under this program an NEP Technology Project has been established, whose major goal is to demonstrate ground-based technology readiness of a safe and reliable NEP system to support a piloted mission to Mars and which include identification of safe and reliable NEP concepts that are responsive to SEI requirements, demonstration of component, subsystem, and systems technologies, and validation of design analyses, methodologies, and models to provide a comprehensive technology base in the required disciplines[18].

The NEP Technology Project will be organized by disciplines in the Concept Development/Systems Engineering, NEP Technology (both Enabling and Innovative), NEP Facilities (nuclear and non-nuclear), and Safety/Reliability/ Quality Assurance/Environment functional elements. The panel recommends an approach to NEP technology development as summarized by Figure 3.5.

Since the overall goal of the NEP Technology Project is to demonstrate, in a timely manner, ground-based technology readiness of a safe and reliable NEP system to support a piloted mission to Mars and return safely to Earth, the chief milestone in the technology project schedule is testing to TRL-5 of the reactor, power conversion, and thruster subsystems. This milestone, shown within the "subsystem tests" activity under "Concept Development and System Engineering" element, designates the completion of reactor and power conversion testing subsystem testing up to 10 MWe, and electric thruster testing up to 2.5 MWe. All other activities ultimately support and bring bearing to this milestone. This milestone should be reached by the year 2005 in order to affect President Bush's goal.

Because the demonstration of high power, dynamic space power conversion is all that is required to yield the nuclear electric power technologies needed for megawatt-class NEP (assuming parallel demonstration of the SP-100 reactor technology), testing of either Potassium-Rankine or Brayton cycle conversion should occur in a manner timely enough to meet the need for MW-class NEP. This milestone, also shown within the "subsystem tests" activity, designates the completion of testing of a dynamic power conversion (and accompanying heat rejection) subsystem up to 2.5 MWe. This milestone should be reached by the year 2001 to achieve the required technology for an NEP cargo vehicle to enhance the implantation of lunar and Mars exploration infrastructure in the time frames recommended by the Stafford Synthesis Committee.

In addition to subsystem testing to TRL-5 of the technologies required for MW-class NEP, another important milestone under the "Concept Development and Systems Engineering" element is the performance of a system/subsystem trade study early in the project. This trade study performs the comparison of NEP systems (comprised of the candidate technologies) using common ground rules and assumptions, to identify leading candidate NEP systems for interplanetary robotic, lunar and Mars cargo, and Mars piloted missions, and to provide the specific technology requirements for the safety and performance of these systems. Because this activity will provide strong justification for NEP technology activities in light of SEI mission and system requirements, it should be completed by 1993.

The NEP Technology and Innovative Technology elements will be the heart and soul of the NEP Technology Project. It is within the NEP Technology element that desirable technologies identified as having high benefit/risk ratios will be developed and validated. Component level validation testing will be performed under this element. Important milestones that have been identified are: completion of fuel element tests (1998), completion of power conversion component tests (1998), radiator segment tests (1997), development of high temperature - 500°K (1997) and 600°K (2004) - PMAD technology, design of kW-class ion thruster, and down-select of MW class thruster technology.

Certain technology issues need to be addressed no matter what ultimate system is selected to meet SEI mission needs. High performance fuels and materials[19], efficient high power, long life thrusters, high temperature, radiation tolerant semiconductor technology, and high temperature, light weight heat rejection are all critical for MW NEP. From the outset of the project, efforts should be initiated to determine performance and life limits of kW-class and MW-class electric thrusters, to determine efficiencies, lifetimes, and radiation tolerance of high temperature power electronics, and address fundamental technology issues associated with light weight, high temperature heat rejection subsystems.

The Innovative Technology element of the project will consider candidate technologies having significant potential to impact NEP mission applications, but having unresolved technical issues too fundamental to warrant their inclusion in the baseline enabling technology element. Under the Innovative Technology element, studies and modeling, as well as proof-of-concept activities will be conducted. Innovative technology is expected to be an on-going functional element of the project, funded at a reasonable percentage of the overall effort.

The technology demonstration milestones of the NEP Technology Project can only be met if adequate test facilities exist. NEP ground test requirements were considered by the NEP Facilities Subpanel[20] and a Nuclear Propulsion Test Facilities database has been assembled[21]. To bring the needed technologies to TRL-5, four major facilities appear to be needed: a thruster performance facility, a thruster life facility, a power conversion facility, and a reactor facility. The thruster performance facility would have the capacity to test thrusters under realistic space vacuum conditions for relatively short periods of time. The thruster life facility would have the capacity to test MW-class thruster models for long periods of time in a realistic environment to verify thruster performance and system lifetimes. A power conversion test facility would be required to "proof out" component hardware for the desired power conversion system and possibly test the full-up power conversion system in a thermal vacuum environment. But very possibly, the complete power conversion subsystem would be co-tested with the reactor in the fourth facility, the reactor test facility. It appears that there are candidates for all four facilities located within the United States, but funding will be required to modify those facilities for NEP Technology Project use.

An element in Safety, Quality Assurance, Reliability, and Environment will be established as an important part of the project. In light of overall programmatic safety recommendations given by the Nuclear Safety Policy Working Group [22], specific safety requirements will be established to guide studies, conceptual and detailed designs, development, test, as well as deployment, operation, and disposal. Strategic plans for quality assurance and reliability will be developed and implemented. Environmental impact assessments will be made for all activities to be conducted which may affect the environment, including fabrication, testing, ground transportation, pre-launch, launch, operation, abort, and disposal.

3.4 SUMMARY

A project in NEP technology is being established to develop the NEP technologies needed for advanced propulsion systems. A paced approach has been suggested which calls for progressive development of NEP component and subsystem level technologies, leading to major facility testing to achieve TRL-5 for megawatt NEP for SEI mission applications. This approach is designed to validate NEP power and propulsion technologies from kilowatt class rating to megawatt class rating. Such a paced approach would have the benefit of achieving the development, testing, and flight of NEP systems in an evolutionary manner. This approach may have the additional benefit of synergistic application with SEI extraterrestrial surface nuclear power applications, also.◆

Technology Readiness Level Applicable to Project Plan

Level 1	Basic principles observed and reported	The earliest stages of basic research, where physical principles are established.
Level 2	Technology concept and/or application formulated	Basic concepts are incorporated into concepts for hardware or software, and research begins to determine the feasibility of the applications.
Level 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Critical functions are proven for hardware and software, either by analysis or experiment.
Level 4	Component validation in the laboratory	Hardware and software concepts are fabricated and validated in a laboratory environment against predetermined performance objectives.
Level 5	Component demonstration in a relevant environment	Test-bed hardware and software are tested in an environment that is relevant to proving that the technology will operate in the operational environment of the projected mission application. This may include–if required–flight research and validation
Level 6	System validation model demonstrated in a simulated environment	The proof-of-concept hardware and software are integrated into a system and tested in a simulated operational environment to evaluate the system interactions.

Table 3.1

MAJOR FACILITY REQUIREMENTS FOR TESTING NEP SUBSYSTEM TECHNOLOGIES IN A RELEVANT ENVIRONMENT

SUBSYSTEM	REQUIREMENT
Reactor	50 MW heat rejection, Vacuum vessel Reactor containment, Capability to test shielding Outlet temperature = 1500 - 2000°K Liquid metal handling facility Control room; Maintenance, storage, decontamination and disposal facility Lifetime = 5 - 7 years
Power Conversion	2.5 MW (electric load), 12.5 MW (heat source/dump) Vacuum or inert gas insulation, Support facilities Lifetime = 5 - 7 years Upgradable to 5 MW (electric load)
Thermal Management	10 MW, Upgradable to 20 MW
Power Management and Distribution	No Major facility required
Thruster	Up to 1.2 grams per second effluent flowrate 2.5 MW electric power 10 meter (m) diameter by 30 m long tank size

TABLE 3.2

NEP SUBSYSTEM TECHNOLOGY OPTIONS

REACTOR	POWER CONVERSION	THERMAL MANAGEMENT	POWER MANAGEMENT & DISTRIBUTION	THRUSTER
Liquid Metal Cooled	Dynamic	Heat Pipe	Silicon	Steady State Electrostatic
Growth SP-100	Rankine	Refractory Metal	Gallium Arsenide	Ion
Advanced Pin	Brayton	Carbon-carbon	Aluminum-Gallium Arsenide	Steady State Electromagnetic
Cermet	Stirling	Ceramic Fabric	Silicon Carbide	Magnetoplasma-dynamic (MPD)
Boiling Potassium	Static	Pumped Loop		Electron Cyclotron Resonance
Gas Cooled	Thermoelectric	Liquid Sheet/ Droplet		Ion Cyclotron Resonance
NERVA Derived	Thermionic	Bubble Membrane		Variable Specific Impulse
Particle Bed	in core			Pulsed Electromagnetic
Pebble Bed	ex core			Deflagration
Cermet	Electrochemical			Pulsed Plasmoid
Incore Thermionic	Magnetohydro-dynamic			Pulsed Inductive
Vapor Core				Pulsed Electrothermal/ Electromagnetic
				Pulsed Electrothermal - MPD

TABLE 3.3

PROJECTED TECHNOLOGY READINESS OF NEP TECHNOLOGY OPTIONS FOR SEI MISSIONS

NEP SUBSYSTEM	TECHNOLOGY OPTIONS THAT COULD REACH TRL-5 BY YEAR 2005 (WITH ADEQUATE FUNDING)	TECHNOLOGIES NOT EXPECTED TO REACH TRL-5 BY YEAR 2005
Reactor	Growth SP-100, Advanced Pin Cermet, NERVA Derived Particle Bed, Pebble Bed Incore Thermionic	Boiling Potassium Vapor Core
Power Conversion	Rankine Brayton	Electrochemical Magnetohydrodynamic
Heat Rejection	Refractory Metal Heat Pipe Carbon-carbon Heat Pipe	Ceramic Fabric Heat Pipe Liquid Sheet Radiator Bubble Membrane
Power Management and Distribution	Silicon, Gallium Arsenide Aluminum Gallium Arsenide Silicon Carbide	
Thrusters	Ion Manetoplasmadynamic (MPD)	Very high power MPD Electron Cyclotron Resonance Ion Cyclotron Resonance Variable Specific Impulse Deflagration Pulsed Plasmoid Pulsed Inductive

TABLE 3.4

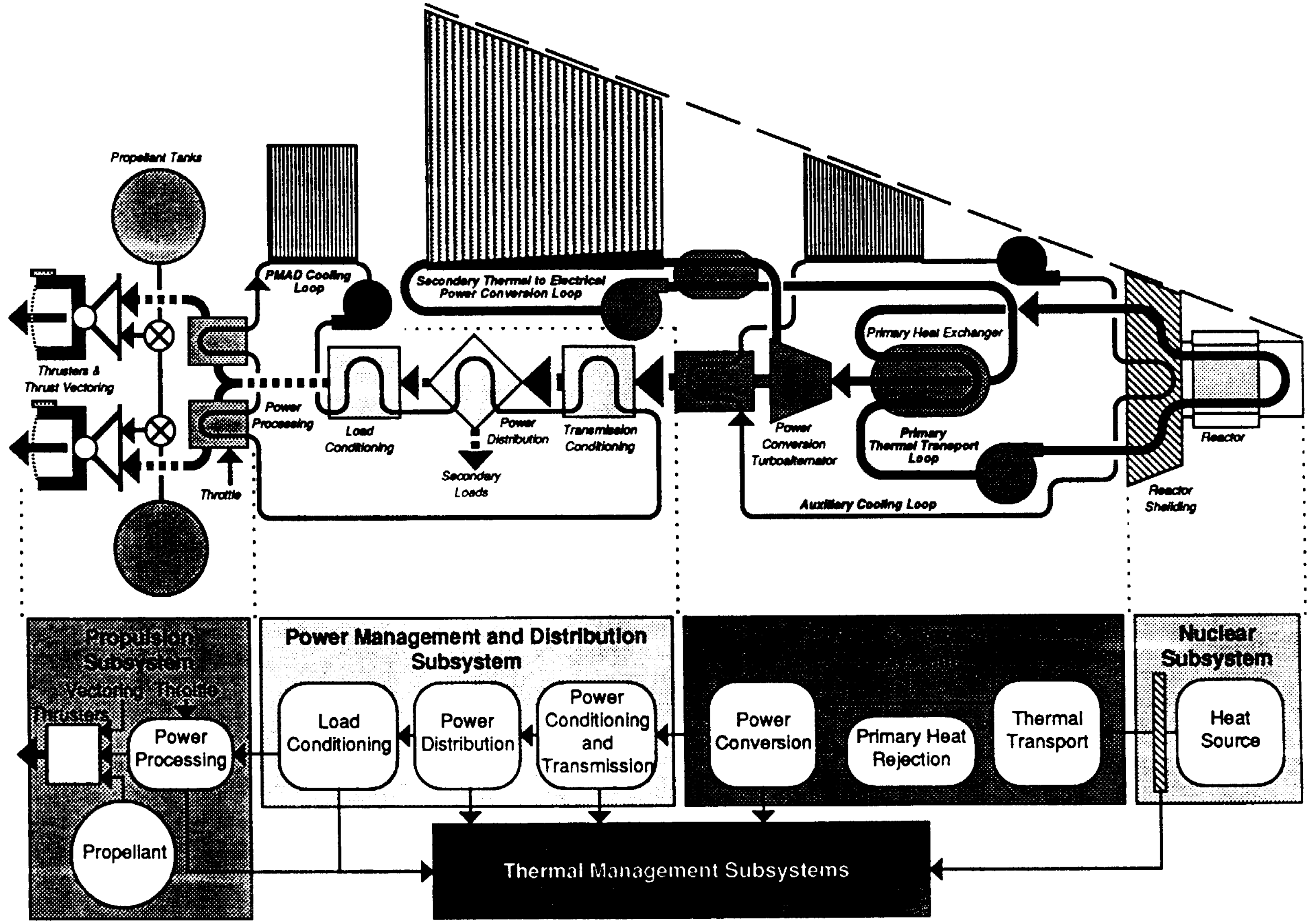


Figure 3.1: Nuclear Electric Propulsion System Schematic.
(Example High Power Dynamic System for Piloted Missions)

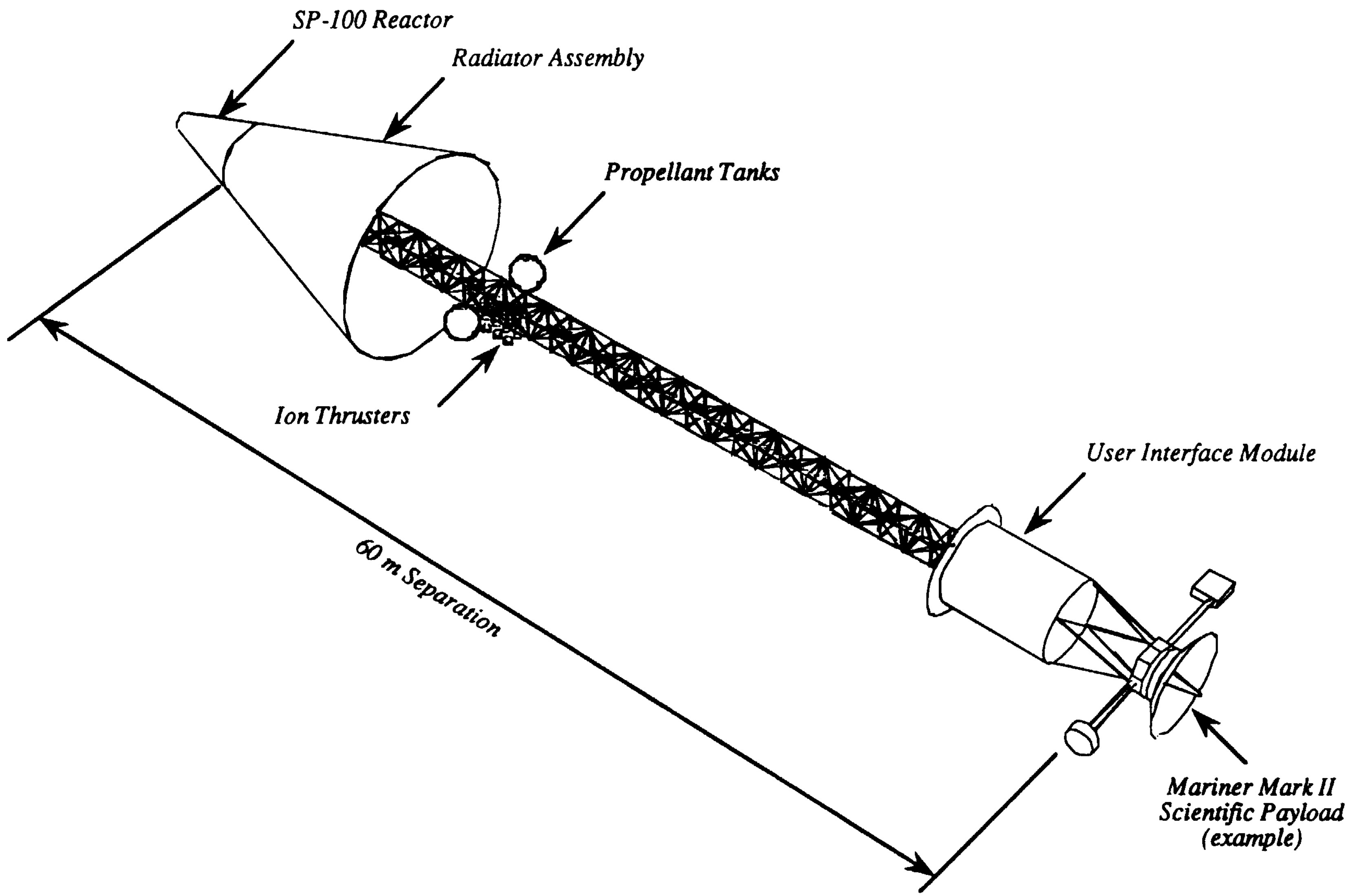


Figure 3.2: 100 kWe SP-100 NEP Vehicle for Scientific Missions

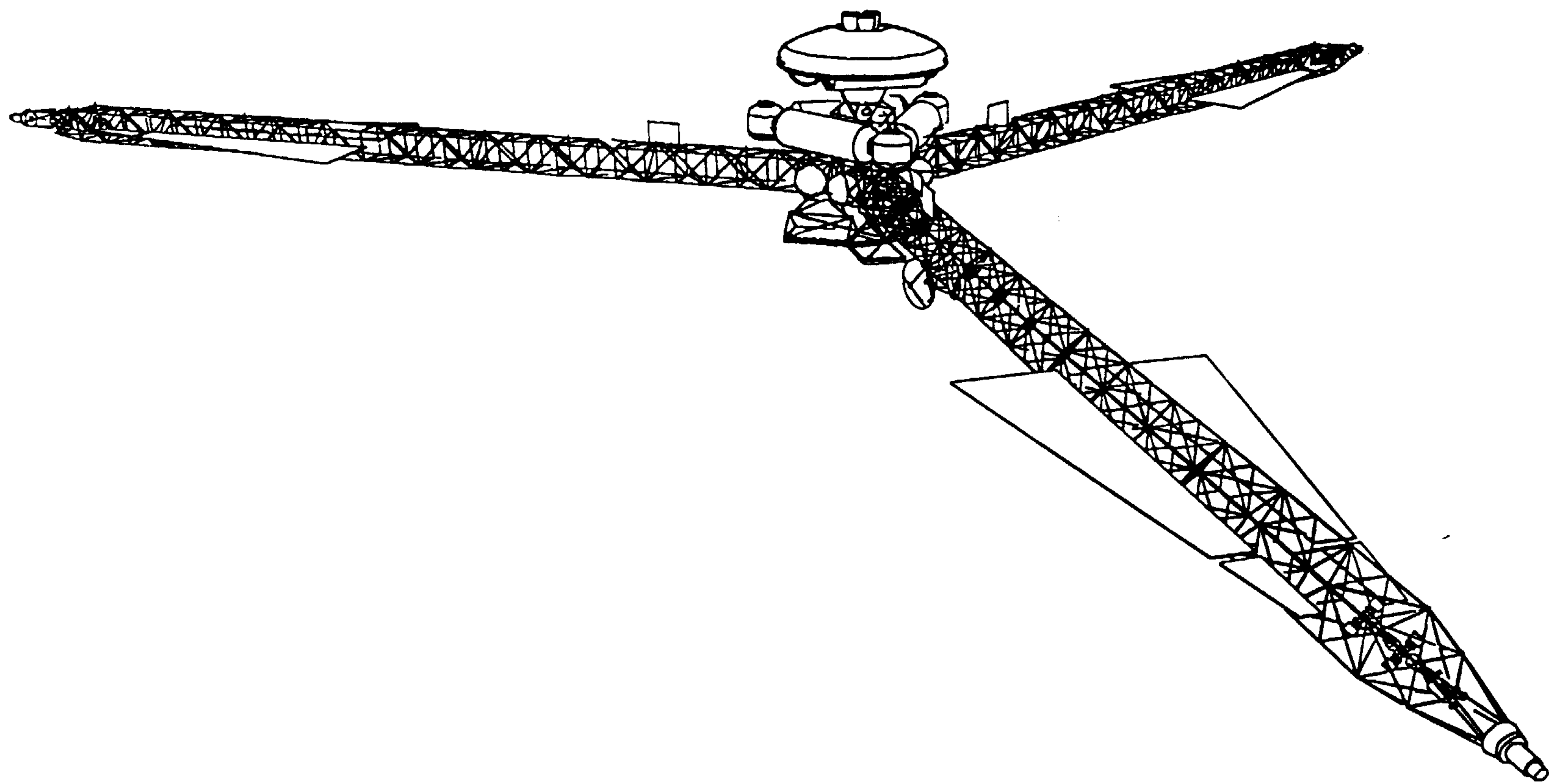


Figure 3.3: Conceptual Design for a 15 MWe Modular Piloted Mars NEP Vehicle.

SUMMARY GROUND TEST PLAN FOR MEGAWATT NEP

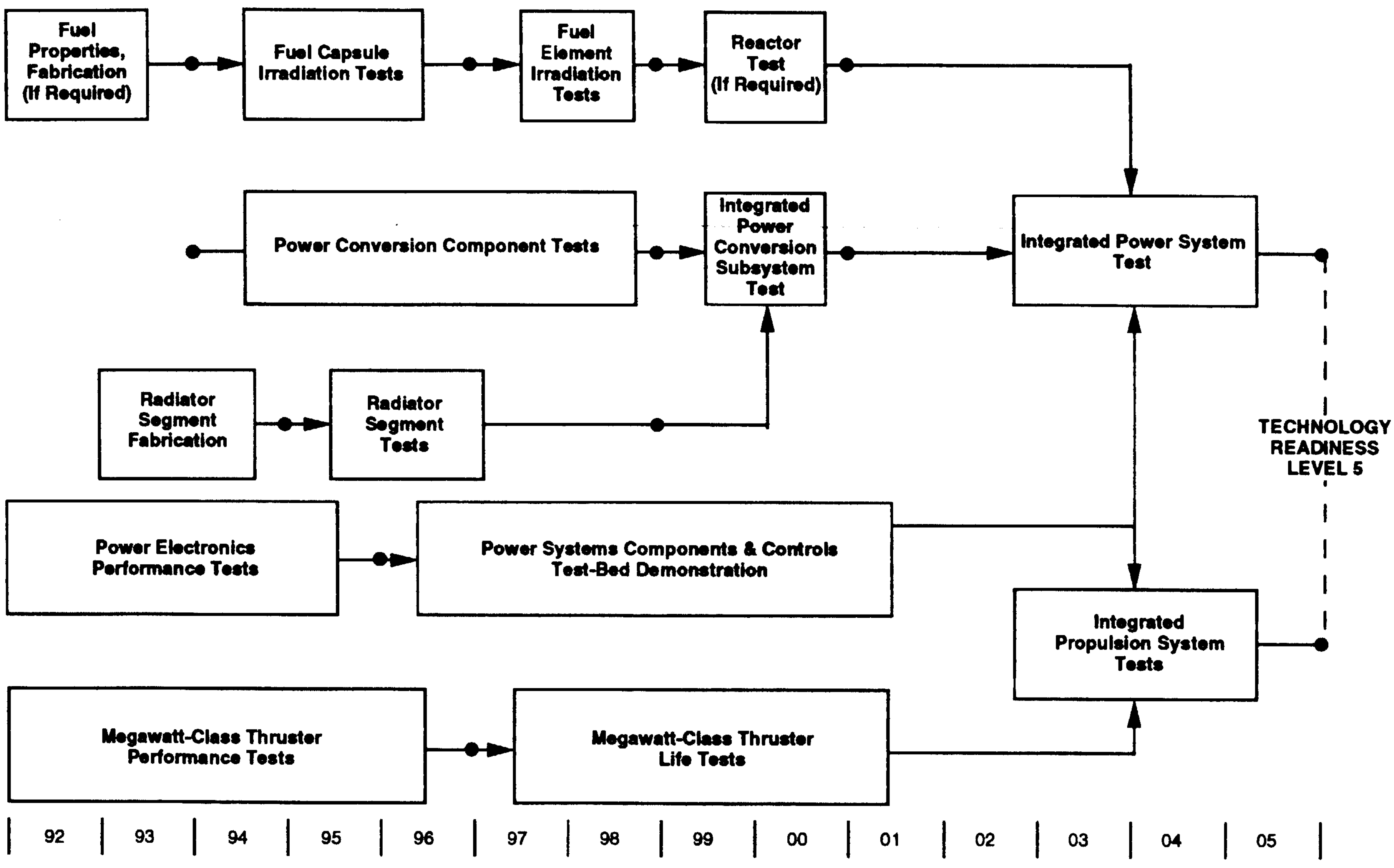


Figure 3.4

NEP PROJECT PLAN OVERVIEW

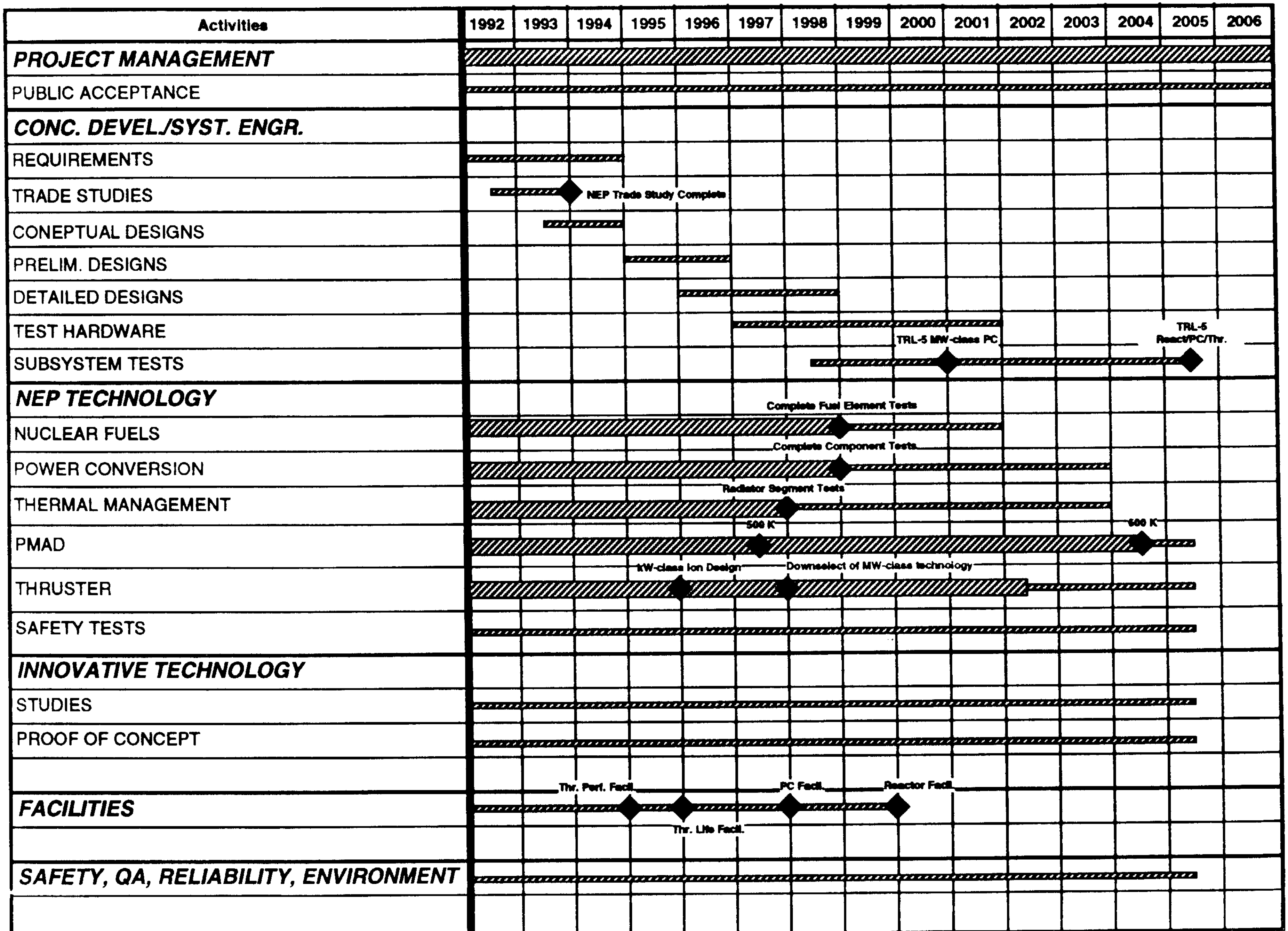


Figure 3.5

4.0 BACKGROUND

Two major national workshops were held in the summer of 1990 at which concepts for Nuclear Electric Propulsion and Nuclear Thermal Propulsion were presented. In September of 1990, a joint NASA/DOE/DOD interagency steering committee for nuclear propulsion reviewed the results and recommendations from the two workshops and identified the high priority issues for near term implementation[1]. These issues resulted in a set of "marching orders" for FY 1991 (Figure 4.1).

To address this set of marching orders and maintain programmatic momentum in the wake of the workshops, interagency panels were formed. These panels focused on six programmatic areas for nuclear propulsion:

1) Mission Benefits
2) Safety
3) NTP Technology
4) NEP Technology
5) Fuels and Materials Technology
6) Test Facilities

A bullet chart showing the products of each of the six panels appears as Figure 4.2. A more detailed description of the purpose of each of the panels, as well as preliminary accomplishments of each, has been published[2]. The resulting final reports, some of which have been already referred to, are referenced herein[3,4,5,6,7,8,9].

The NEP Technology Panel was specifically chartered to address the high priority activities associated with NEP. The objectives and products of the NEP Technology Panel are shown in Figure 4.3, while the government/academia/industry membership of the panel is shown in Figure 4.4. A preliminary description of the findings and recommendations of the NEP Technology Panel was documented[10].

Within the NEP Technology panel, six subpanels were formed to address the panel objectives. Each subpanel, its membership, and products appears in Figures 4.5 through 4.10. The panel met monthly from January to July of 1991 (except for June). The activities and products of the subpanels helped the panel to achieve its results and conclusions, and this final report was a group effort, with most of the panel members providing input.◆

INTRA-AGENCY PANELS/WORKING GROUPS PLANS AND GOALS

(Recommendations of Steering Committee)
September 1990

	PANEL*
• DEVELOP A CONSISTENT BASIS FOR COMPARING NP CONCEPTS TO GUIDE SELECTED CONCEPTUAL DESIGN EFFORTS IN FY92 • DEFINE PROOF OF CONCEPT EXPERIMENTS • CATEGORIZE CONCEPTS INTO NEAR, INTERMEDIATE, AND LONG TERM	NTP, NEP
• COMPLETE FACILITY ASSESSMENT FOR FUEL AND SYSTEM TESTING	F/M, FAC
• COMPLETE DRAFT OF INTEGRATED SAFETY PROCESS WITH ISSUES IDENTIFIED THAT REQUIRE RESOLUTION	NSPWG
• COMPLETE MISSION IMPLEMENTATION ANALYSIS TO TAKE ADVANTAGE OF NUCLEAR PROPULSION CHARACTERISTICS	MA
• DEVELOP INTERAGENCY AGREEMENTS WITH DOE AND DOD	HQ
• DEVELOP AND IMPLEMENT HIGH PRIORITY TECHNOLOGY EFFORTS IN BOTH NUCLEAR AND NONNUCLEAR AREAS	NPO

*NTP,NEP = NTP Technology Panel, NEP Technology Panel, respectively; F/M = Fuels/Materials Technology Panel; FAC = Facilities Assessment Committee(Test Fac ilities Panel); NSPWG = Nuclear Safety Policy Working Group; MA = Mission Analysis Panel; HQ = NASA Headquarters; NPO = Nuclear Propulsion Office (NASA LeRC)

FIGURE 4.1

INTERAGENCY TECHNICAL PANELS

MISSION ANALYSIS:

- REFERENCE MISSIONS
- OPERATIONS
- ABORT SCENARIOS
- BENEFITS OF NP
- FIGURES-OF-MERIT

FUELS/MATERIALS TECH.:

- TEST & DEVELOPMENT NEEDS
- FACILITY REQUIREMENTS
- REACTOR TECHNOLOGY

NTP TECHNOLOGY:

- TEST & DEVELOPMENT NEEDS
- CONSISTENT COMPARISONS
- DEFINE P-O-C EXPERIMENTS

TEST FACILITIES:

- TEST REQUIREMENTS
- EVALUATE EXISTING FACILITIES
- FACILITY MODS
- NEW FACILITIES

NEP TECHNOLOGY:

- TEST & DEVELOPMENT NEEDS
- SYSTEM LEVEL COMPARISONS
- TECHNOLOGY REQUIREMENTS

NUCLEAR SAFETY POLICY:

- INTERAGENCY POLICY
- MAN-RATING
- INADVERTENT REENTRY (SUB-CRITICALITY, IMPACT)
- REDUNDANCY, PROB. RISK
- DISPOSAL CRITERIA

FIGURE 4.2

NEP TECHNOLOGY PANEL

OBJECTIVE: TO CHARACTERIZE NEP SYSTEM OPTIONS, INCLUDING INTEGRATED REACTOR/THRUSTER CONSIDERATIONS, USING COMMON GROUND RULES AND ASSUMPTIONS. TO INITIATE PLANNING FOR A NEP TECHNOLOGY PROGRAM.

PRODUCTS:

- METHODOLOGY FOR EVALUATING CANDIDATE POWER/ PROPULSION SYSTEMS
- IDENTIFICATION OF NUCLEAR AND NON-NUCLEAR TECHNOLOGY NEEDS/PLAN
- DEFINITION OF FACILITY REQUIREMENTS FOR NEP
- REQUIREMENTS FOR NEP SYSTEMS TRADE STUDY
- FINAL REPORT

FIGURE 4.3

NEP TECHNOLOGY PANEL MEMBERSHIP

MEMBERS

MIKE DOHERTY	LeRC
MONTE PARKER	LANL
WAYNE SCHMIDT	AFAL
HANS LUDEWIG	BNL
JOHN DEARIEN	INEL
JIM LAKE	INEL
JOHN BARNETT	JPL
JACK MONDT	JPL
K. SCHOENBERG	LANL
H. BLOOMFIELD	LeRC
JOHN DICKMAN	LeRC
JEFF GEORGE	LeRC
JIM GILLAND	LeRC
AL JUHASZ	LeRC
JOE NAINIGER	LeRC
JIM SOVEY	LeRC
BICK HOOPER	LLNL
BOB HOLCOMB	ORNL
DICK WIDRIG	PNL
DON GALLUP	SNL
FRANK THOME	SNL

INDUSTRY OBSERVERS & INVITED PARTICIPANTS

SAMIM ANGHAIE	INSPI
FRANK BIANCARDI	UTRC
LEE DAILEY	TRW
DALLAS EVANS	JSC
IRA HELMS	NUS
ANDREW KLEIN	OSU
JIM MANGUS	WEC
JOE MILLS	R/D
DON ROY	B&W
JOHN WHEALTON	ORNL
TOM MAHEFKEY	WPAFB

FIGURE 4.4

NEP TECHNOLOGY PANEL

CANDIDATE SYSTEMS SURVEY SUBPANEL

PURPOSE: PROVIDE OVERALL ASSESSMENT OF CANDIDATE POWER/PROPULSION SYSTEMS

ACTIVITIES: PROVIDE SYSTEM LEVEL CHARACTERIZATION (MATRIX) OF POWER/PROPULSION CONCEPTS

- CATEGORIZE INTO NEAR, MID, AND FAR-TERM
- USE COMMON GROUND RULES

PRIORITIZE CANDIDATE CONCEPTS

SUPPORT THE DEVELOPMENT OF WORK STATEMENTS FOR INDUSTRY "MIX/MATCH" STUDY

SUBPANEL MEMBERSHIP:

J. LAKE (LEAD)
J. NAINIGER
J. BARNETT
J. DEARIEN
J. DICKMAN

FIGURE 4.5

NEP TECHNOLOGY PANEL

SYSTEMS ANALYSIS SUBPANEL

PURPOSE:	PROVIDE BASIS FOR SYSTEM ANALYSES WHICH ADDRESS SEI MISSION REQUIREMENTS/STUDIES
ACTIVITIES:	PERFORM SYSTEMS ANALYSES WHICH ADDRESS SEI MISSION REQUIREMENTS
	PROVIDE STANDARDIZATION OF NEP POWER/PROPULSION MASS CALCULATIONS
	ENCOURAGE DEVELOPMENT OF "QUICK TRIP" REFERENCE MISSION
PRODUCTS:	PROVIDE SYSTEMS ANALYSIS OF "STRAWMAN" HIGH POWER (20 MWe OR GREATER) POWER/PROPULSION SYSTEM APRIL 1991
SUBPANEL MEMBERSHIP:	J. GEORGE (LEAD), D. GALLUP, H. LUDEWIG, K. SCHOENBERG, B. HOLCOMB, J. GILLAND, H. BLOOMFIELD, J. NAINIGER

FIGURE 4.6

NEP TECHNOLOGY PANEL

BASE/FOCUSED TECHNOLOGY SUBPANEL

PURPOSE:	PROVIDE TECHNOLOGY PROGRAM PLANNING TO ADDRESS SEI MISSION GOALS
GOALS:	CLARIFY TECHNOLOGY REQUIREMENTS AND SCHEDULE FOR THE NUCLEAR PROPULSION PROJECT PLAN MARCH 1991
	IDENTIFY NUCLEAR AND NON-NUCLEAR TECHNOLOGY NEEDS
	PROVIDE TECHNOLOGY "MUST DO'S" FOR FIRST FIVE YEARS (REACTOR, POWER, PROPULSION) APRIL 1991
ACTIVITIES:	IDENTIFY PROOF-OF-CONCEPT TESTS
SUBPANEL MEMBERSHIP:	J. SOVEY (LEAD) J. BARNETT W. SCHMIDT J. MONDT M. PARKER J. GILLAND J. DICKMAN A. JUHASZ H. BLOOMFIELD

FIGURE 4.7

NEP TECHNOLOGY PANEL

FACILITIES REQUIREMENTS SUBPANEL

PURPOSE: PROVIDE FACILITY REQUIREMENTS FOR NEP GROUND SYSTEM AND FLIGHT QUALIFICATION TESTING

ACTIVITIES/ PRODUCTS:

PROVIDE FACILITY REQUIREMENTS TO NP FACILITIES PANEL MARCH 1991

SUPPORT ASSESSMENT OF EXISTING FACILITIES

SUPPORT CONSTRUCTION OF FACILITIES BUDGET PROCESS IN A TIMELY MANNER

SUBPANEL MEMBERSHIP:

B. HOOPER (LEAD)
J. DEARIEN
J. SOVEY
B. HOLCOMB
J. DICKMAN
H. BLOOMFIELD

FIGURE 4.8

NEP TECHNOLOGY PANEL

SAFETY/RELIABILITY/CONTROLS SUBPANEL

PURPOSE:	PROVIDE BASIS/RATIONALE FOR SAFE, RELIABLE CONTROL OF POWER/PROPULSION SYSTEM
ACTIVITIES:	INTERPRET SAFETY POLICY REQUIREMENTS OF NP SAFETY PANEL (HUMAN RATING, RELIABILITY, REDUNDANCY, ETC.) MAKE RECOMMENDATIONS ON TECHNOLOGY PROGRAM APPROACHES WHICH INSURE SYSTEM SAFETY, RELIABILITY AND CONTROLLABILITY - GROUND SYSTEM TESTING...ENTIRE SYSTEM UNDER ONE ROOF?
GOALS:	FORMULATE CONCEPTUAL I&C SCHEMES FOR CANDIDATE MAN-RATED SYSTEM JULY 1991
SUBPANEL MEMBERSHIP:	F. THOME (LEAD) K. SCHOENBERG

FIGURE 4.9

NEP TECHNOLOGY PANEL

FUELS/MATERIALS REQUIREMENTS SUBPANEL

PURPOSE: PROVIDE FUELS AND MATERIALS REQUIREMENTS TO ENABLE NEP TECHNOLOGY TO MEET MISSION DEMANDS (POWER, MASS, AND LIFE)

ACTIVITIES: CONVEY TECHNOLOGY REQUIREMENTS TO FUELS/ MATERIALS PANEL

- (SPECIFIC POWER, SPECIFIC MASS, TEMPERATURE)

SUBPANEL MEMBERSHIP: D. WIDRIG (LEAD)

FIGURE 4.10

5.0 NUCLEAR ELECTRIC PROPULSION CANDIDATE MISSIONS

The advent of the national Space Exploration Initiative (SEI), in conjunction with NASA's active robotic planetary exploration program, and a burgeoning interest in augmented near-Earth missions have led to interest in Nuclear Electric Propulsion (NEP) for future missions.[1,2,3,4] These missions span a range of activity:

- Near Earth: orbit transfer, maneuvering, station keeping
- Planetary Exploration: robotic probes to the outer planets, comet nucleus sample return, asteroid exploration
- SEI: lunar piloted and cargo missions, Mars piloted and cargo missions, including short trip time missions

With specific impulse values of 2,000 - 10,000 seconds, NEP systems allow propellant mass efficient means of accomplishing almost all of these missions, utilizing common technology development as the mission requirements evolve.

5.1 BACKGROUND

NEP systems are inherently low acceleration ones, due to the high specific impulses (Isp) attained, and to the requirement of an on-board power system. Since propulsion system power is proportional to the product of Isp and thrust, such high specific impulse systems require high power levels to generate thrust. The nature of power generation technology is such that the power densities of even space nuclear power systems are not high enough to allow large amounts of thrust to be produced by a lightweight system. As a result, NEP missions are accomplished through extended periods of continuous thrusting. The integrated change in velocity over a period of days to months allows the low acceleration systems to attain the same velocity obtained by short term, high thrust propulsion. This integrated acceleration profile introduces both performance benefits and analysis difficulties to NEP missions. The benefit is derived from the capability to reach interplanetary velocities in a propellant-efficient manner. The difficulty arises from the close coupling of system performance (thrust, mass, Isp, efficiency) and trajectory analysis, in the form of the acceleration profile. Because of the integral nature of the problem, changes in system performance can drastically affect the optimal mission profile and performance, and the trajectory analysis must be carefully integrated with the system design.

NEP system/mission performance can be defined in terms of 4 system parameters and the mission ground rules. The four system parameters are:

- Specific Mass (alpha): Ratio of power and propulsion system mass to electric power input to the thrusters, typically in units of kg/kWe.
- Isp: Thrust per unit weight flow - determines propellant requirements as per the rocket equation.
- Efficiency (eta): Ratio of thrust power output to electric power input.
- Power (Pe): Electric power generated by the power system for propulsion.

Of the above parameters, Isp is obviously of primary importance in that the high specific impulse allows NEP systems to be competitive with other concepts. The high Isp of all NEP systems enables the systems to operate with a minimal propellant requirement. Beyond this fundamental benefit in performance, the other parameters govern the total mission performance in terms of trip time and initial mass. First of these parameters is the specific mass. This parameter, in combination with Isp, Power, and Efficiency, determines the acceleration levels possible for the system. Alpha determines the maximum acceleration possible for a system, regardless of specific impulse or power. The specific mass is therefore the primary performance parameter of an NEP system.

Mission parameters are:

- Trip time
- Payload
- Initial Mass.

Mission performance is generally assessed in terms of initial mass and trip time; however, other less quantifiable parameters such as safety, economics, and flexibility may become equally important as analysis progresses. In combination with the systems parameters above, the mission trip time and payloads define the power requirements for a given system alpha. Once again, the tight intertwining of system and mission requires that parameters from both sides of the interface be specified to reach a solution to the mission performance question.

As noted earlier, a wide range of missions exist to which NEP can be applied. The differences in mission objectives and payloads result in a range of performance requirements for NEP. It is an opportunity for a project in NEP technology to address this full range of missions in a rational, cost-effective fashion; therefore, each mission should be addressed in terms of NEP system requirements.

5.2 NEP MISSIONS

A description of potential NEP missions and the requirements that each imposes on the NEP system follows.

5.2.1 Orbital Transfer

Transfer of payload from LEO (Low-Earth Orbit) to GEO (Geosynchronous or Geostationary orbit) using NEP has been extensively studied by both NASA and the military. The benefits of NEP have been expressed in terms of cost savings from reduced vehicle mass. The reduction in mass results from either using a smaller launch vehicle to lift the NEP transfer vehicle, or launching multiple vehicles on the same launch vehicle. NEP also may provide the added benefit of an on-board power supply for payload use at the destination. Payloads of 1-2 tons are typically of interest to the user. Transfer trip times of 6 months to 1 year are typically of interest to the user. Transfer trip times of 6 months to 1 year are typically considered reasonable. The time frame for such OTV missions is flexible, and depends somewhat on the programs such as the Strategic Defense Initiative (SDI) and Earth Observing System (EOS) which are underway at present. Based on technology readiness and mission projections, a date in the late 1990s or early 2000 might be expected. The mission characteristics translate into the following system requirements:

Specific Mass (kg/kWe)	Power (MWe)	Isp (kilo-sec)	Thruster Operating Time (y)	Total Mission Time (y)
10 - 30	.1 - 1	2 - 8	1 - 2	3 - 10

(Obviously, lower alpha or higher power would result in better performance. An additional purpose for such near-Earth missions is gathering practical flight testing and operational experience and data to be used for later missions.

5.2.2 Robotic Interplanetary Probes

Robotic exploration of the Solar System, in particular the outer planets, has typically used chemical propulsion with extensive exploitation of planetary gravity assists, at the expense of payload capability and launch window and opportunity flexibility. The high Isp of NEP has been shown repeatedly to accomplish difficult interplanetary missions with either higher payload, reduced trip time, greater launch flexibility, or with increased mission capability in terms of number of targets visited or data gathering capability. In some cases, NEP enables missions, such as the Jovian Grand Tour or a Pluto Rendezvous[5]. The high specific impulse of the NEP systems allows such increases in mission capability, and the sun-independent nuclear power supply is particularly advantageous for outer planet exploration at large distances from the sun. Payloads of 1 - 2 tons, similar to a Mariner Mark II spacecraft, are of interest for most missions. Trip times for most outer planet missions are high; on the order of 5 - 10 years, depending on the mission. Currently, projected mission time frames (based on chemical propulsion system limitations and launch opportunities) begin in early 2000. System requirements determined from mission analysis thus far are:

Specific Mass (kg/kWe)	Power (MWe)	Isp (kilo-sec)	Thruster Operating Time (y)	Total Mission Time (y)
30 - 50	.1 - 1	5 - 10	6 - 10	10 - 12

5.2.3 Lunar Cargo

Most of the mission performance advantages seen in using NEP for near-Earth orbital transfer missions also hold for Lunar Cargo missions. The primary difference in the missions is the magnitude of payload mass to be transported, as well as a later need date for the system, allowing some advances in technology. In addition, the presence of men on the moon implies development of nuclear power for the lunar base, which could provide increased NEP power system capabilities. Past studies have focussed on delivering payloads on the order of 50 metric tons/year using a reusable system over a 5 year period. Reusable NEP systems have been found to reduce the total initial mass delivered to Earth orbit for lunar cargo transportation by 50% over a 5 year period. The start of the lunar initiative is uncertain at present; nominal mission application based on Synthesis Group recommendations would be 2005. The system requirements for such a mission are:

Specific Mass (kg/kWe)	Power (MWe)	Isp (kilo-sec)	Thruster Operating Time (y)	Total Mission Time (y)
10 - 20	.5 - 5	3 - 10	1 - 2	3 - 10

5.2.4 Mars Cargo

Interplanetary cargo missions are well suited for using NEP. The cargo nature of the payload reduces the importance of trip time in mission performance, and the large amount of payload makes minimizing vehicle mass imperative. The high specific impulse of the NEP systems ensures that mass is reduced significantly. The eased requirement on trip time serves to reduce alpha and power requirements. Vehicle reuse further improves the benefit of a Mars NEP vehicle. As with the Lunar cargo vehicle, power requirements are governed by the amount of payload to be transported. Current estimates of payload masses range from 100 to 200 MT. Initial use of Mars cargo vehicles would occur in the 2010 to 2014 time frame. Although power requirements are slightly higher for this mission, the potential exists for a great deal of commonality between Lunar and Mars cargo vehicles:

Specific Mass (kg/kWe)	Power (MWe)	Isp (kilo-sec)	Thruster Operating Time (y)	Total Mission Time (y)
10 - 20	2 - 10	5 - 10	2 - 3	2 - 10

5.2.5 Mars Piloted

Piloted Mars missions impose the most stringent requirements upon NEP systems. Most missions have payloads comparable to the Mars cargo mission, but must perform the round trip mission in trip times of 600 days or less. The most demanding mission profiles assume trip times of ~ 1 year. Because of the combination of short trip time, high payload mass, and the desire to keep initial mass to a minimum, specific masses are required to be lower than those previously identified. For the same reasons, power requirements increase significantly.

A typical piloted mission scenario has certain characteristics unique to low thrust systems. First, due to the slow spiral escape times inherent in low acceleration systems in planetary orbits, and because of the Earth's Van Allen Radiation Belts, the crew does not board the piloted NEP vehicle unit it has spiralled beyond the belts. Similarly, rather than waste valuable crew time spiralling in and out of Mars orbit, the vehicle would be located at a high Mars orbit, such as Aerosynchronous orbit. The crew should disembark for Mars before the spiral was completed. Upon return to Earth, the crew would disembark prior to entering the Radiation Belts. The NEP vehicle could capture into Earth orbit and spiral down for refurbishment and reuse, or it could be allowed to fly by Earth. Because of the early stage of piloted Mars mission design, numerous mission options such as split/sprint, opposition, conjunction have yet to be considered for NEP systems. A proposed time frame for initial piloted Mars exploration is 2014 - 2019. The system requirements listed below are intended to bracket the possible mission scenarios:

Specific Mass (kg/kWe)	Power (MWe)	Isp (kilo-sec)	Thruster Operating Time (y)	Total Mission Time (y)
< 10	5 - 40	5 - 10	1 - 2	2 - 10

The total power levels listed may be achieved using 5 - 10 MWe modules, rather than a single system. This multiple unit strategy may prove desirable from a mission/crew safety viewpoint, providing a level of redundancy in the propulsion system. A redundant, modular approach also allows mission abort modes for the NEP system. In general, the continuously thrusting nature of low acceleration systems does not allow for non-propulsive abort options, as the low acceleration vehicle is never on a trajectory that allows it to "coast" to its destination. Instead, the vehicle is constantly adjusting its trajectory to arrive at its destination. The modular option allows for reduced power or full power abort modes.

5.3 SUMMARY

As a technology, NEP has been found to provide benefit over a range of missions of interest to NASA. The mission characteristics in terms of destination, payload, and trip time have been identified to varying degrees of accuracy. Mission analysis of NEP systems for orbital transfer, robotic interplanetary, lunar cargo, Mars cargo, and Mars piloted missions have identified minimum NEP system requirements to satisfy each mission type. These data have been summarized in Subsection 5.2. The requirements listed therein depend upon the mission definitions; should these change, the system parameters may change as well. Both quantified figures-of-merit, such as Initial Mass, Trip Time, and Cost, as well as less mathematical factors such as safety, robustness, mission commonality, and technology commonality, must all be considered in the assessment and development of technology.◆

6.0 NEP SUBSYSTEM/TECHNOLOGY OPTIONS

A host of technologies offer substantial benefit to NEP for the missions discussed in Section 5. In order to make an initial assessment of candidate NEP technologies for SEI, NASA, DOE, and DOD jointly sponsored a Nuclear Electric Propulsion workshop, held at the Jet Propulsion Laboratory in Pasadena, California, June 19-22 1990. Concepts, presented by invited speakers from government, industry, and academia, fell under the general headings of space nuclear power and electric propulsion[1]. A non-advocate rating of these concepts is to be published[2].

In order to characterize NEP system options, including integrated reactor/ thruster considerations, the NEP Technology Panel decided to substantiate technologies by subsystem, namely:

- Reactor
- Power Conversion
- Thermal Management (or Heat Rejection)
- Power Management and Distribution (PMAD), and
- Thruster

The panel identified the specific NEP technologies embodied in the concepts presented at the JPL workshop, and grouped them according to subsystem (Table 6.1). This exercise was performed not only to provide a deeper substantiation of technology options, but to curtail the use of trade names to describe concepts. A brief description of each of these subsystem/ technology options, a cursory citing of other recent programs related to NEP technology, and the panel's position on the technology's applicability and readiness for SEI missions follows.

6.1 DESCRIPTION OF TECHNOLOGY OPTIONS

6.1.1 Reactor

The nuclear reactor subsystem serves as a source of heat for the power conversion subsystem. Types of nuclear reactors considered for NEP fall under the headings of: liquid metal cooled, gas cooled, thermionic, and vapor core.

6.1.1.1 Liquid Metal Cooled Reactor

This type of reactor uses liquid metal as the means to transfer heat away from the reactor core where it can be used to do useful work. Lithium, potassium and NaK are the liquid metals of choice. Liquid metal cooled reactors are generally compatible with a number of dynamic and static power conversion technologies, including Rankine, Brayton, thermoelectric, and ex-core thermionic options. Technology options include Growth SP-100, Advanced Pin, Cermet, and Boiling Potassium.

The liquid metal-cooled reactor was the principle type under development in the space nuclear power program in the 1960s. The SNAP 50 reactor, designed by Pratt and Whitney Aircraft, was a 2.2 MWt lithium-cooled fast reactor coupled to a 300 kWe potassium Rankine power conversion system. The MPRE reactor, designed by Oak Ridge National Laboratory was a 1 MWt boiling potassium fast reactor that generated potassium vapor which went directly to a 150 kWe turbine-generator. Both of these reactors were designed to employ pin-type fuel elements. Both of these projects were terminated before either of these reactors were actually built and operated. A significant amount of testing was done, however, on electrically-heated non-nuclear models of the reactors.

A long development program was carried out on liquid metal-cooled fast breeder reactors for application to large central station electric generating plants. All of the designs employed pin-type fuel elements composed of UO_2 or UO_2-UC pellets enclosed in stainless steel tubes. Sodium was employed as the coolant, with coolant exit temperatures of 800-900°K. The breeder program has now evolved into the Advanced Liquid Metal Reactor program, whose focus is on uranium metal fuel in pin-type fuel elements. Several sodium-cooled fast reactors were built for testing and were or are still being operated, including the EBR-2, Fermi, and Fast Flux Test Reactor.

The SP-100 Reactor represents the current state-of-the-art for high temperature liquid metal-cooled reactors (Figure 6.1). It employs pin-type fuel elements composed of UN pellets enclosed in Nb-1Zr clad tubing, cooled by liquid lithium circulated by electromagnetic pumps. It is designed for an outlet lithium temperature of 1375°K at a power output of 2.3 MWt and a full-power life of 7 years. A "Growth", or scaled up, SP-100 has been studied. No technology breakthroughs beyond the current SP-100 program are required.

Advanced pin reactors, employing higher temperature cladding materials such as T-111, ASTAR-811C, and W-Re, could operate at temperatures in the range of 1500-1600°K, beyond that of the SP-100 fuel technology. A Cermet (ceramic metal) fueled reactor employs block-type fuel elements with built-in coolant channels (Figure 6.2). Its ceramic metal matrix would enable it also to operate at temperatures beyond the SP-100 fuel technology. Lastly, a boiling potassium reactor involves the direct heating of liquid potassium in the reactor core. The advantage of this option is the elimination of a secondary cooling loop for Rankine cycle power conversion, decreasing the overall system specific mass. The major disadvantage is the increased risk of reactor local overheating due to uncertainties associated with boiling heat transfer.

6.1.1.2 Gas Cooled Reactor

This type of reactor uses a gas as the means to transfer heat away from the reactor core where it can be used to do useful work. Helium, Helium-Xenon, and Hydrogen are the gases of choice. Gas cooled reactors are compatible with Brayton power conversion technology. Technology options include NERVA Derived, Particle Bed, Pebble Bed, and Cermet.

Gas-cooled reactors with fuel-graphite matrix fuel elements and graphite moderator have been under development for application to central station electric generating plants since about 1960. The first plant of this type in the U.S. was the Peach Bottom plant, which was rated at 40 MWe. It employed helium as the coolant with a reactor outlet temperature of 1000°K. Heat from the helium coolant was transferred to water in a steam generator to drive the Fort St. Vrain plant, which was rated at 330 MWe. This plant operated from 1974 until 1990.

The NERVA Derived Reactor (NDR) option claims its heritage from the Nuclear Engine for Rocket Vehicle Applications, a program terminated in the early 1970s. The fuel form is a composite matrix comprised of Uranium Carbide-Zirconium Carbide dispersed within a graphite substrate. The fuel is extruded to form an element containing coolant channels, coated both on the internal and external surfaces to prevent attack (Figure 6.3). Particle and pebble bed reactors would employ UC-ZrC embedded in graphite, coated with ZrC. This fuel would be packed in an annular bed surrounded by two frits (porous tubes), through which the reactor coolant gas would flow. The advantage of a reactor employing either of these fuel forms is a large heat transfer area, leading to high power density. Cermet fuel forms could be employed within gas cooled reactor concepts also. A gas cooled reactor might be designed to operate at gas exit temperatures up to 2000°K.

6.1.1.3 Incore Thermionic Reactor

This type of reactor, comprised of thermionic cells which directly produce an electric current, serves as a reactor and power conversion subsystem in one. The thermionic cell is comprised of a nuclear-fuel-filled cylindrical emitter cup, surrounded by a concentric collector (Figure 6.4). Nuclear fission heats the emitter to the point of thermionic emission. The emitted electrons cross a small gap to the collector. In this way, the emitter and collector serve as electrodes which can be connected across an outside electrical load to produce a DC electrical current. Thermionic cells can be connected in series to comprise a thermionic fuel element (TFE). An array of TFEs makes up a thermionic reactor. Coolant is required to maintain the temperature of the collector, with liquid metal coolants often used for this purpose.

6.1.1.4 Vapor Core Reactor

The type of vapor core reactor concept considered by the panel as a heat source for power generation for NEP relies upon an ionized uranium plasma or vapor, sustained in a core at a critical mass by fluid confinement, circulated throughout a closed loop to do useful work. The working fluid considered is comprised of Uranium-tetrafluoride and potassium-fluoride. This concept would be most compatible with Magnetohydrodynamic (MHD) power conversion technology (Figure 6.5).

6.1.2 Power Conversion

The power conversion subsystem converts energy from the reactor (usually in the form of heat) into usable electrical power. Types of power conversion technologies fall under the headings of: dynamic and static.

6.1.2.1 Dynamic Power Conversion

Dynamic power conversion involves a heated working fluid (either liquid or gas) driving rotating or reciprocating machinery to produce electricity. Technology options include Rankine, Brayton, and Stirling.

6.1.2.1.1 Rankine

In Rankine cycle conversion, the heat source produces a phase change from liquid to gas in the working fluid (potassium, for high temperature space power), the energy from the gaseous phase is extracted in a turbine as useful work, the saturated vapor is condensed back into a liquid, and then pumped back through the heat source to repeat the cycle (Figure 6.6).

Rankine cycle conversion is applicable over a range of 10s of kWe to MMWe levels. Cycle efficiency can range from 20 - 30 percent (thermal to electric). Due to high, near-constant heat rejection temperatures, only relatively modest waste heat radiator sizes are required with Rankine cycle power conversion systems. Thus, the use of Rankine cycle power conversion can lead to low system specific mass.

System configurations vary, with the most common space-borne system being a two loop system where the heat source is in the primary loop and the boiling-power extraction-condensing portion of the cycle is in the secondary loop. Nearly as common (in terrestrial nuclear power production and fossil fired steam plants) is a direct cycle where the gas phase is generated at the primary heat source and returned to that point after the power extraction-condensation portion of the cycle. A boiling-potassium reactor would use this approach. Rankine cycles are noted for having a rather complex piping system as a result of the need for pumping and controlling a 2-phase fluid.

The technology issues of space-based Rankine cycle are: 1) making the system functional at high operating temperature (turbine inlet temperatures from 1200 - 1600°K), and 2) the operational aspects of the system which can be affected by space conditions. Issues under item 1) include materials (high temperature strength, light weight, and compatible with working fluids), and reliable components (pumps, valves, radiators) over long periods of time and in a harsh space environment. Issues under item 2) include the operation of 2-phase flow pumps and condensers in zero gravity, and rethaw of liquids if frozen during operational outages.

6.1.2.1.2 Brayton

In Brayton cycle conversion, a single phase, inert working fluid (a gas) serves as the energy transfer medium between the heat source and the power turbine. Because an inert gas is used, the temperature range of applicability for the Brayton cycle is limited only by the materials from which the machine components are fabricated. Higher temperature operation is desired to decrease system specific mass. Heat rejection occurs across a varying temperature range (constant pressure), unlike

Rankine cycle heat rejection. Brayton cycle efficiency can range from 25 - 35 percent (thermal to electric).

Brayton cycle conversion is applicable in the range of 1 kW to MMWe levels. For a given heat source, Brayton cycle conversion tends to lead to a higher system specific mass than Rankine cycle conversion because of the larger radiator surfaces associated with lower temperature heat rejection for Brayton. Brayton machines are much simpler in operation and component count than Rankine machines, basically being capable of operating as a "one moving part" machine. With non-contacting foil or magnetic bearings, Brayton machines can be fabricated as an extremely long life machine.

Space power Brayton machines consist of a heat source which heats a compressed gas flow and then discharges that flow into a gas turbine. The power imparted to the turbine is extracted with a generator or alternator. Excess cycle temperature is removed through a radiator and the gas is returned to a compressor where it is compressed and the cycle repeated (Figure 6.7). The compressor, turbine, and generator are commonly on the same shaft, resulting in a very rugged, compact power package. Recuperated cycles are possible to increase cycle efficiency, at the disadvantage of greater system complexity.

The primary technology issue with the Brayton cycle is making the system functional at high operating temperature (turbine inlet temperatures from 1200 - 2000°K). Resolution of this issue requires high temperature, high strength, and light weight materials. There are no operational characteristics of the Brayton cycle that are affected by zero gravity, but concerns have been raised regarding subsystem reliability in light of the damage of plumbing components by space debris.

6.1.2.1.3 Stirling

A Stirling engine takes gas heated by an external power source, uses the energy in that gas to move a piston, and then extracts the energy from the moving piston. Excess heat is removed from the gas stream after exiting the power piston portion of the cycle (through radiation to space) and returning to the external heat source to repeat the cycle.

Stirling engines, in a space application, are applicable from a few kW to several 100s of kW. The maximum power space design now being considered is the 25 kW unit being developed by NASA. Future needs for higher power might be met by using designs up to 200 kWe. Stirling engines have reciprocating elements and must be carefully designed to keep vibration out of the system.

Stirling engines operate with a basic thermodynamic cycle where the energy is supplied by a heat source (a nuclear reactor in this case), the heated gas is supplied to a volume and used to impart mechanical energy to a piston. The mechanical energy in the piston can be extracted in a number of ways, with the NASA engine using the piston as the moving element of an electrical generator (i.e., no mechanical linkage to the moving piston). A radiator is used to reject waste heat to space and the gas is returned to the heat source to repeat the cycle.

Materials which will maintain their strength and tight tolerances at high temperatures and long life are required.

6.1.2.2 Static Power Conversion

Except for incore thermionic power conversion, all static power conversion options shown in Figure 6.1 involve a heated working fluid (either liquid or gas) being used as an impetus in a process which creates electricity without the use of rotating or reciprocating machinery. As discussed in paragraph 6.1.1.3, incore thermionic power conversion occurs directly within the reactor, by the use of a TFE. Types of static power conversion are: thermoelectrics, ex-core thermionics, electrochemical, and magnetohydrodynamic.

6.1.2.2.1 Thermoelectric

Thermoelectric devices use the temperature difference (created by a heat source) across a thermocouple junction (semi-conductor device) to generate an electric current and voltage. The high temperature thermoelectric material, Silicon Germanium, is being designed for use at 1275°K hot junction and 575°K cold junction temperatures under the SP-100 program.

Thermoelectric systems are most applicable at electrical outputs of 10 to 100 kWe. A specific mass of 30 -50 kg/kWe at 100 kWe for reactor, thermoelectric power conversion, and radiator subsystems is typical to the SP-100. Output of the SP-100 system is DC power at 100 to 600 volts and a variety of amps, depending on power level. Heat transport for the SP-100 requires pumping of liquid lithium between the heat source and the thermoelectric converters and between the converters and the heat rejection subsystem.

Thermoelectric element design for high temperatures and long life is needed to obtain a reasonable cycle efficiency and keep the specific mass down. Because of low thermal to electric conversion efficiency (less than 10 percent) thermoelectric power conversion is probably not practical for space propulsion beyond the 100 kWe level.

6.1.2.2.2 Thermionic

Thermionic devices operate on the basis of developing a large temperature difference across a small gap between two materials acting as thermionic emitter and collector, to produce an electrical current. An ex-core thermionic device uses a heat source independent, although thermally connected, from the power generating gap. The hot side of the gap must be heated by some heat source and the cooler side cooled by some heat transfer process.

Ex-core thermionic devices are usually considered for long term power sources in the 10s of kWe range. Output of the system is DC power at a variety of voltages and amps, depending on connection geometry of individual elements and power level.

Lower power thermionic devices (10s of kWe) can be configured for radiation cooling of the cool side of the thermionic element, making for a very compact, static power source. Higher power devices (>100 kWe) generally require some form of dynamic heat removal system, usually a pumped liquid metal system dumping the waste heat of the system to a radiator for radiation cooling to space. These pumping cooling systems can be powered by electromagnetic pumps which result in a very stable, near static type operating system.

6.1.2.2.3 Electrochemical

Two similar static power conversion systems based on thermally regenerative electrochemical processes have been proposed to date[34]. These concepts have promise for thermal-to-electric conversion efficiencies of greater than 10 percent. These concepts have only been recently developed to a suitable form for feasibility testing.

6.1.2.2.4 Magnetohydrodynamic

In this form of static power conversion, an extremely high temperature, highly energized plasma interacts with an applied magnetic field, to produce electric power[5]. Efficiencies on the order of 20 percent are postulated. The concept has only begun to be tested for feasibility.

6.1.3 Heat Rejection

The heat rejection subsystem serves to reject, using radiative heat transfer to black body space, that heat which is not converted into electrical power. Types of heat rejection subsystems are: pumped loop, heat pipe, liquid sheet/droplet, and bubble membrane.

Waste heat rejection is required for all power conversion technology options. Waste heat rejection at high temperature affords the benefit of smaller radiative surface areas, implying less mass. The two principal forms of radiators that have been applied or proposed for space are direct pumped loop radiators and heat pipe radiators.

The direct pumped loop radiator employs radiator tubes connected to a common manifold in which the heat transfer fluid, liquid or gas, is circulated from the waste heat exchanger of the power conversion subsystem through the radiator tubes, where it is cooled. A break anywhere in the radiator loop would lead to a loss of the coolant from an entire radiator subsection.

The heat pipe radiator employs a large number of individual heat pipes. Since each heat pipe is a separate closed system, a break in one of them represents only a small loss in the capacity of the radiator, thus enhancing the overall reliability of the system.

Development of advanced radiator designs has focused on reducing the mass. The emphasis in heat pipe radiators has been on lightweight materials, such as carbon-carbon composites and ceramic fiber material, which will be compatible with the required working fluid. Advanced heat rejection concepts include liquid sheet/droplet and bubble membrane.

6.1.4 Power Management and Distribution

The power management and distribution (PMAD) subsystem serves to condition, transmit, and process the electric power used in the thruster. Technology options are categorized on a material basis.

Electric power produced by the power system most frequently must be altered in its form for use by the electric thrusters, depending on the form of the output power and the specific type of thruster used. Either the voltage, frequency, or both may have to be changed. At the very least, the power must be distributed from the point of its generation and put in usable form for the thrusters. The result is that a significant amount of electrical and electronic hardware will be required for power management and distribution. The components available with the present-day silicon technology must be cooled to maintain them at temperatures of approximately 300°K. Even though the high efficiencies of these components lead to low heat rejection rates, the low temperature heat rejection subsystems associated with them will have large radiator areas and mass. Advanced development is needed to attain electrical and electronic components, fabricated from Gallium Arsenide, Aluminum Gallium Arsenide, or Silicon Carbide, which can operate at higher temperatures and thus, greatly reduce the area and mass of their radiators.

6.1.5 Electric Thrusters

The electric thruster subsystem serves to accelerate a propellant, generating thrust Types of electric thrusters fall under the headings of: steady state electrostatic, steady state electromagnetic, pulsed electromagnetic, pulsed electrothermal/electromagnetic. For each concept, a basic description, projected or demonstrated specific impulse range, projected or demonstrated input power range, the form of the input power required, and candidate propellants are given.

6.1.5.1 Steady-State Electrostatic Concept

"Ion engine" is the term used for the steady state electrostatic concept. In ion engines, propellant atoms are ionized by electron bombardment and the resultant ions are accelerated to high velocities by an electrostatic field applied between two closely spaced electrodes (Figure 6.8). The exhaust beam of positive ions is neutralized by electron injection. The demonstrated specific impulse of these devices is 1,600 to greater than 20,000 seconds. A steady-state power source, supplying kilovolts at ten to hundreds of amperes is required. The noble gases, alkali metals, and mercury have been used as propellants. Present research emphasis is on the use of noble gases. The ion engine is highly efficient with demonstrated efficiencies of greater than 70 percent, and is well understood, with a substantial development history.

Ion engines have been tested in space several times: the first ballistic test flight was in 1964, and the SERT II (Space Electric Rocket Test) orbit test extended from 1970 to 1981. The 2.7 kWe J-series mercury ion engine was developed nearly to flight readiness for NASA's Solar Electric Propulsion Stage (SEPS) program, and engines at the 1 kWe power level are commercially available. A 250 kWe thruster, 1.5 m in diameter, was demonstrated in 1968. The principle advantage of ion engines is that the electrostatic acceleration process is efficient (very near 90% of input power is converted to beam power). This enables the development of very efficient engines, and minimizes the thermal loading on the engine structure allowing the engines to be self-radiating even at input levels of hundreds of thousands of kilowatts. Ion engines are under development in the U.S., Japan and Europe. Scaling ion engine operation to the megawatt level will require the development of long life, large area accelerator grids, and hollow cathodes which can operate at hundreds to thousands of amperes.

6.1.5.2 Steady-State Electromagnetic Concepts

6.1.5.2.1 Magnetoplasmadynamic (MPD) Thruster

In the MPD thruster, current flowing through ionized gas in a coaxial thrust chamber interacts with a magnetic field to produce thrust (Figure 6.9). In the self-field MPD thruster, the magnetic field is generated by the current flowing between concentric electrodes. In the applied-field thruster, an external field coil is used to augment the self-induced magnetic field providing additional thrust mechanisms. MPD thruster operation is characterized by a specific impulse range of 2,000 to 10,000 s. At the megawatt level, the thruster requires steady-state input power in the form of tens of kiloamperes and hundreds of volts. Candidate propellants include hydrogen, ammonia, the noble gases, and alkali, with hydrogen and ammonia currently being the most promising. The potential advantages of this device include simplicity of design, the ability to process megawatts of power in a relatively compact device, and a large experience base.

The MPD thruster has been investigated for over 25 years, with ongoing research and development efforts in the U.S., U.S.S.R., Japan and Europe. In the U.S., 50 hours of steady-state operation at 122 kWe has been demonstrated, in addition to quasi-steady (pulsed) operation up to 10 MWe. Operation of a steady-state device in Germany has reached 600 kWe, while unsubstantiated claims of operation up to 10 MWe have come from the Soviet Union. Steady-state efficiencies of 30 percent on hydrogen and 60 percent on lithium have been reported for operation at input powers below the 100kWe level. The chief developmental requirements are for demonstration of steady-state operation at megawatt power levels, with efficiency greater than 50 percent and thruster lifetime greater than 5,000 hours.

6.1.5.2.2 Electron Cyclotron Resonance (ECR) Engine

In the ECR engine, microwave power is used to ionize propellant gas, which is electromagnetically accelerated in a diverging magnetic field (Figure 6.10). The frequency of the circularly polarized microwave radiation and the applied magnetic field strength are selected so that the frequency of the electron cyclotron motion about the magnetic field lines matches that of the microwaves. This resonance efficiency couples the microwave power into plasma. A range of specific impulses from 2,000 to 10,000 s is projected for the ECR engine. The engine requires steady-state microwave power. Candidate propellants include the noble gases and possibly oxygen. The absence of electrodes in the ECR engine may facilitate development of engines with long useful lifetimes. In addition, the electrodeless design also allows the possibility of using certain propellants containing oxygen, which may be available in situ at mission destinations throughout the solar system.

Developed in the 1960s, laboratory characterizations at power levels of < kWe have demonstrated efficient (over 97 percent) coupling of the microwave power to the ionized gas. A basic theoretical description is being developed which will be used in conjunction with experiments to verify the acceleration process and to study loss mechanisms. Development of the ECR engine requires the completion and verification of the theoretical description subscale tests to demonstrate high performance and identify wear mechanisms, and scaling up to the megawatt power levels including thermal management.

6.1.5.2.3 Ion Cyclotron Resonance (ICR) Engine

The ICR engine uses radiofrequency power to accelerate ionized propellant in cyclotron motion about magnetic field lines (Figure 6.11). The propellant is convected in a diverging magnetic field to produce thrust. A range of specific impulses from 5,000 to 10,000 s is projected. The ICR requires steady-state radiofrequency power. Heavy atomic and molecular ions, such as Xe, I_2 and IF_5 are candidate propellants. The potential advantages of the ICR engine are similar to those of the ECR engine: an electrodeless design which may lead to long life, and highly efficient coupling between the input radiofrequency power and the ionized propellant.

The ICR concept was developed in the 1960s, and was demonstrated at 0.5 kWe level. Higher power devices are in the analytical study stage, however, key high power components are available. Developmental requirements include detailed thruster design and demonstration; investigation of power coupling mechanisms; and possible dissociation of molecular ions at high power density; and study of system issues, including magnet weight and power requirements, and engine thermal management.

6.1.5.2.4 Variable Specific Impulse Plasma Rocket

The Variable Specific Impulse Plasma Rocket (VSIPR), based on the mirror machine developed for fusion research, ionizes propellant gas with electron cyclotron resonance (ECR) heating, then further heats the resulting plasma with radiofrequency power (Figure 6.12) The heated plasma is exhausted through a hybrid magnetic/ conventional nozzle that uses a thin hypersonic gas envelope for thermal insulation and magnetic field detachment. The projected range of specific impulse is 800 to 35,000 s, using hydrogen as the propellant. Steady-state radiofrequency power is the primary power input. A wide range of thrust and specific impulse at constant power may be achievable with this device which would allow optimization of propulsive efficiency throughout a mission. The electrodeless design may also lead to long engine lifetimes.

Pulsed operation at power levels up to 100 kWe have been demonstrated in experimental studies that began in 1989. Three dimensional, time dependent modelling of the plasma and gas dynamics in the device have been performed. The ongoing theoretical effort includes modelling of power absorption in the propellant. Important near-term development requirements include the optimization of cold gas injection for nozzle protection and plasma detachment from the magnetic field, measurement of performance, and system studies in the context of the multimegawatt mission applications of interest.

6.1.5.3 Pulsed Electromagnetic Concepts

6.1.5.3.1 Deflagration Thruster

The deflagration thruster is a pulsed, coaxial plasma gun (6.13). A current discharge begins in the rear of the thrust chamber and propagates downstream, propelled by the interaction of the distributed current with its own induced magnetic field. Propellant gas is accelerated in the moving discharge. The anticipated range of specific impulse is 5,000 to 30,000 s. The deflagration thruster consumes power pulses with mega-amperes of current at kilovolt levels. Deuterium, hydrogen, xenon and plastic are possible propellants. Potential advantages of this concept include high specific impulse capability with high thrust and a highly directed thrust vector. There may also be decreased electrode erosion compared with the steady-state, megawatt level MPD thruster because of the strong magnetic field near the electrodes.

The deflagration thruster has over 25 years of development for NASA, DOE and DOD applications. The device has been demonstrated at the gigawatt power level for pulses up to 12 microseconds. Preparation of the deflagration thruster for the missions of present interest requires thrust stand measurement of performance, and the development of a high repetition rate pulsed power network. Thruster wear mechanisms and thermal management at high pulse rates need to be investigated. Development of a fast pulsed gas injection system or the use of a solid propellant ablation method is also needed.

6.1.5.3.2 Pulsed Plasmoid Thruster

In this concept, propellant is ionized and formed into a toroid-shaped plasma (Figure 6.14). The plasma is expanded in a diverging, electrically conducting nozzle. Magnetic and thermal energies are converted to directed kinetic energy by interaction of the plasma with the image currents which it generates in the nozzle. A specific impulse range of 5,000 to 20,000 s is projected. The required power is in the form of pulses of mega-ampere level current. Hydrogen, deuterium, lithium, nitrogen, carbon dioxide, sodium and aluminum are possible propellants. Potential advantages of the pulsed plasmoid thruster include its power ratio (0.3 kg/kWe). Ionization losses in the device are projected to be a small fraction of the total input power.

The pulsed plasmoid thruster is presently in an analytical study phase. The inductive initiation of a discharge has been experimentally demonstrated. Development of the thruster will require analyses of the losses incurred during initiation and acceleration processes, and development of high repetition rate power management and propellant injection systems.

6.1.5.3.3 Pulsed Inductive Thruster

In the pulsed inductive thruster (Figure 6.15), a high current pulse through a coil in the wall of the thruster induces ionization of the propellant gas. Current induced in the ionized gas interacts with the coil current, resulting in a force which expels the propellant. The device is characterized by a specific impulse between 3,000 and 5,000 s. Input power in the form of 5 to 10 kilojoule pulses, with pulse durations of tens of microseconds, is required. Air, nitrogen, ammonia, carbon dioxide and biowaste have been suggested as possible propellants. The potential advantages of this concept are the electrodeless design, which may lead to long engine lifetimes, and the ability to use propellants (nitrogen, carbon dioxide) which could be obtained in situ in the solar system.

The device has been under development for several years, and has been demonstrated in the laboratory at pulsed energy levels on the order of 5 kilojoules. Development of the pulsed inductive thruster for the missions of present interest will require performance measurements at the appropriate power levels, optimization of the propellant injection process, and engine thermal management designs for high power, rapid pulse rate operation. The input power circuit inductance must be minimized, and a fast discharge switch requires development.

6.1.5.4 Pulsed Electrothermal/Electromagnetic Concept

In this concept, propellant in a liquid form is injected into a discharge chamber where energy is added by a short, high energy pulse (Figure 6.16). The heated propellant is exhausted through a nozzle. The variant of primary interest uses an electromagnetic body force to further accelerate the flow, with a specific impulse of 4,000 to 6,000 s projected. Pulsed power with a current of tens of kiloamperes and voltages of hundreds of volts is required. The primary candidate propellants are liquid nitrogen or hydrogen. A principal potential advantage of the pulsed electrothermal thruster is a relatively low frozen flow loss due to the high nozzle pressure. The high nozzle pressure also yields a high thrust density. In addition, the propellant flow is continuous, contrasted with the pulsed flow of some other pulsed thrusters; this simplifies the propellant feed apparatus.

The pulsed electrothermal thruster with electromagnetic acceleration has not been experimentally demonstrated, although the pulsed electrothermal thruster without electromagnetic acceleration has demonstrated 40 percent efficiency at a specific impulse of 1500 s (on ethylene). Performance of the thruster with liquid nitrogen and hydrogen, at the power levels of interest, must be characterized. Application of this concept also requires the development of high repetition rate, pulsed power supply.

6.2 RECENT MAJOR PROGRAMS RELATED TO NEP TECHNOLOGY

Other programs, both recent and on going, provide major contribution to the technology base for NEP system development. Two outstanding examples of such programs are the SP-100 program and the SDI Multimegawatt Space Nuclear Power Program.

The SP-100 program, sponsored jointly by NASA, DOE, and DOD has the objective of developing a space-rated nuclear power system capable of producing 100 kWe for application to appropriate space missions[6]. The design consists of a refractory metal alloy-clad pin-type-fueled reactor cooled by liquid lithium. The lithium transfers heat to thermoelectric converters which produce DC power. Waste heat is transferred to heat pipes where it is rejected to space. The fuel pins are composed of Uranium Nitride fuel enclosed in Niobium-1Zirconium cladding and form a reactor core which has a rating of about 2.3 MWt, with a reactor outlet lithium temperature of 1375°K. The thermoelectric converters generate about 108 kWe at 200 volts DC with a hot side temperature of about 1350°K. The average radiator temperature is about 790°K. The total system mass including shielding is estimated at 4600 kilograms.

The multimegawatt (MMW) program started in the mid 80s to develop a nuclear power source for the Space Defense Initiative weapon platforms. Power sources were designed in the multimegawatt power range (exact power levels are classified) for both open cycle and closed cycle operation. Three types of closed cycle systems were funded to final evaluation prior to suspension of the program. These three systems were Brayton-based, Rankine-based, and Incore Thermionic power systems.

6.3 TECHNOLOGY READINESS

The panel judged the NEP subsystem technology options according to their projected technology readiness. Table 6.2 displays the projected readiness of those technology options in Table 6.1 that would apply to the SEI missions. Within Table 6.2, any of the options listed in the middle column could be ground tested in a relevant environment - Technology Readiness Level 5 (TRL-5) - by the year 2005 (with adequate funding) and have been classified as enabling for the SEI missions. Those options not expected to reach TRL-5 by 2005 are listed in the right-hand column of this table, and have been classified as "innovative". The year 2005 was chosen so that the technologies would be available in time to be considered for the SEI missions.

K-Rankine, Brayton, and Incore Thermionic based power systems are the recommended choices for SEI applications in the 2008-2020 time frame, which require TRL-5 by 2001-2010. Other power system concepts are either suitable only for NEP applications requiring less power, or are presently deemed to have benefit-to-risk ratios too low as to expect their readiness in this time frame (innovative). All of the reactor concepts (except for Incore Thermionic) listed in the middle column of Table 6.2 are relevant to either Rankine or Brayton based power systems.

Ion and MPD propulsion systems are the recommended choices for SEI applications in the 2008-2020 time frame, requiring TRL-5 by 2001-2010. Ion propulsion is more mature than MPD propulsion, but has the disadvantage of being less power dense, requiring large thruster areas to accomplish the SEI missions. MPD, while being compact and having demonstrated high power operation, must show suitable efficiencies. Both propulsion technologies must demonstrate acceptable life. Other propulsion system concepts are either suitable only for applications requiring less specific impulse, or are presently deemed to have benefit-to-risk ratios too low as to expect their readiness in this time frame (innovative). If further studies indicate an advantage to developing any of these technologies, and feasibility issues have been resolved, then with adequate funding any of these technologies could be made available within the needed time frame.◆

NEP SUBSYSTEM TECHNOLOGY OPTIONS

REACTOR	POWER CONVERSION	THERMAL MANAGEMENT	POWER MANAGEMENT & DISTRIBUTION	THRUSTER
Liquid Metal Cooled Growth SP-100 Advanced Pin Cermet Boiling Potassium	Dynamic Rankine Brayton Stirling	Heat Pipe Refractory Metal Carbon-carbon Ceramic Fabric	Silicon Gallium Arsenide Aluminum-Gallium Arsenide Silicon Carbide	Steady State Electrostatic Ion
Gas Cooled NERVA Derived Particle Bed Pebble Bed Cermet	Static Thermoelectric Thermionic in core ex core Electrochemical Magnetohydro-dynamic	Pumped Loop Liquid Sheet/ Droplet Bubble Membrane		Steady State Electromagnetic Magnetoplasma-dynamic (MPD) Electron Cyclotron Resonance Ion Cyclotron Resonance Variable Specific Impulse
Incore Thermionic Vapor Core				Pulsed Electromagnetic Deflagration Pulsed Plasmoid Pulsed Inductive
				Pulsed Electrothermal/ Electromagnetic Pulsed Electrothermal - MPD

Table 6.1

PROJECTED TECHNOLOGY READINESS OF NEP TECHNOLOGY OPTIONS FOR SEI MISSIONS

NEP SUBSYSTEM	TECHNOLOGY OPTIONS THAT COULD REACH TRL-5 BY YEAR 2005 (WITH ADEQUATE FUNDING)	TECHNOLOGIES NOT EXPECTED TO REACH TRL-5 BY YEAR 2005
Reactor	Growth SP-100, Advanced Pin Cermet, NERVA Derived Particle Bed, Pebble Bed Incore Thermionic	Boiling Potassium Vapor Core
Power Conversion	Rankine Brayton	Electrochemical Magnetohydrodynamic
Heat Rejection	Refractory Metal Heat Pipe Carbon-carbon Heat Pipe	Ceramic Fabric Heat Pipe Liquid Sheet Radiator Bubble Membrane
Power Management and Distribution	Silicon, Gallium Arsenide Aluminum Gallium Arsenide Silicon Carbide	
Thrusters	Ion Manetoplasmadynamic (MPD)	Very high power MPD Electron Cyclotron Resonance Ion Cyclotron Resonance Variable Specific Impulse Deflagration Pulsed Plasmoid Pulsed Inductive

TABLE 6.2

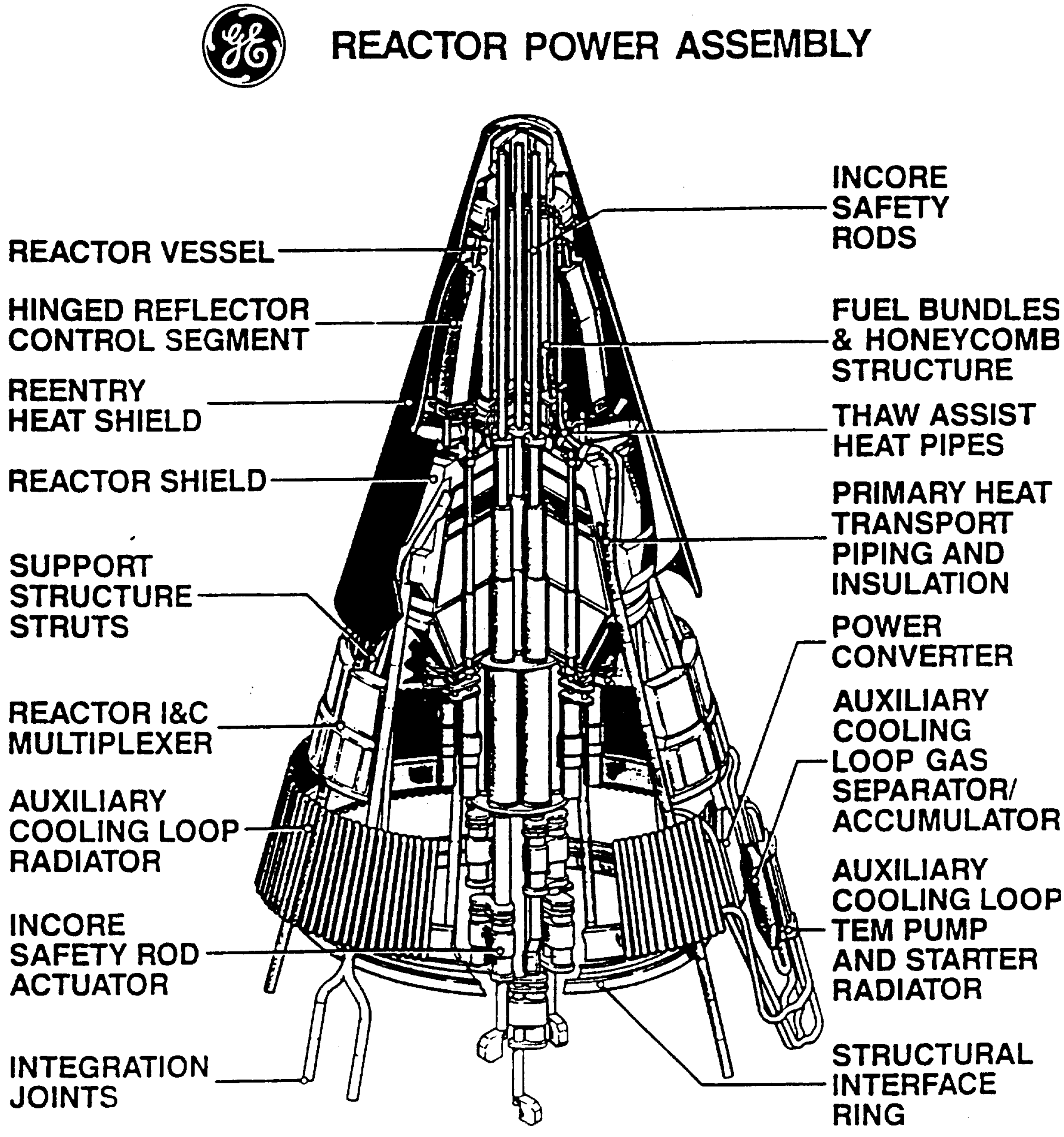
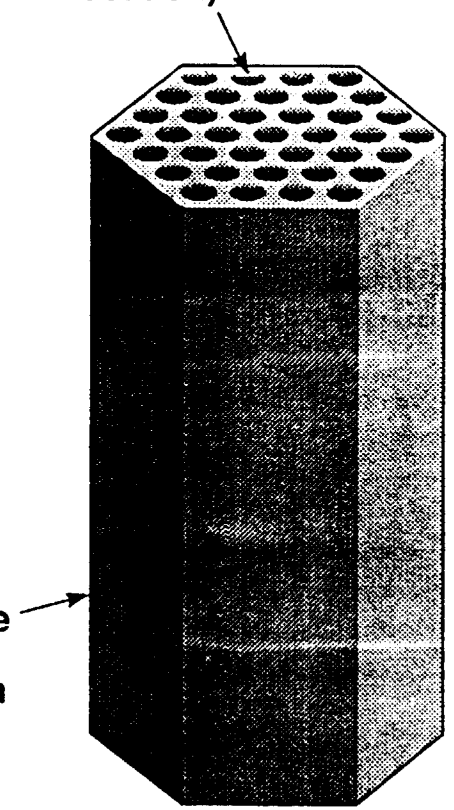


Figure 6.1: SP-100 Reactor Power Assesbly

Uranium Nitride Cermet Fuel



- High strength
- High thermal conductivity
- Low thermal expansion
- High temperature capability
- High burnup capability
- Favorable safety characteristics
  - Small coolant fraction
  - Intrinsic fission gas retention

90c-23-12
M859

Figure 6.2

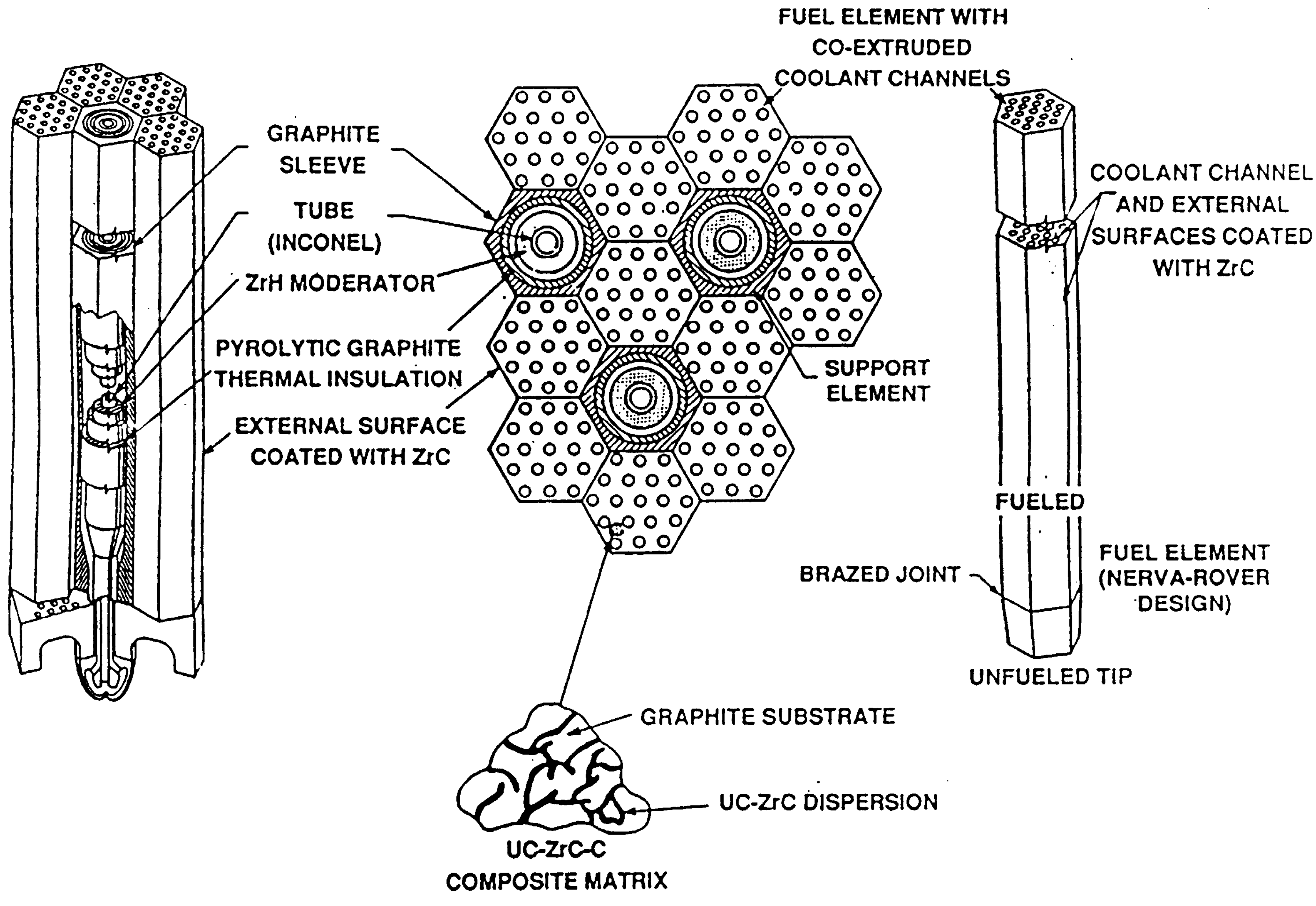


Figure 6.3: UC-ZrC-C Composite Matrix Fuel Element

GENERAL ATOMICS

ANATOMY OF THERMIONIC CELL

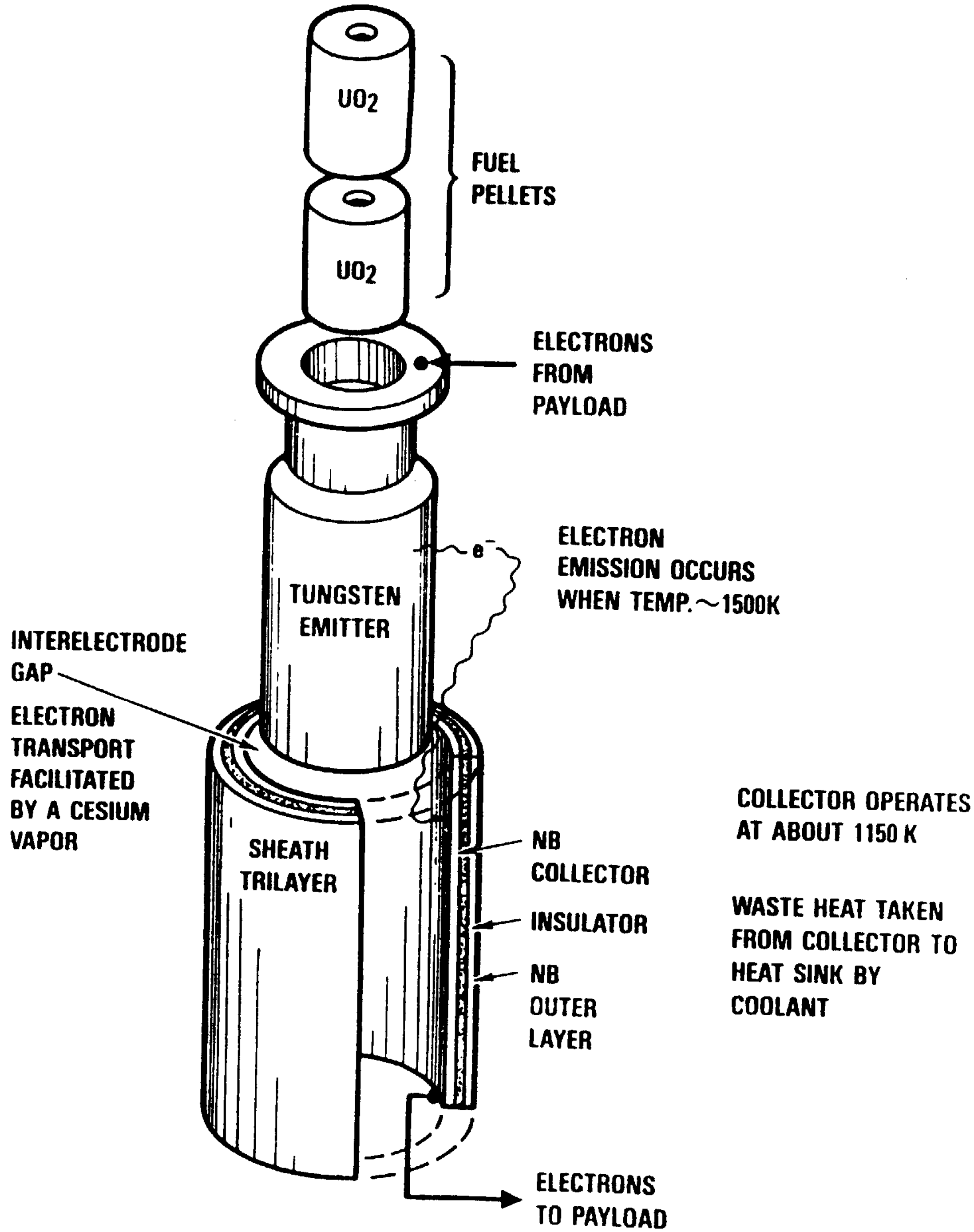


Figure 6.4

INNOVATIVE NUCLEAR SPACE
POWER & PROPULSION INSTITUTE

200 MWe ULTRAHIGH TEMPERATURE VAPOR CORE REACTOR WITH MHD GENERATOR SPACE POWER SYSTEM

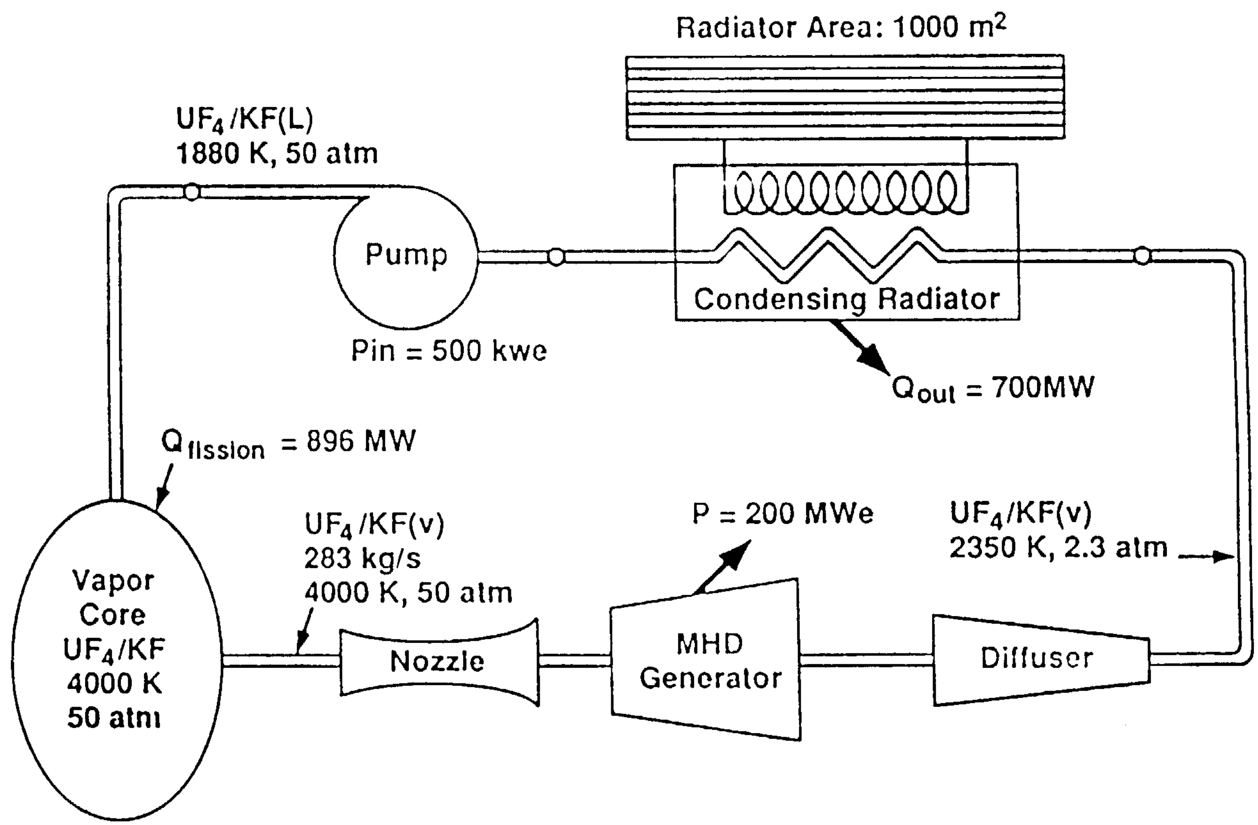


Figure 6.5

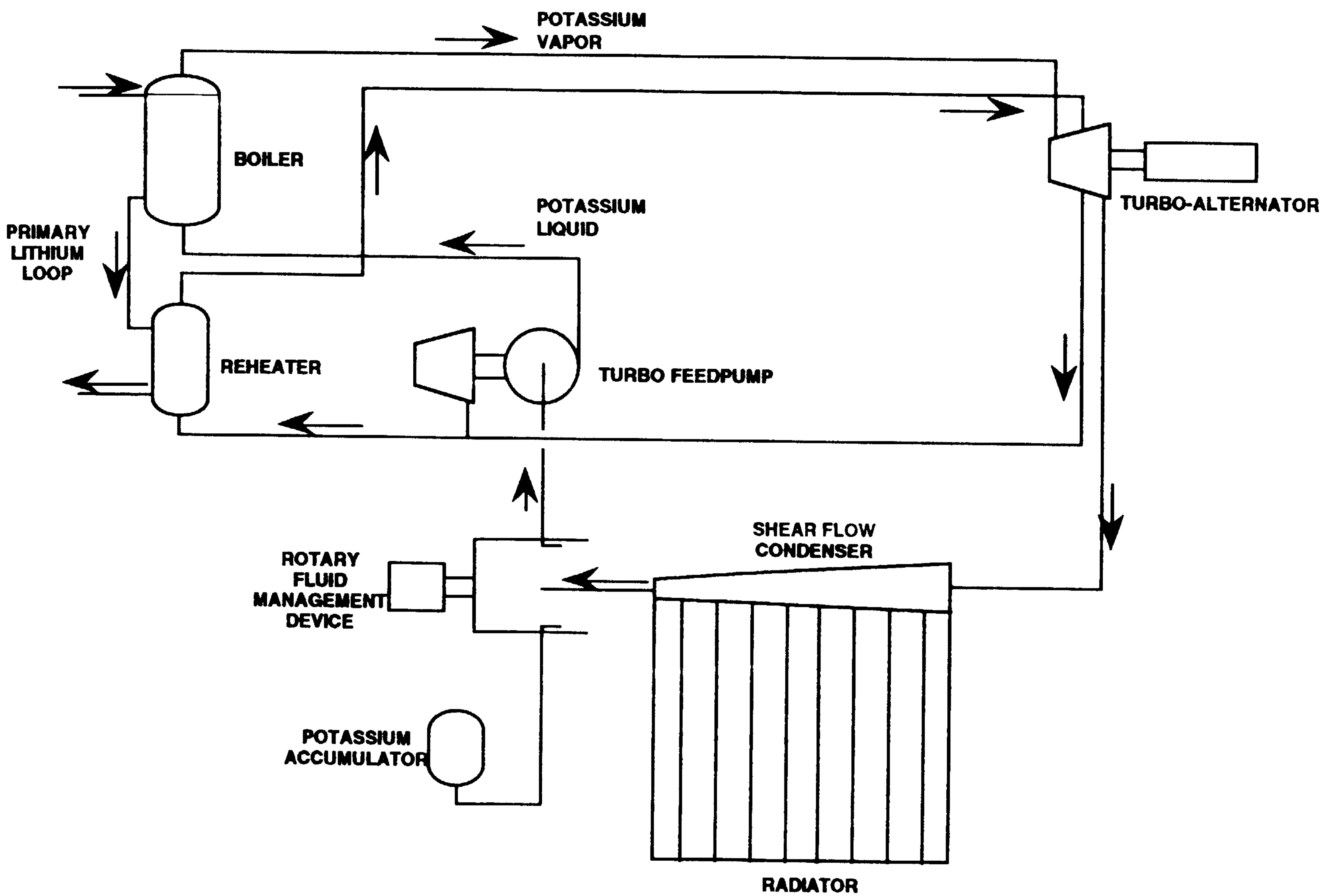


Figure 6.6: Potassium Rankine Power Process Flow Diagram

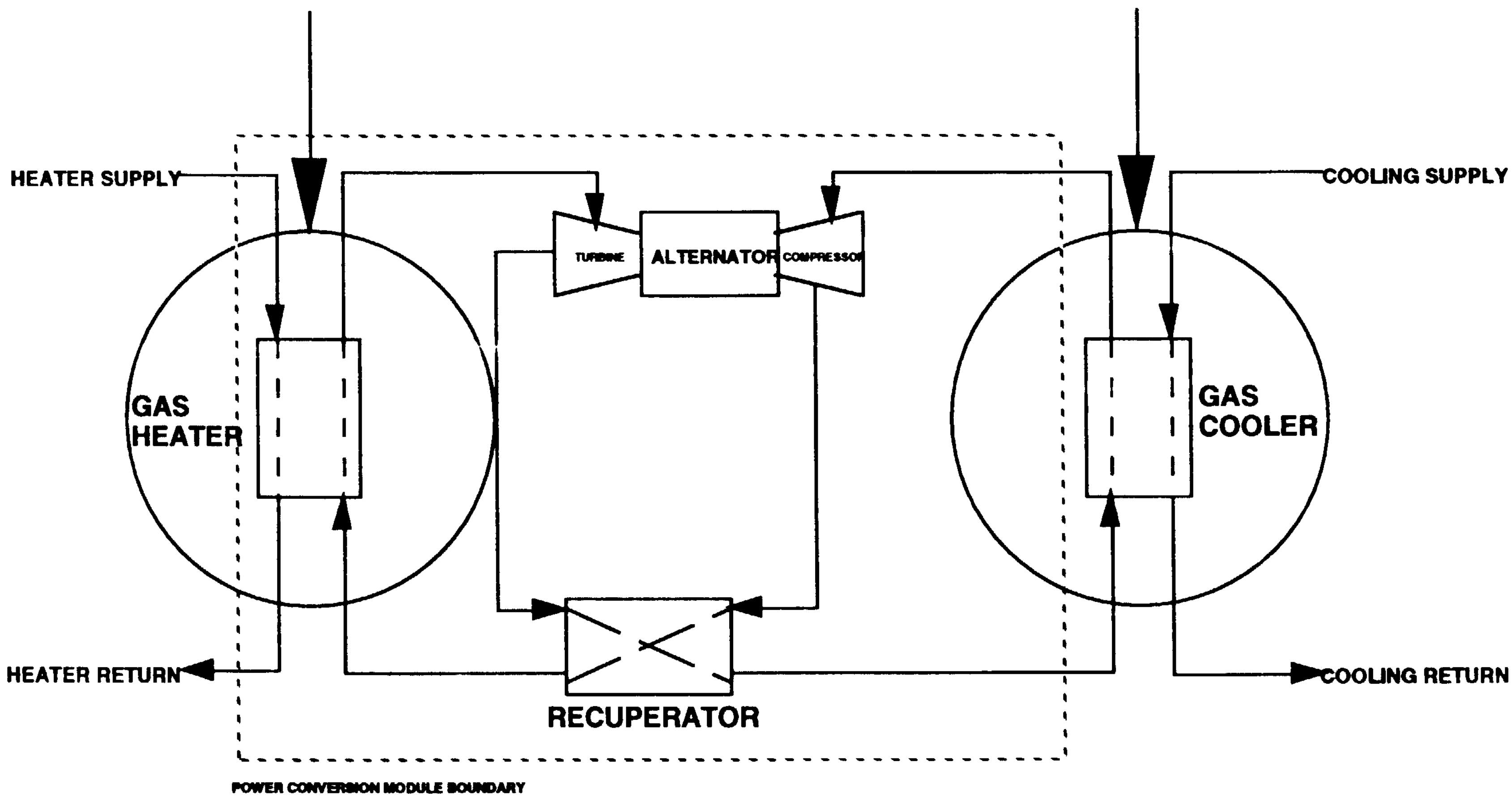


Figure 6.7: Brayton Process Flow Diagram

ION PROPULSION SCHEMATIC

HUGHES

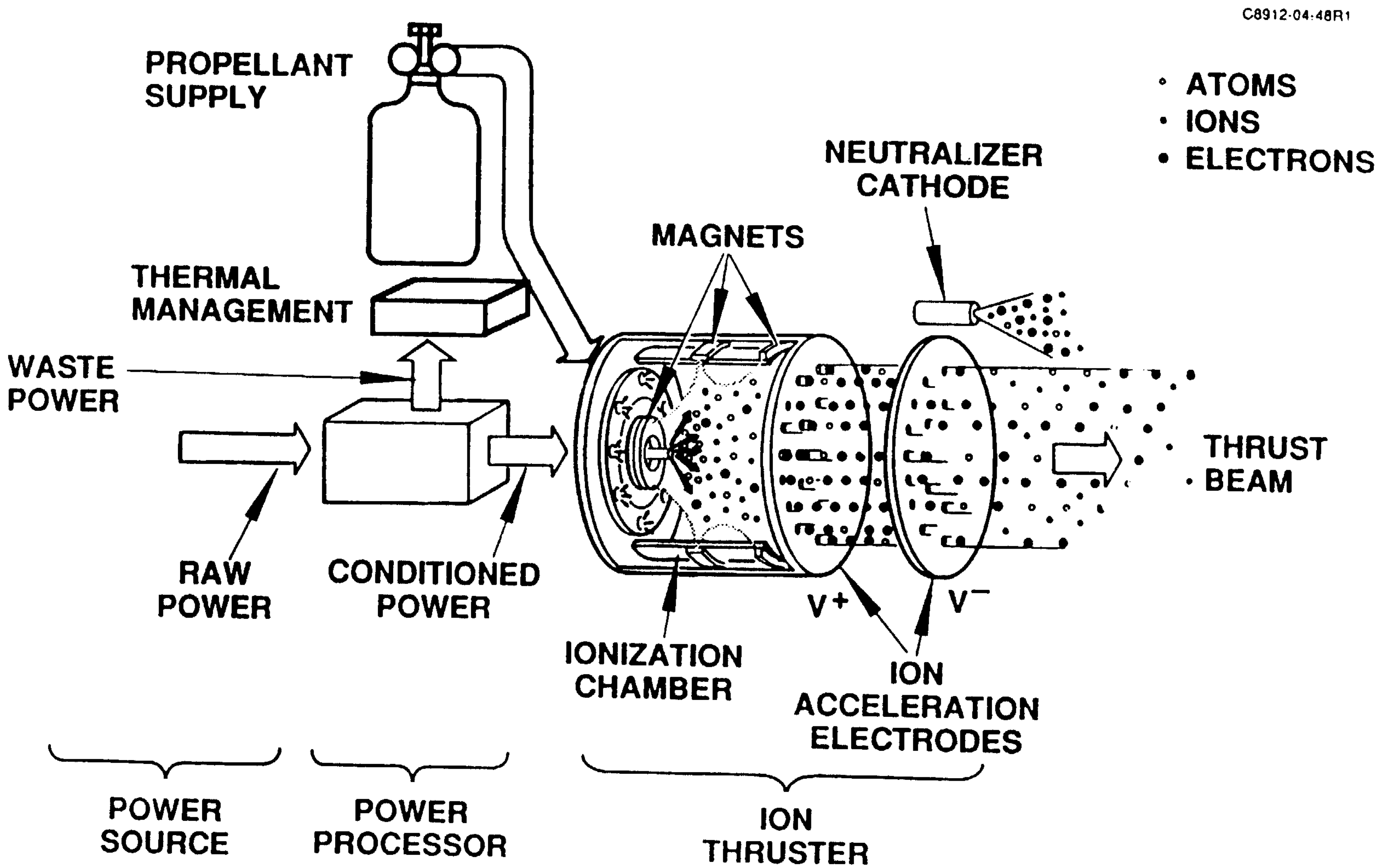
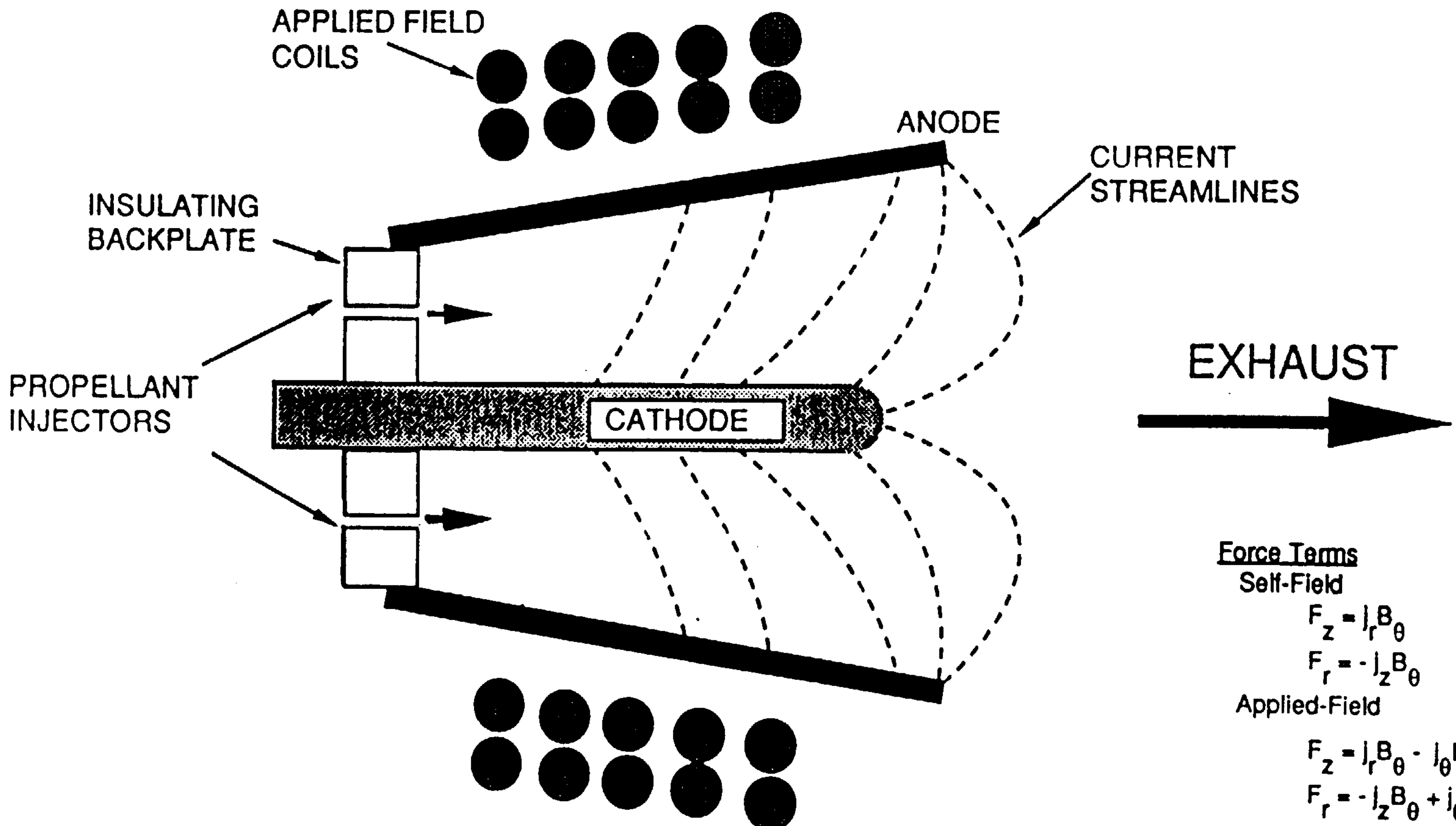


Figure 6.8



Force Terms

Self-Field

$F_z = j_r B_\theta$

$F_r = -j_z B_\theta$

Applied-Field

$F_z = j_r B_\theta - j_\theta B_r$

$F_r = -j_z B_\theta + j_\theta B_z$

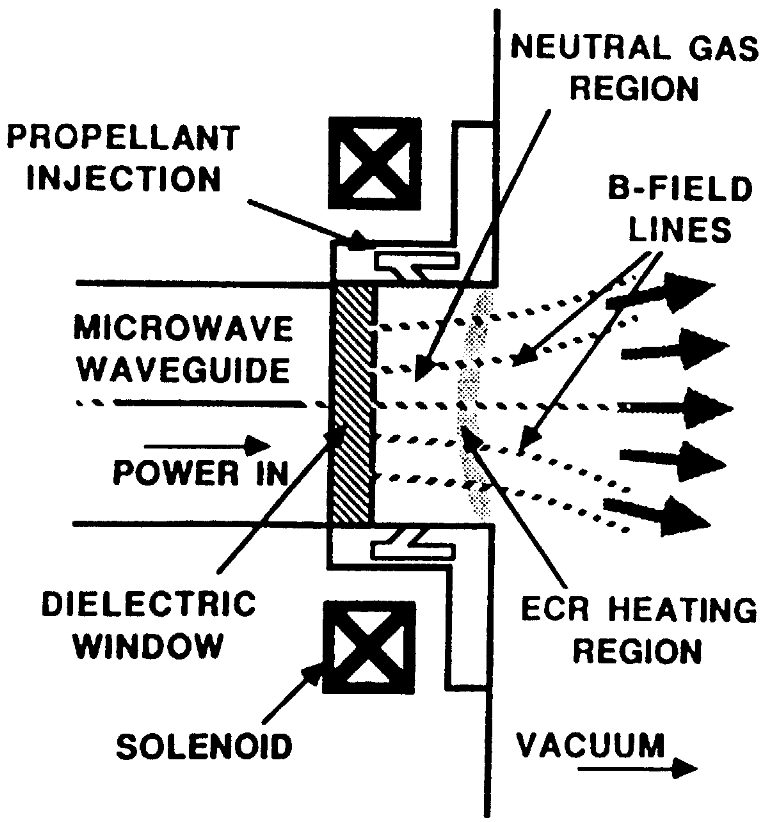
$F_\theta = j_z B_r - j_r B_z$

SIMPLIFIED MPD THRUSTER SCHEMATIC

Figure 6.9

JPL

THE ECR PLASMA ENGINE



CONCEPT:

MICROWAVE POWER IS USED TO CREATE A PLASMA WHICH IS ACCELERATED THROUGH A DIVERGING MAGNETIC FIELD

BENEFITS:

ELECTRODELESS DESIGN MAY ENABLE
- SCALABILITY FROM KW TO MW
- LONG LIFE
- HIGH EFFICIENCY
- CHOICE OF PROPELLANTS (e.g. lunar oxygen)

Figure 6.10

RF ION CYCLOTRON RESONANCE THRUSTER
Technology Description: Schematic

Excitation by Electrostatic Ion Cyclotron Waves
Acceleration by $\mu \nabla|B$ Force

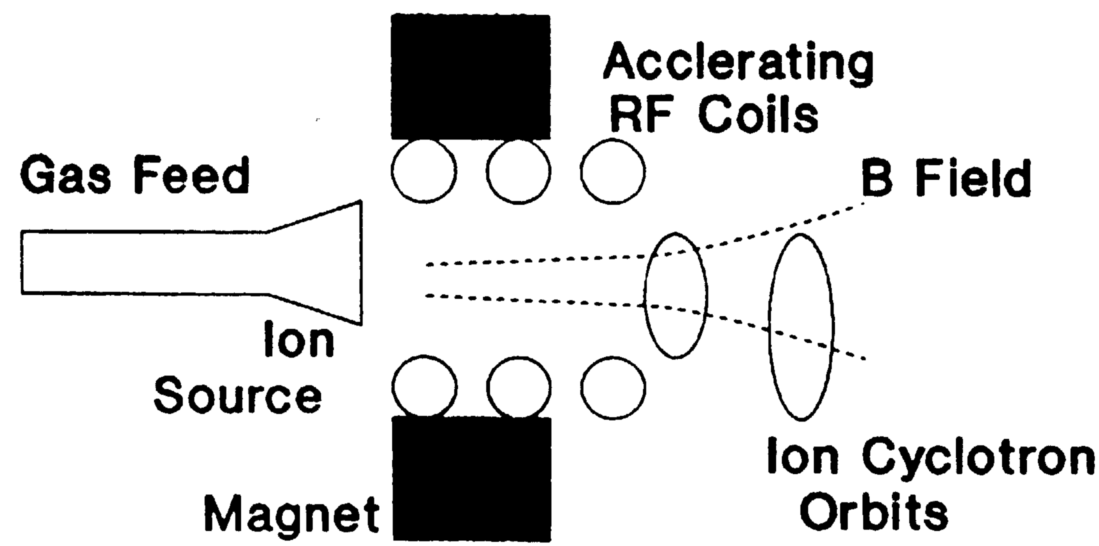


Figure 6.11

Variable I_{sp} Plasma Rocket Concept

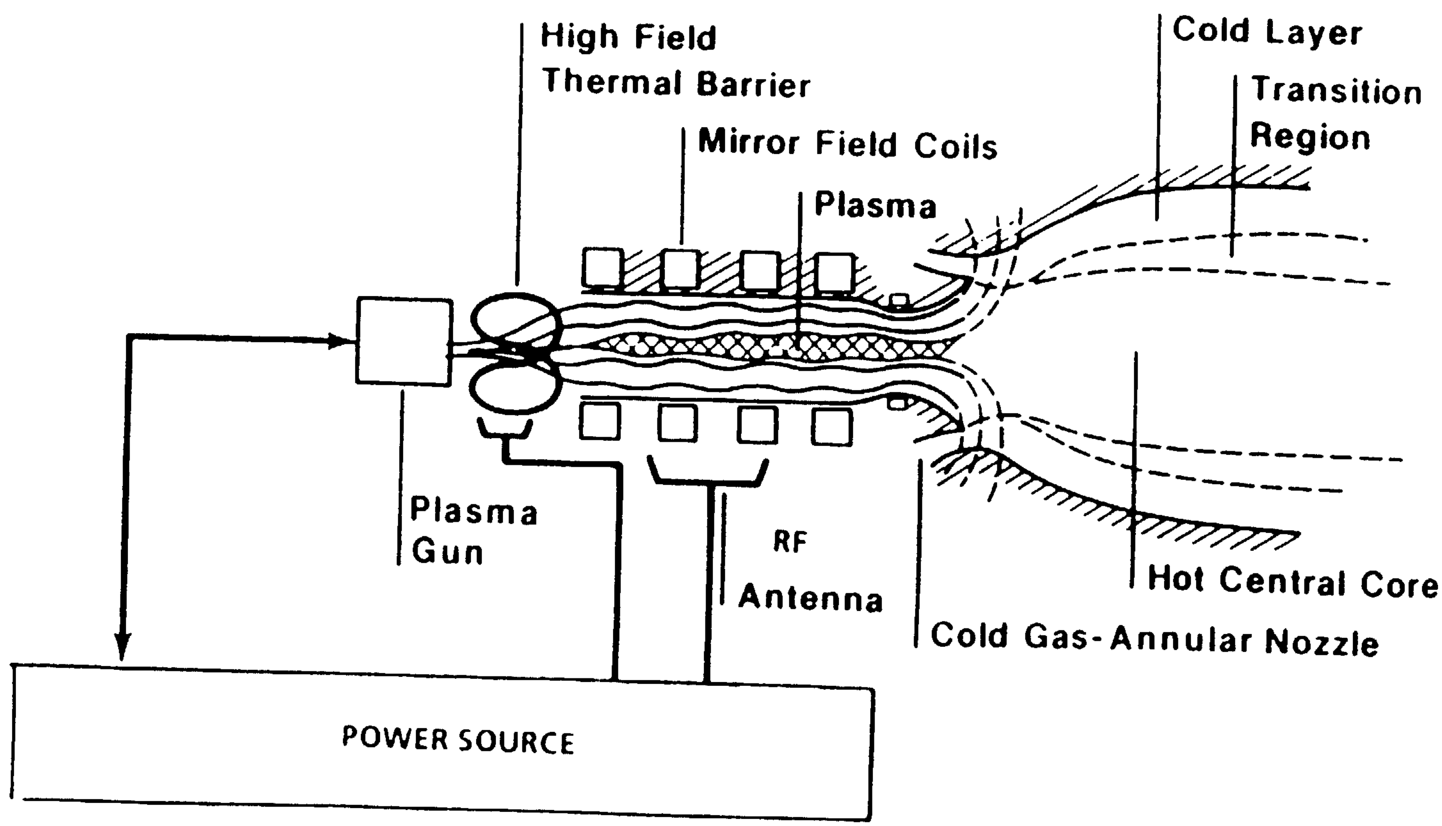


Figure 6.12

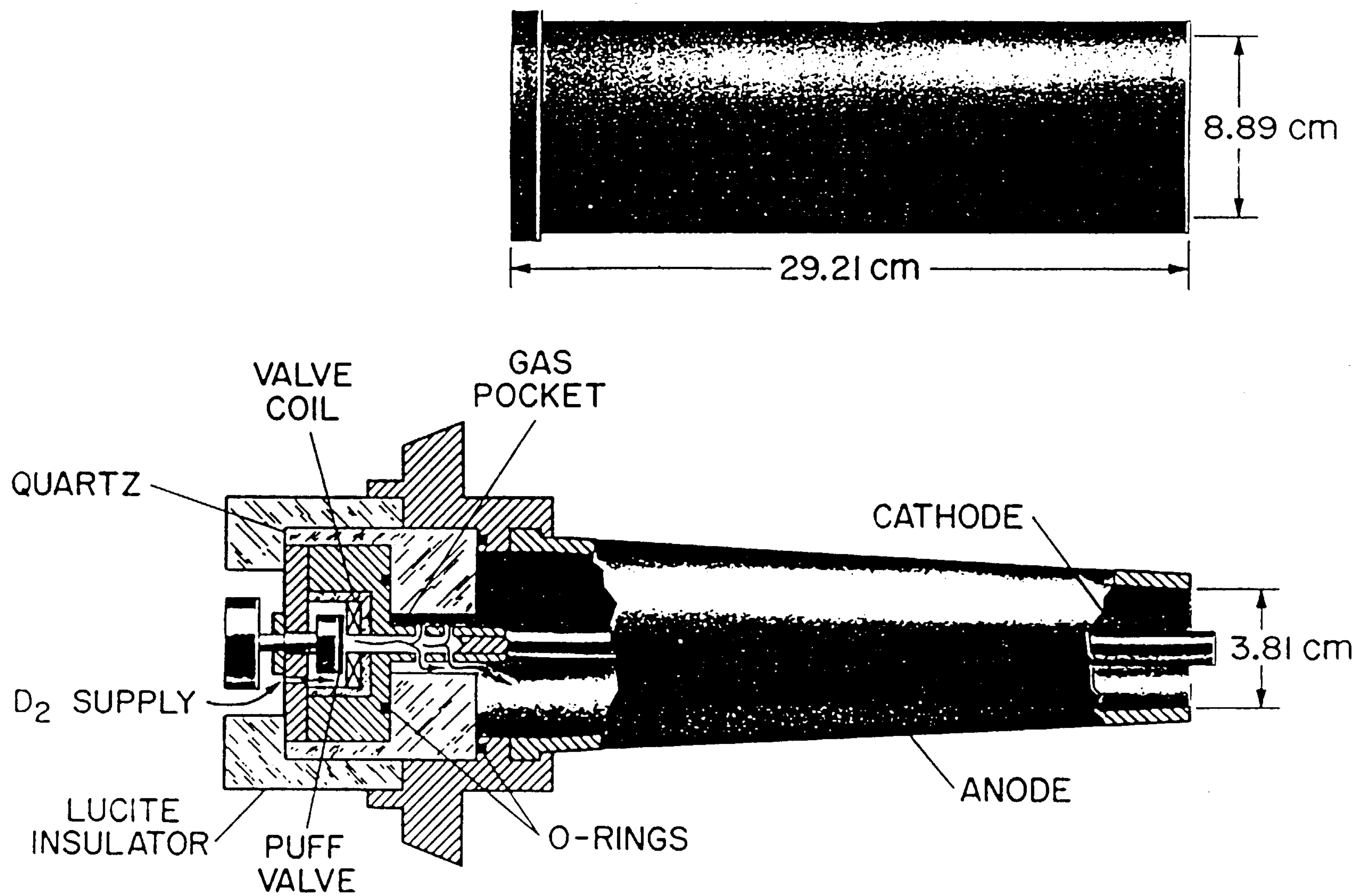


Figure 6.13: Deflagration Thruster

OPTIMIZED NOZZLE MINIMIZES ACCELERATION TIME

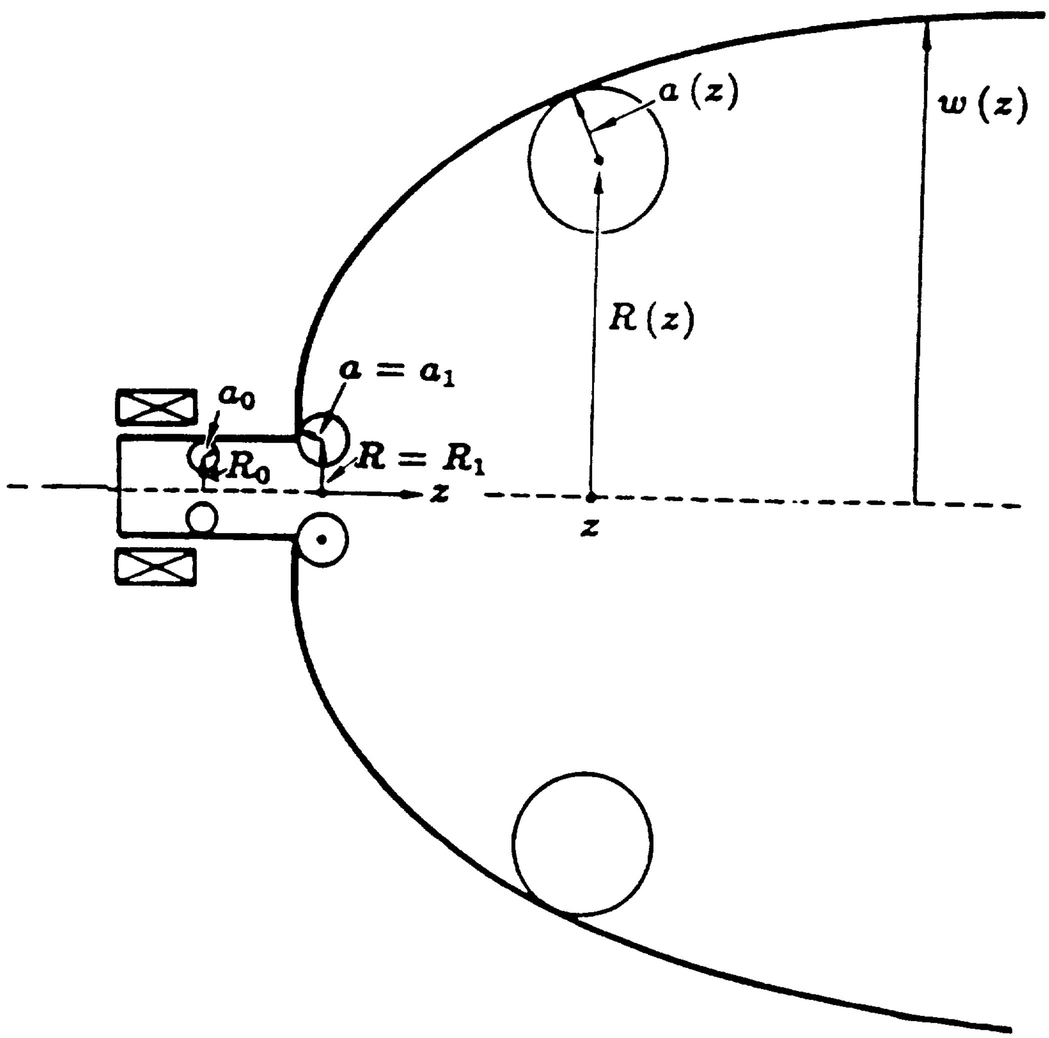


Figure 6.14: Pulsed Plasmoid Thruster

TRW Federal Systems Division
Space & Technology Group

Proposed Thruster for Mars Mission
Pulsed Inductive Thruster (PIT)

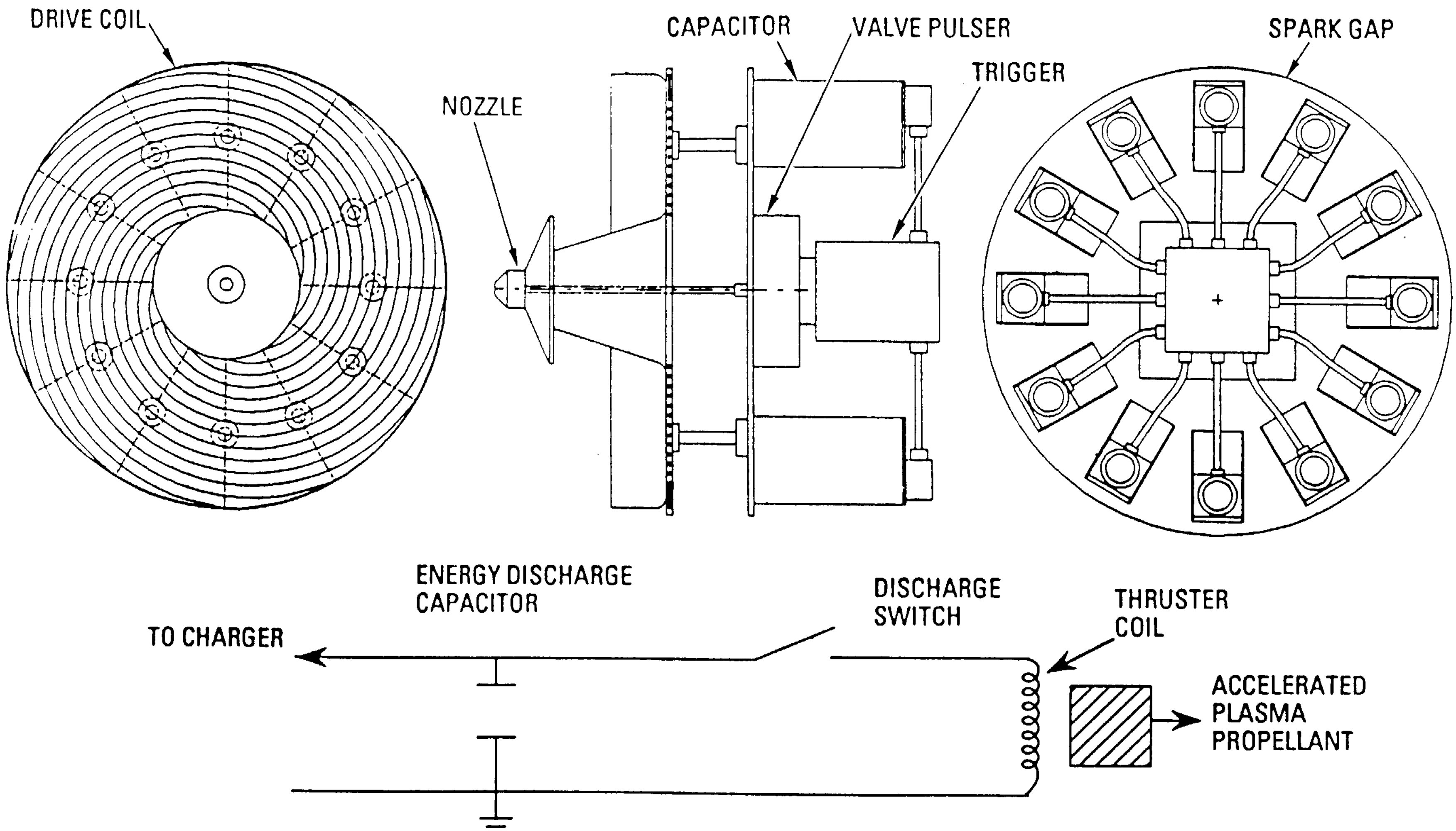


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Figure 6.15

MPD-PET THRUSTER

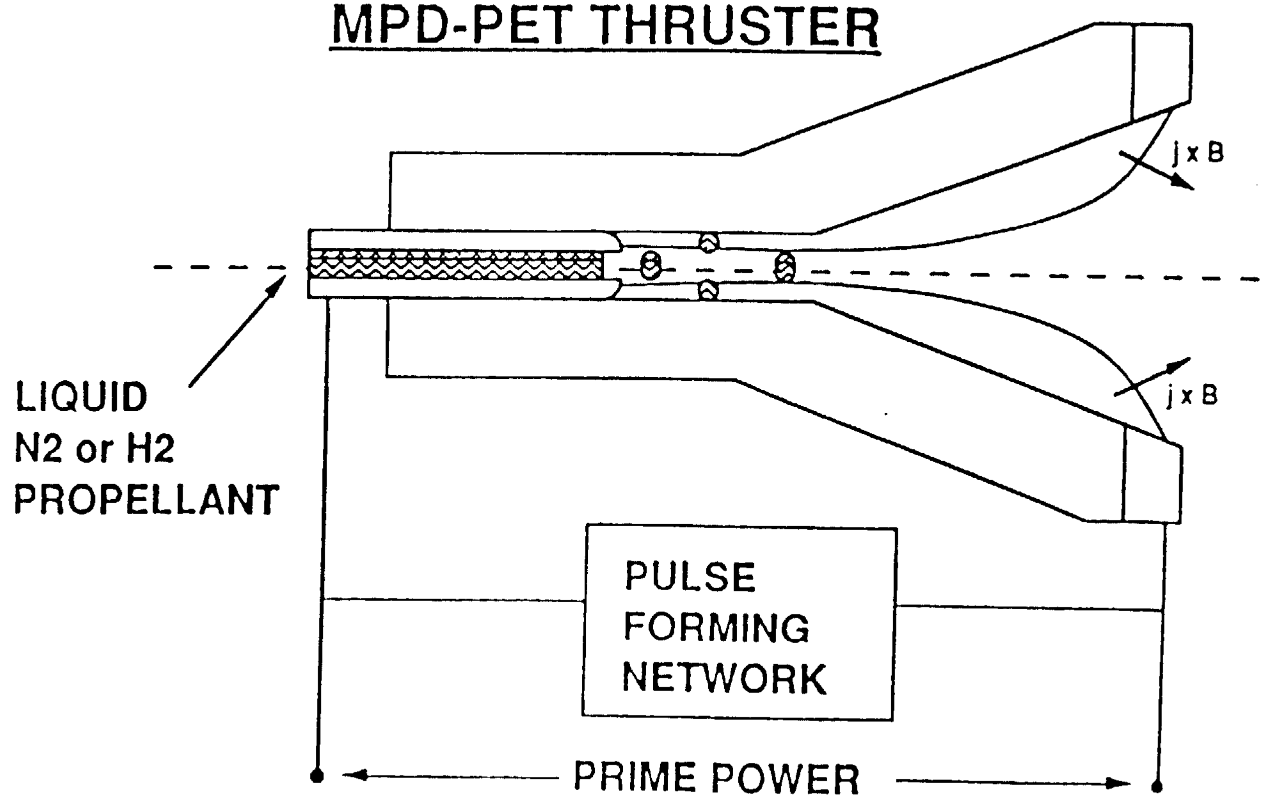

Figure 6.16

7.0 NEP SYSTEM CANDIDATES

Preceding sections of this report have presented a variety of applicable mission classes and technology options for NEP utilization. Major mission classes of interest include robotic interplanetary probes, lunar and Mars cargo missions, and piloted Mars missions. A number of component and subsystem technology options were also presented. Various combinations of these subsystem technologies can be compiled to provide complete NEP systems which address the above missions. Each mission will drive varying requirements on system power level, lifetime, shielding, reliability, readiness date, and allowable specific mass. Some system combinations will make more sense than others for certain mission categories, while other combinations will prove impractical due to conflicting technologies.

Table 7.1 represents a listing of the broad trade space of NEP subsystem technologies considered for this effort. Technologies are grouped into columns by subsystem, including reactor, power conversion, heat rejection, power management and distribution (PMAD), and electric propulsion. A wide range in maturity is evident across these technologies, ranging from proof-of-concept to existing development programs. Various reactor types were identified, including liquid-metal cooled, gas-cooled, in-core thermionic, and vapor core. Pin-type liquid-metal cooled reactors were separated into SP-100 reactor technology versus more advanced, higher temperature pin-type reactors. A large number of potential power conversion schemes were identified, both dynamic and static. Heat rejection was broken down into heat pipe, pumped loop, and liquid sheet or droplet concepts. Further distinction of heat pipe technologies was made by material. PMAD technologies are distinguished by operating temperature, voltage, and radiation hardening requirements, with high efficiencies and low masses the ultimate goal. A very broad range of electric propulsion technologies was identified, including steady state and pulsed thrusters, and varying voltage and current input requirements.

Although an almost limitless number of NEP systems can be obtained by arranging various combinations of these subsystem technologies, only a limited number of combinations will make sense for each of the above mission classes of interest. Certain technologies are incompatible with other technologies within a real system. Limitations on achievable power level, specific mass, and readiness date will further reduce the set of systems suitable for a given mission class.

7.1 CANDIDATE SYSTEMS BY MISSION CLASS

The above factors were considered along with the appropriate mission requirements on system power level, lifetime, shielding, reliability, readiness date, and allowable specific mass in order to identify appropriate NEP system candidates for each mission class. Table 7.2 lists the trade space of systems deemed most appropriate for application of NEP to interplanetary robotic probes and precursors. This relatively near term application drives requirements for more mature technologies, power levels from 50 kWe to 1.0 MWe, specific masses on the order of 50 kg/kWe or less and full power lifetimes of up to 10 years.

Early utilization would suggest the selection of candidate system technologies which are relatively mature and/or currently under development. The most obvious choice for a near term power system in this range would be the SP-100 space nuclear power system, currently in the technology development stage. The SP-100 system utilizes a lithium cooled pin-type fast reactor and thermoelectric power conversion. Ion electric propulsion would likely represent a first thruster choice, having already demonstrated operation at relevant power levels, although extended lifetimes remain to be demonstrated. This grouping of technologies would result in a system which efficiently leverages existing technology programs, while providing an excellent transportation system for unmanned planetary exploration.

Other candidate systems of interest for robotic missions might utilize an SP-100 reactor with dynamic power conversion, such as Stirling, Brayton, or Rankine. This option would be especially attractive for early implementation of technology for later multimegawatt systems, and could serve as a stepping stone between thermoelectric robotic and high powered piloted systems. Other candidate systems might consist of a derivative gas-cooled NERVA reactor with Brayton power conversion, or thermionic systems. The gas-cooled option might be attractive if such a reactor were developed as part of a nuclear thermal propulsion program. Variations on these systems could result from MPD, ECR, or PIT thrusters.

Table 7.3 lists the potential candidate NEP systems for lunar and Mars cargo missions. System requirements for such missions include a 1-5 MWe power level and full power lifetimes of up to 10 years for the reusable option. Although a prime candidate for the previous application, thermoelectric power conversion is precluded in the multimegawatt range due to low conversion efficiency and the relatively heavy systems which result. Reactor technology from the SP-100 program could still be used, however, in a scaled-up, or "growth," SP-100 reactor in conjunction with one of the aforementioned dynamic conversion schemes. Such a reactor would utilize the same fuels, materials, and other technologies from the SP-100 program to create an essentially similar, yet larger, reactor[1]. Thermal power would be increased an order of magnitude from 2.5 MWt for the 100 kWe thermoelectric baseline, to 25 MWt for a 5 MWe dynamic system. Rankine and Brayton are prime choices for dynamic power conversion in the 1-5 MWe power range due to their high conversion efficiency and ease of integration with the primary lithium loop via a heat exchanger. Ready integration with various dynamic conversion schemes was, in fact, one of the reasons a lithium-cooled reactor was selected for the SP-100 program. Stirling engines are not cited because they do not readily scale beyond a few hundred kilowatts electric per engine. Configurations of Stirling power systems of 1-5 MWe would require a large number of engines and would result in a relatively high specific mass.

Systems leveraging the reactor technologies currently developed in the SP-100 program would be attractive for a nuclear propulsion program. Savings would be expected in program cost, risk, and development time. However, along with these savings and performance benefits come the inherent limitations in operating temperatures and stresses associated with this set of materials and technologies. If the performance enabled by SP-100 reactor technology is sufficient for the intended mission, it will make for a very compelling option. If not, more advanced reactor concepts must be investigated.

Advanced cladding and structural materials beyond the niobium alloys of the SP-100 program would allow advanced lithium cooled pin-type space reactors to operate at higher temperatures and achieve lower overall power system specific masses. Rankine and Brayton dynamic power conversion would again make good choices for integration. A matrix CERMET might be used as an alternate fuel form for the lithium-cooled reactor. A number of gas-cooled reactors have been proposed for use in space power systems, including NERVA derivative, particle bed, and CERMET reactors. All of these concepts would make for natural integration with a Brayton cycle, either directly or indirectly. A final candidate for use in cargo missions is the in-core thermionic power system. This technology is currently being evaluated through a number of research programs and offers the potential for light weight, static power systems in the few megawatt range. Concerns about extended lifetimes must be resolved, however.

Heat rejection subsystems for both the cargo and piloted applications will typically utilize heat pipes of varying material based on temperature and degree of technical sophistication. An alternative solution for Brayton systems may lie in a pumped loop radiator. A variety of electric propulsion concepts including ion, MPD, ECR and PIT thrusters are candidates, and would span the range of potential candidates. Ion engines currently represent the most mature technology. However, as more ambitious missions are desired, so increases the payoff for less mature, innovative thruster concepts.

Table 7.4 lists the potential candidate NEP systems for piloted Mars missions. Requirements for piloted missions vary depending upon the mission design and performance objectives. In general, however, power levels of 10-20 MWe will allow "All Up" missions of under 600 days piloted duration and "Split" missions of under 400 days for the most conservative system presented. Full power system lifetime requirements will vary from 2 years for a single use system to as high as 10 years for a reusable system. A very broad spread in maturity and technological readiness is seen, ranging from the more near term SP-100-derived systems to the more speculative vapor core system. Thus, although all of the systems presented are potential candidates for piloted application, some will be more appropriate for meeting more immediate needs, while others will be better suited for farther term missions.

A scaled-up "Growth" SP-100 reactor, using present-day SP-100 fuel pin technology, in conjunction with potassium Rankine power conversion would make an excellent choice for early configuration of a multimegawatt power supply. In fact, use of such a multimegawatt power supply having only a two year lifetime requirement can enable short piloted vehicle transit times to Mars that are comparable to NTP[2]. The leveraging of reactor technologies being developed in the existing SP-100 program would allow a programmatic "head start," as well as enabling reductions in cost and risk. Brayton power conversion will probably not allow sufficiently low specific masses to be achieved with the rather moderate temperatures of SP-100. Substitution of advanced cladding and structural materials, beyond niobium alloys, would allow advanced lithium cooled pin-type reactors to achieve higher operating temperatures and lower specific masses than a growth SP-100 system, although at increased program cost and risk. Both Rankine and Brayton would be potential candidates for power conversion. Additional substitution of an advanced CERMET fuel could allow additional mass savings, and/or allow a direct potassium boiling core.

Various high temperature gas-cooled reactors such as NERVA derivative, particle bed, or CERMET reactors in conjunction with Brayton power conversion are also possible candidates for use in a piloted application. These systems might again be attractive if some appreciable commonality were to exist with direct thrust reactors of a nuclear thermal rocket development program. Electric power and thermal propulsion applications are quite different, however, and may drive unreconcilable differences in reactor design, materials, and engineering.

A final candidate system might utilize a vapor core reactor with magnetohydrodynamic (MHD) power conversion. This would certainly be the most speculative of the systems presented. However, it may represent an option for ultimate growth beyond the liquid-metal and gas-cooled reactor power systems. Again, all of the above systems would utilize either heat pipe based heat rejection subsystems, with the option for pumped loop systems with Brayton or MHD. Ion, MPD, ECR, or PIT thrusters serve as representative electric propulsion concepts across a range of technology levels, power processing requirements, and performance characteristics.

7.2 EVOLUTIONARY PATHWAYS

An evolution in missions is seen as progressively more demanding mission requirements unfold. Starting with robotic interplanetary probes and extending to lunar and Mars cargo missions and piloted Mars missions, requirements for increasing power levels and lighter systems are seen. Power level requirements start at around 100 kWe, and rise to a few megawatts for cargo missions, to tens of megawatts for piloted missions. Specific mass requirements, conversely, are seen to drop from roughly 50 kg/kWe to 10 kg/kWe or less.

Just as missions evolve, so can candidate systems be evolved to meet a range of missions required while minimizing the number of technologies, systems, and overall programmatic cost and risk[3]. One evolutionary pathway would seem an obvious choice given current programmatic direction, and would leverage technology from the existing SP-100 space nuclear power system and ion electric propulsion, technologies already under development. This same reactor technology can be scaled up to a "growth" version and integrated with potassium Rankine power conversion to provide power systems in the 1 to 5 MWe range. Integration with higher powered ion electric propulsion would allow highly efficient lunar and Mars cargo missions to be performed. Finally, these same technologies could be scaled up further to provide piloted NEP systems of 10 to 20 MWe, either as multiple use systems for cumulative mass savings benefit or expendable systems for short transit time benefit[4].

This evolutionary pathway would support both near and far term missions, enabling mission benefit across a variety of missions while leveraging existing reactor and thruster technology programs. It does not represent the only pathway, however, and is certainly not the most advanced. If this evolutionary pathway does not result in a piloted system with satisfactory mission performance, based on whatever figures of merit are eventually chosen, then by definition, an alternate pathway leading to more advanced systems and technologies must be chosen. Leading candidates for this more advanced application may lie in a higher temperature liquid metal-cooled reactor, either Rankine or Brayton, or in a high temperature gas-cooled reactor with Brayton power conversion. Although ever lighter and more efficient thruster technologies will obviously enhance mission performance, thrusters represent only a relatively small fraction of the total NEP system. Thus, advanced EP technologies alone will not allow substantial performance enhancements without advancing power system technology as well.

A simpler system evolution could eliminate one step by utilizing a modular piloted power system and vehicle architecture to allow both cargo and piloted missions to be performed with a common power system design and hardware[5]. A family of NEP vehicles configured with common 5 MWe power modules is shown in Figure 7.1. A single 5 MWe power module is sufficient to power lunar and Mars cargo missions, while multiples of 2 to 4 are sufficient to fly 10 to 20 MWe piloted missions. Use of a modular multi-reactor piloted vehicle would provide enhanced system and mission reliability.

7.3 NEP TECHNOLOGY ALTERNATIVES STUDY

Although it was possible to make some distinctions about which NEP systems and technologies would be most suitable to the performance requirements and readiness dates of the three mission classes of interest, broad respective arrays of candidate systems remain. Many of these systems have been analyzed before by various groups. However, differences in assumptions, ground rules and methodologies discourage direct comparison of results.

A large scale system analysis effort is recommended to assess the relative potential of various candidate NEP systems and technologies. The study would perform systems analysis of as many of the aforementioned candidate systems as feasible, and would be performed according to strict and consistent ground rules and assumptions, allowing systems to be compared on a fair basis.

Such a study would likely be contracted due to the limited availability of government staff resources compared to the magnitude of the project. Since no single contractor will likely have expertise across all facets of all NEP technologies of interest, the formation of diversified contractor teams representing various companies may be desirable. It would also be advantageous to have two or more independent contractor teams performing similar or overlapping systems analysis in order to provide varying perspectives on the problem, allow a benchmark of each others results, and minimize any concerns of contractor partiality towards certain technologies.◆

NEP SUBSYSTEM TECHNOLOGY OPTIONS

REACTOR	POWER CONVERSION	HEAT REJECTION	PMAD	THRUSTER
Liquid Metal Cooled	Dynamic	Heat Pipe	High vs. Low Temp.	Ion
Growth SP-100	K-Rankine	Refractory Metal	High vs. Low Voltage	MPD
Adv. Pin Type	Brayton	Carbon-Carbon	Radiation Hardening	Deflagration
Cermet	Stirling	Ceramic Fabric		Pulsed Plasmoid
Boiling K		Pumped Loop		PET
	Passive	Liquid Sheet/Drop.		ECR
Gas Cooled	Thermoelectric			ICR
Nerva Derivative	Thermionic			PIT
Particle Bed	in core			Variable Isp
Pebble Bed	ex core			
Cermet	Electrochemical			
	MHD			
Incore Thermionic				
Vapor Core				

Table 7.1

CANDIDATE SYSTEMS FOR NEAR TERAM LOW POWER (0.1-1.0 MWe) INTERPLANETARY PROBE AND PRECURSOR MISSIONS

REACTOR	POWER CONVERSION	HEAT REJECTION	THRUSTER
SP-100	Thermoelectric	Heat Pipe	
	K-Rankine	Heat Pipe	
	Brayton	Heat Pipe/Pumped Loop	
	Stirling	Heat Pipe	
Nerva Derivative	Brayton	Heat Pipe/Pumped Loop	Ion MPD ECR PIT
Thermionic	In core	Heat Pipe	
	Ex core	Heat Pipe	

Table 7.2

CANDIDATE SYSTEMS FOR MEDIUM POWER (1-5 MWe) LUNAR AND MARS CARGO MISSIONS

REACTOR	POWER CONVERSION	HEAT REJECTION	THRUSTER
Growth SP-100	K-Rankine	Heat Pipe	
	Brayton	Heat Pipe/Pumped Loop	
Adv. Pin Type	K-Rankine	Heat Pipe	
	Brayton	Heat Pipe/Pumped Loop	
Cermet	K-Rankine	Heat Pipe	Ion
	Brayton	Heat Pipe/Pumped Loop	MPD
Gas Cooled			ECR
Nerva Derivative	Brayton	Heat Pipe/Pumped Loop	PIT
Particle Bed	Brayton	Heat Pipe/Pumped Loop	
Cermet	Brayton	Heat Pipe Pumped Loop	
Thermionic	In core TFE	Heat Pipe	

Table 7.3

CANDIDATE SYSTEMS FOR HIGH POWER (10-20 MWe) "ALL-UP" PILOTED MARS MISSIONS

REACTOR	POWER CONVERSION	HEAT REJECTION	THRUSTER
Liq. Metal Cooled			
Growth SP-100	K-Rankine	Heat Pipe	
Adv. Pin Type	K-Rankine	Heat Pipe	
	Brayton	Heat Pipe/Pumped Loop	
Cermet	K-Rankine	Heat Pipe	Ion
	Brayton	Heat Pipe/Pumped Loop	MPD
Gas Cooled			ECR
			PIT
Nerva Derivative	Brayton	Heat Pipe/Pumped Loop	
Particle Bed	Brayton	Heat Pipe/Pumped Loop	
Cermet	Brayton	Heat Pipe Pumped Loop	

Table 7.4

CANDIDATE SYSTEMS FOR HIGH POWER (10-40 MWe) "QUICK TRIP" PILOTED MARS MISSIONS

REACTOR	POWER CONVERSION	HEAT REJECTION	THRUSTER
Liq. Metal Cooled			
Adv. Pin Type	K-Rankine	Heat Pipe	
Cermet	K-Rankine	Heat Pipe	
Boiling K	K-Rankine	Heat Pipe	Ion
			MPD
Gas Cooled			ECR
			PIT
Nerva Derivative	Brayton	Heat Pipe/Pumped Loop	
Particle Bed	Brayton	Heat Pipe/Pumped Loop	
Cermet	Brayton	Heat Pipe Pumped Loop	
Vapor Core	MHD	Heat Pipe/Pumped Loop	

Table 7.4 (Continued)

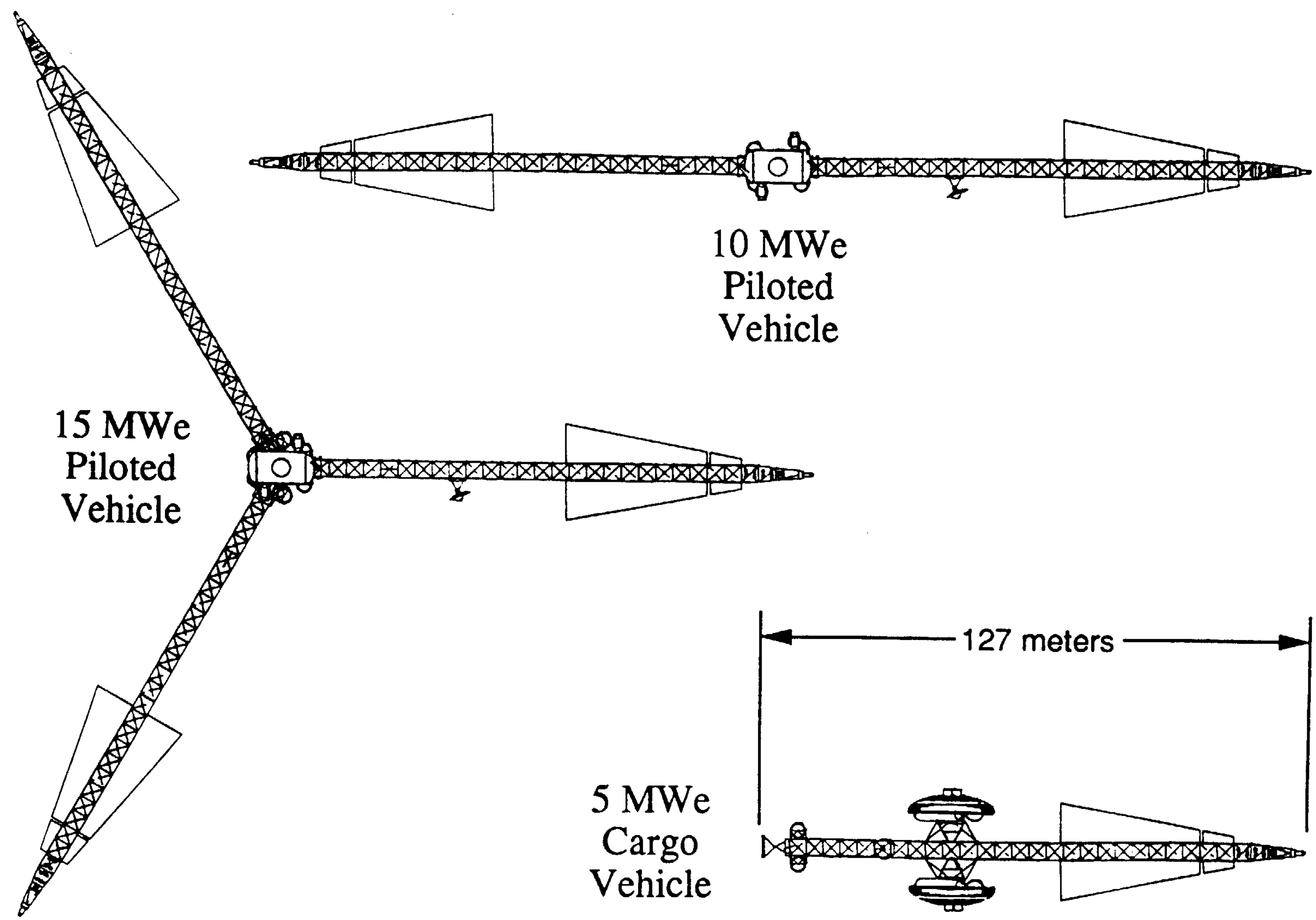

Figure 7.1: Family of Piloted and Cargo NEP Vehicles using Common 5 MWe Modules

8.0 TECHNOLOGY PLANNING IMPLICATIONS

Because NEP has applicability over a wide range of mission scenarios from low power orbit raising to Mars piloted vehicle applications, technology goals and milestones should be established along an evolutionary path. In following this evolutionary path, the technologies required for low power applications may be developed on the way to achieving the enabling technologies for the Mars piloted application.

Reference mission timelines have been established for possible space missions employing NEP (Figures 8.1 through 8.3). These reference mission timelines give example of facility, technology, and advanced development milestones required to affect interplanetary robotic, Moon/Mars cargo, and Mars piloted NEP applications. The launch dates shown on these figures in no way imply a formal commitment.

It is from these reference mission timelines that the subsystem/technology goals and milestones have been developed.

There is considerable variation in the status of the existing technology base of the subsystems which would constitute an NEP system. In general, there is a significant technology base for most of the subsystems that is sufficient to warrant optimism that a system could be developed successfully, while recognizing that a concentrated effort will be required.

Major technology issues and projected developmental efforts for NEP subsystems are presented in this section.

8.1 REACTOR

From the discussions in Section 6.0 on technology options and the experience to date with programs such as SP-100 and MMW, the only reactor options with potential to achieve a TRL-5 (subsystem ground test) by year 2005 are liquid metal cooled, gas cooled, and incore thermionic reactor options. Liquid metal cooled reactors are commonly associated with Rankine cycle power conversion, while gas cooled reactors are commonly associated with Brayton cycle power conversion. While the fundamentals of the two cycles are well known and a tremendous amount of data and experience exists on the use of both of these cycles in industry, the particular requirements of their applications in space requires significant development efforts in several areas. Incore thermionic reactors have been already flight tested at low power levels, but doubt still remains as to their scalability to megawatt power levels. This section will discuss major technology issues associated with liquid metal cooled (LMC) and high temperature gas cooled (HTGC) reactors, and give a an overview of the development effort associated with a liquid metal cooled reactor.

8.1.1 Major Technology Issues

The planning and development of LMC or HTGC reactors for space applications is driven primarily by the need for higher temperatures, long life, and extreme reliability and safety. These requirements very quickly lead to the need for:

- High temperature, high strength lightweight materials
- High temperature, long life, and stable nuclear fuel forms
- Simple, rugged, reliable system components .

Satisfaction of all these basic requirements is nearly a paradox, but the design, analysis, and technology work to date on LMC and HTGC concepts provide a great deal of encouragement that they can be met. It is not clear at this time which dynamic power conversion cycle will best satisfy the basic requirements, but there are features, or requirements, common to both cycles which are in need of development and which, when proven, would greatly benefit the ultimate application of either system. These features include all the basic requirements listed above and are discussed below.

8.1.1.1 High Temperature, High Strength, Light Weight Materials

Development of woven ceramic or carbon-carbon components (with high temperature metallic foil liners) for use in pressure vessels, piping, component housings, structural members, etc., should be actively pursued. The development and application of this technology will benefit both LMC and HTGC reactor technologies.

8.1.1.2 High Temperature, Long Life, and Stable Nuclear Fuel Forms

A discussion of high temperature, long life, and stable nuclear fuel forms appears in section 8.7.1.

8.1.1.3 Simple, Rugged, Reliable System Components

For an NEP system, the job of the reactor is to supply a heated medium to a component which will extract that heat energy and turn it into usable electrical energy. The reactor can be made relatively light weight, compact, rugged, and reliable, whether it is driving a Brayton or Rankine system. The majority of the weight, complexity, and reliability of the system will be dictated by the balance of plant. Reactor components that should be investigated immediately due to their potential weight and safety impact are biological shields and reactor operation and control systems that allow for multiple failures and gradual failure modes.

8.1.2 Projected Development Effort - Liquid Metal Reactor

Liquid metal reactor technology can be extended to higher performance levels by developing fuel pins with cladding which can withstand higher operating temperatures. Candidate materials are T-111, ASTAR-811C and Tungsten-Rhenium. Development of fuel elements that can operate with 1500-1600 K lithium outlet temperatures for design lifetimes of 2-5 years will contribute to attaining much lower values of specific mass for the system.

A proposed schedule for the development of an advanced pin reactor is shown in Figure 8.4 The early effort would be focused on fabricating high temperature fuel elements and testing them in existing reactors. This would be followed by design, fabrication, and installation of a 25-50 MWt prototype reactor in an existing reactor test facility which would be modified for this purpose. It is estimated that the reactor could, with adequate funding, be installed and made ready for testing by about the beginning of 2002.

8.2 POWER CONVERSION - POTASSIUM RANKINE

Development of liquid metal vapor Rankine cycle power systems began in the early 1960s in conjunction with the Space Nuclear Auxiliary Power (SNAP) programs, jointly sponsored by NASA and AEC. Power conversion components, such as boilers, pumps, turbines and condensers, were designed, fabricated, and tested to support development of SNAP systems to produce 100-300 kWe. A considerable technology base on materials and small components was established. The development program was continued until about 1972 but was terminated before a complete power system was tested. As a result, there is variation in the status of the technology among the components of the systems. For example, corrosion test loops on niobium and tantalum alloys were operated for tens of thousands of hours at temperatures of 1300-1500°K, and potassium boiling tests were run in small boilers at temperatures of up to 1400°K, but the longest test of a turbine was 5,000 hours at a temperature of about 1100°K. Overall, the results were positive and indicated a high likelihood that Rankine cycle systems can be successfully developed for operation at high temperature. In general, the development task remaining is to extend the existing technology base to higher temperatures and larger components and conduct longer term component system tests.

8.2.1 Major Technology Issues

The major technology issues of the development of the Rankine cycle power conversion system include: refractory metal parts fabrication, turbine blade endurance, turbine bearings and seals, and generator winding seal.

8.2.1.1 Refractory Metals Parts Fabrication

There is limited experience in the fabrication of parts from high temperature refractory metals such as T-111 and ASTAR-811C. The fabrication experience needs to be extended to more complex and larger parts such as turbine blades, rotors, and casings.

8.2.1.2 Turbine Blade Endurance

Test turbines were operated in potassium vapor at just over 1100°K with a moisture content of around 8% for about 5,000 hours with negligible turbine blade wear. The operating experience needs to be extended to high temperatures (1400-1500°K) to determine the allowable limits of turbine blade tip speed and potassium moisture content for long life of the turbine blades.

8.2.1.3 Turbine Bearings and Seals

The previous experience with turbine bearings and seals needs to be extended to higher temperatures and pressures of the potassium vapor. Liquid potassium lubricated tilting pad journal bearings were successful previously, and it is anticipated that they will perform well at the new conditions. Labyrinth-type shaft seals to protect the bearings from high temperature vapor should also prove successful at the new conditions.

8.2.1.4 Generator Winding Seals

An enclosure of non-magnetic metal (or alternatively, ceramic) is required to protect the conductor windings in the rotor and stator from potassium vapor (or liquid) which may leak past the shaft seals into the generator. Development of the attachment of the enclosure, by welding or otherwise, to the rotor and stator core is a technology issue.

8.2.2 Projected Development Effort

The proposed approach to the development of the power conversion system is as follows: establish a reference design of the system that meets the NEP mission goals, develop each component individually up to the point that a viable prototype has been proven, install the prototype components in a combined power conversion system, and conduct performance and endurance tests until technology readiness is demonstrated. A power conversion module with an output of 0.5-1 MWe would be a useful capacity for the first system test. Following this, a module of a capacity of 2.5-5 MWe should be tested.

Development work on each of the components would be initiated and proceed in parallel to the point that a viable prototype of each component is available to install in a system test.

8.2.2.1 Rotary Fluid Management Device

The function of this component is to control the liquid-vapor interface in the system at a point between the condenser and the boiler feed pump under zero-g conditions. It consists of a motor-driven centrifugal separator with a pilot probe liquid pickup where liquid is fed to the inlet of the boiler feed pump. In addition to controlling the liquid-vapor interface, it provides a pressure rise sufficient to prevent cavitation in the boiler feed pump. It has been developed for organic Rankine cycle systems and adaption to potassium as the working fluid is required.

8.2.2.2 Zero-G Flight Package Test

The purpose of this test is to observe the behavior of an elementary two-phase fluid loop containing a boiler and condenser under zero-g conditions. The test package would be flown in low Earth orbit in the space shuttle to permit a reasonably long period of operation. Key observations will be liquid and vapor bubble distribution in a boiler tube, vapor distribution in a tapered tube condenser, and liquid-vapor interface control between the condenser and boiler feed pump. The initial test would be conducted with a low-boiling point fluid in a loop constructed of a transparent material. Later tests would extend the investigation to boiling and condensing potassium in a metal loop with temperature and pressure instrumentation.

8.2.2.3 Boiler

The proposed approach to boiler development is to conduct performance and endurance tests on a subscale capacity boiler composed of full-scale tubes but only a few in number (4 to 7). The test boiler would be coupled to an electrically heated liquid lithium loop and a potassium condenser with a feed pump to return the liquid to the boiler. Since the boiler loop would operate at high temperature (1400-1500°K), it would be constructed of a high temperature refractory metal alloy and would, of necessity, have to be enclosed in a vacuum chamber to protect it from oxidation by air. Performance tests would be conducted to determine exit quality or superheat as a function of vapor flow rate and pressure. Endurance tests would be run to find the structural integrity and chemical compatibility of the boiler tube material and potassium. A prototype boiler would be fabricated and installed in the power conversion system test loop.

8.2.2.4 Boiler Feeder Pump

A turbine-driver centrifugal pump is the favored design for a potassium boiler feed pump. The development approach would be to design and build a test model of the full-scale turbopump out of stainless steel and test it initially on steam and water. Successful demonstration of the test unit would be followed by fabrication of a prototype out of refractory metal and installing it in the potassium boiler test loop. The potassium boiler would be designed with sufficient capacity to provide the required vapor flow for driving the turbopump. A high liquid recycle flow ratio would be provided so that the full design liquid flow rate could be circulated through the pump.

8.2.2.5 Turbine

A preliminary turbine design would first be established. Test models of bearings and seals would be fabricated and spin tested with oil lubrication and air as the working medium. Bearings of refractory metal parts would be fabricated and tested first with cold, then hot potassium liquid as the lubricant. Test turbine wheels of the first, middle, and last stage would be fabricated, spin tested, and fluid dynamically tested with air as the working medium. An exhaust section test model composed of the last 3 stages would be fabricated of refractory metal and first tested with argon as the working medium and then tested with potassium vapor. A prototype turbine would be built and installed in the power conversion system test facility for performance and endurance testing.

8.2.2.6 Generator

The generator would be designed and tested in air with oil-lubricated bearings. Bearings would be fabricated of refractory metal and tested with liquid potassium as the lubricant. The stator and rotor windings would be enclosed in a sealed casing, and the seal would be tested in potassium liquid and vapor. Stator and rotor cooling tests would be run first with organic coolant fluid, followed by tests with liquid potassium coolant. A prototype generator would be built and installed in the power conversion system test facility for performance and endurance testing.

8.2.2.7 Condenser

Because of the zero-g environment, the condenser must be designed to utilize dynamic forces to push the vapor and subsequent condensing liquid through the condenser. Also, the condenser is close-coupled to the heat-pipe radiator, so the development of the condenser is closely-related to that of the radiator. Test models of the condenser could be fabricated from transparent material, glass or plastic, and tested with low boiling point fluids (water, freon, etc.). Subscale models should be tested in zero-g flight tests. Coupling tests of the condenser-heat pipe radiator combination would be run on a section of the condenser-radiator with potassium. A prototype of the condenser-radiator would be fabricated and installed in the power conversion system test facility for performance and endurance testing.

8.2.2.8 Power Conversion System Test

The power conversion system test would be a major test facility which would be designed to accommodate testing of a 0.5-1 MWe module. It would employ a non-nuclear heat source to generate hot lithium to go to the potassium boiler. Prototypes of the potassium components would be installed throughout the system. The system would be contained in a vacuum chamber to protect the high temperature refractory metals from oxidation. Shakedown, performance tests, and endurance tests would be conducted to demonstrate technology readiness. This would be followed by a second system test in which a 2.5-5 MWe module would be assembled and tested.

8.2.3 Schedule

A preliminary schedule for development of the power conversion system is shown in Fig. 8.5. The objectives are to have the 0.5 - 1 MWe module to TRL-5 by the year 2000 to support the Lunar/Mars cargo mission application, and the 2.5 - 5 MWe module ready by 2005 to support the Piloted Mars mission application.

8.3 HEAT REJECTION

Because all thermal heat produced by the reactor is not able to be converted into useful power, heat rejection subsystems are a critical element of the NEP system. Heat rejection subsystems, accounting for a substantial portion of NEP system mass, are a prime area to focus lightweight materials advancements. This issue is the primary development area for space-based heat rejection.

A number of candidate materials technologies have been identified for NEP heat rejection requirements: refractory metal alloy, carbon-carbon, and ceramic fabric. The refractory metal alloy option, a near term approach, is being focused on by the SP-100 program. Both carbon-carbon and ceramic fabric radiator technologies are being pursued[1]. A candidate development plan to meet the heat rejection requirements of SEI is shown in Figures 8.6 and 8.7.

8.4 POWER MANAGEMENT AND DISTRIBUTION

A Power Management and Distribution (PMAD) subsystem with the power and specific-mass levels required for megawatt NEP cannot be built using existing technologies. In order to achieve the NEP goals, high-temperature, multimegawatt, radiation-resistant, power electronics must be developed. Candidate semiconductor technologies for power electronics such as Silicon Carbide (SiC) and Aluminum Gallium Arsenide (AlGaAs) must be developed for the temperature range of 300-400°C. In addition, basic technologies such as dielectrics, insulations, and packaging must be developed to support a 300-400°C system. While large power systems are being developed for space applications, the specific masses of these systems are in the 100s of kg/kWe level. NEP requires PMAD specific masses in the sub 3 kg/kWe range.

The PMAD component and subsystem technologies will be developed in three phases for three applications: 100 kW class robotics mission, megawatt class cargo mission, and megawatt piloted Mars mission. The feasibility and practicality of meeting the power levels and specific-mass goals for the three missions will be assessed.

A major challenge of this program is to demonstrate that power electronics can be built to operate at high temperatures with long lifetimes and high efficiencies. PMAD subsystems will be built using low specific-mass components to demonstrate operational stability, fault tolerance, high efficiency, and long life.

While all spacecraft require power management, controls, and distribution, little effort is made to optimize this subsystem. As a result, the PMAD subsystem in spacecraft has a very high specific-mass, on the order of 100s kg/kWe. Even the design for Space Station Freedom, calls for a PMAD subsystem with a specific mass of over 150 kg/kWe. Achieving sub 3 kg/kWe for a PMAD subsystem requires more than just scaling to multimegawatts. A new power electronics technology must be developed.

Conventional power electronics are based on silicon devices. These Si devices successfully operate at temperatures up to ~200°C before suffering thermal runaway. Using conventional silicon power electronics and power components, it will be possible to achieve the goals of the first mission: 100 kW class robotics mission by the late 1990s.

To achieve the goals of the later missions, it will be necessary to develop power electronics with wider band gap semiconductors. SiC is the best choice based on material properties and band gap. However, the maturity of the SiC technology is so low that it would be risky to base this program solely upon this one technology. Some support should be given to the SiC power electronics development in order to leverage the results of the ongoing program for the NEP program; but other, more mature, semiconductor technologies should receive the majority of the support.

The maturity of the semiconductor device technology in AlGaAs, whose band gap is larger than Si but smaller than SiC, is such that there are many sources for device quality AlGaAs substrates. AlGaAs is predominately being used to fabricate high frequency devices. Because of the wide band gap and maturity of the device technology, AlGaAs is a prime candidate for high-temperature, power electronics with high efficiencies and long life for NEP PMAD subsystems.

High-power, high-temperature electronics based upon Si devices and conventional power components operating at 200°C will be the baseline technology for the 100 kW NEP robotics mission. The main effort for this mission is to insure long-life and high-efficiency for the PMAD subsystem operating at 200°C.

AlGaAs and SiC high-temperature, power electronics will be the baseline for the megawatt class NEP missions. The program will concentrate on determining the efficiencies and lifetimes of the power devices. Because of the high operating temperatures, new predictive technologies will be established in order to characterize the power electronics lifetimes. Component and subsystem scaling technologies will be accomplished through modelling, and verified through testing. Devices, components, and subsystems will be built and used as test beds to evaluate new materials and new fabrication technologies.

Other high-temperature, high-power electronics technologies such as solid state tubes will undergo feasibility tests. If results of the feasibility tests so warrant, these alternative technologies will be supported.

Once the power conversion and thruster technologies have been selected for the megawatt NEP missions, an engineering model PMAD subsystem will be developed and brought to Technology Readiness Level 5 for each of the applications. The major products of the focused technology programs will be the demonstration of the PMAD subsystem's performance, lifetime, and definition of critical interfaces.

8.5 ELECTRIC THRUSTERS

Several thruster concepts can provide 5000 to 10,000 seconds specific impulse at power levels required for NEP systems. The most mature concepts are inert gas ion thrusters and magnetoplasmadynamic (MPD) thrusters. Ion thrusters have demonstrated high performance and long life at low power levels (1 to 5 kW), and MPD thrusters have demonstrated high power capability (0.1 to 0.6 MW) for short periods of time. More than six ion propulsion systems and two pulsed MPD arcjets have been qualified for flight at power levels less than 2 kW. At least nine other electric thruster concepts are candidates for the high power/high specific impulse propulsion applications. Electric thruster power levels for robotic precursor flights may range from 10 to 50 kW, while cargo and piloted vehicle applications require thruster operation in the 0.5 to 2.5 MW range.

8.5.1 Major Technology Issues

The thruster component and subsystem technology will be developed in phases with each phase building towards the next. The feasibility and practicality of high power thrusters, along with the power processors, will be assessed for applications involving 100 kW class robotic precursors, megawatt-class cargo vehicles, and multimegawatt piloted vehicle applications. Feasibility issues involve the demonstration of specific impulse in excess of 5000 seconds and a thrust efficiency greater than 50 percent at power levels of interest. Life verification diagnostics and tests will be undertaken to insure thruster lifetimes up to 10,000 hours. In order to implement performance and life demonstrations at power levels from 0.1 to 5 MW, vacuum facility upgrades will be required to insure high fidelity measurements. Major facility modifications will involve the assembly of large area cryopump systems for hydrogen and argon, thruster exhaust thermal management, as well as high fidelity thrust stands. Thrusters will be integrated with power processor breadboards, comprised of low mass components, to demonstrate operational stability, fault tolerance, and a high power efficiency.

Engineering model thrust subsystems comprised of thruster, power processor breadboards, and propellant management systems will be developed and brought to TRL-5 for precursor, cargo, and piloted vehicle applications. The MW-class engineering model designs will be consistent with thruster assembly and power processor component specific mass targets whose upper bounds are 0.5 kg/kW. The major products of the focused technology programs will be the demonstration of thrust subsystem performance (efficiency, specific mass and specific impulse), subsystem reliability, lifetime, and definition of critical interfaces.

At present, the only flight applications of electric propulsion are low power systems used to perform satellite stationkeeping. Resistojets, arcjets, and ion thrusters are being used or being flight qualified for such applications. Electrothermal systems, such as arcjets, do not provide high enough specific impulse to be candidates for NEP planetary missions. Advanced concepts, such as pulsed electromagnetic devices and electrodeless thrusters, may ultimately provide the desired performance and life, but do not have sufficient technical maturity to be incorporated into the early high power technology demonstration programs. The two most mature thruster concepts are the ion and MPD thruster.

Ion thrusters have demonstrated specific impulse (Isp) capability from 1500 s to more than 10,000 s, thrust efficiencies over 0.75 at high Isp, and total impulse as high as 1x10**6 N-s for 10-kW class thrusters. Ion propulsion components and systems have been ground- and flight-tested worldwide for three decades. Mercury ion thrusters were tested at beam power levels of 20 to 200 kW more than 20 years ago. Due to the prospects of modest space power capability, most subsequent ion thruster research has been conducted at power levels less than 5 kW. The Solar Electric Propulsion System (SEPS) technology program in the 1970s developed an ion thrust subsystem to advanced status. Critical elements included large 25 kW solar arrays, power processors at 12 kg/kW, heat pipes, gimbals, 3 kW thrusters, and propellant systems. The SEPS program was a $30M investment over a ten-year period involving NASA Flight Centers and industry. The U.S. development status of ion propulsion is shown in Figure 8.8. While the performance of ion thruster is well known, the scalability, lifetime, and power processing issues for high power thrust systems will be the focal point of early development efforts.

Steady state MPD thrusters have typically been operated at power levels from 30 to 600 kW, while quasi-steady MPD devices have been run at powers exceeding 1 MW. The most promising propellants are hydrogen, deuterium, and lithium. Steady state operation with hydrogen at low power has yielded about 3500 s specific impulse and a thrust efficiency of nearly 50 percent. Thruster lifetimes have been limited by cathode erosion, although an applied field MPD thruster operating at 25 kW delivered a total impulse of $1x10^{**}6$ N-s. The maturity level of MPD thruster technology has been hampered by much lower funding levels than ion propulsion and by the poor prospects of high power in space envisioned for the period 1970 to 2000.

8.5.2 Projected Development Effort

MPD and ion thrusters will be the baseline concepts for the NEP technology project. Other propulsion concepts will undergo preliminary feasibility tests and will be supported by the Innovative Technology WBS element. If the results of feasibility tests indicate prospects for high performance and long life, the thruster technology will be supported by the Electric Thruster WBS element.

The program will concentrate on determining the performance and life limits of precursor-class and MW-class electric thrusters. Facility impacts on the fidelity of performance and durability measurements will be assessed at the beginning of the program. High fidelity thrust stands, as well as in-situ methods of evaluating lifetime will be developed so performance limits can be established for the thruster concepts. Predictive technologies will be established to model the performance and life capabilities of the baseline thrusters. Component and thruster scaling technology will be accomplished through modeling and test validation. Components and laboratory class thruster will also be used as test beds to evaluate new materials and products of new fabrication technologies. Confidence in thruster concepts and designs will be obtained by performing extended tests.

After scaling, performance limits, and life limits are established for a given application and power level, a down-select of thruster concepts will be made for further development under a focused technology program. Focused technology programs will be directed towards NEP precursor, cargo, and piloted vehicle applications. The major products of the focused programs will be the development of high performance, low specific mass engineering model electric thrusters and power processor breadboards. Thrusters and power processors will be integrated, and critical interfaces will be defined for thruster, power, thermal, propellant management, and instrumentation/control systems. Life verification tests will be undertaken in parallel with simulated flight qualification tests which involve thruster vibration and thruster/power processor thermal vacuum characterizations. Thrust subsystem electromagnetic compatibility, plume, and cluster interaction tests will also be performed using the engineering model hardware. Finally, the thrust subsystem including thrusters, power processors, thermal management hardware, propellant management breadboards, as well as instrumentation and controls, will be documented by drawing packages, assembly procedures, assembly records, and reports for technology transfer purposes.

The major elements of the Electric Thruster Technology Plan are shown in Figure 8.9. A base program for component technology establishes thruster feasibility, defines thruster design and interfaces, integrates thrusters and power processors, determines performance/life, and defines requirements for subsequent focused technology programs. The focused programs, directed toward precursor, cargo, or piloted vehicle applications, will also draw on the component technology developed for power processors, propellant management, thermal management, and instrumentation/controls. Throughout the NEP technology effort, the base component program will provide the performance and life predictive technologies, as well as endurance tests of thrusters and thruster/power processor systems.

The major technology milestones for the first 6 years of the NEP program are as follows:

Date	Milestone
1992	Complete test stand for 15 kW ion and MW-class MPD. Complete thermal model of MPD electrodes.
1993	Establish 0.5 MW MPD performance limits and designs for MW-class; 50 kW alkali metal MPD demo; Ion life test.
1994	Integrate power processor unit breadboard (BB) with precursor class ion thrusters.

	Complete MPD plasma/electrode model and experimental verification.
1995	Verify ion life and establish MW-MPD performance limits. Demo MPD cathode life.
1997	Complete BB demo of MW-class thrusters.

A more detailed schedule for the component and focused programs is shown in Figures 8.10 through 8.13. The technical plan starts with facility and test stand modifications. Early component technology work would begin using a nominal 15 kW ion thruster which would be applicable to a 100-kW class precursor mission. In parallel with this activity, MW-class MPD and ion thruster technology efforts would be ongoing to establish feasibility, performance, life, and ease of integration for the higher power applications associated with cargo and piloted vehicles.

8.6 INSTRUMENTATION & CONTROL

Instrumentation and Control (I&C) will be very necessary for the safe, reliable performance of NEP systems. I&C will perform the function of measuring system status, determining if the signals are relevant and accurate, and processing them in such a way that ultimately ends in a control actuation, either autonomously or with some degree of human interface. Technology needs are for high temperature, radiation resistant instrumentation, and for autonomous control.

The instrumentation system consists of sensors and electronics (preamplifier, signal conditioning, and the associated control/computer hardware), as well as boards, packages, and cabling required to support the system.

The primary requirement for sensors is for that which can survive long term irradiation and transmutation, and long times at high temperatures. The sensors needed most are reactor start-up neutron detectors that are useful for a number of restarts after surviving full power operation. This detector would ensure controlled normal start ups of NEP power reactors. Also, new temperature sensors may be required.

In order to guarantee an adequate signal-to-noise ratio, instrumentation electronics are required to be located close to the reactor. For the SP-100 space reactor, the electronics are required to survive a neutron fluency of 1.6E 15 n/cm**2 (1 MeV silicon equivalent damage) and 120 Mrad (silicon) of gamma radiation, as well as an environmental temperature of 425 C. These near term technical challenges are being addressed under the SP-100 program. More stringent requirements envisioned of man rated systems will undoubtedly require advancements in radiation tolerance and high temperature operation for electronics. Electronics will be required to operate reliably for years at temperatures of up 300 C. Alternative materials to today's silicon, such as Gallium Arsenide or Silicon Carbide, may be required.

Given the automation that will be required to meet SEI mission applications, improved, radiation-hardened, single-event-upset (SEU) proof electronics and computer technology will be required to monitor and control systems. A computer technology development effort will be required to accomplish autonomous system operation.

Material development needs include device level (semiconductor, capacitor, magnetics, and packaging), board level (board material, connectors, insulation, and dielectrics), and subsystem level (cables, interconnections, and connectors) hardware.

The I&C engineer and developer must work closely with the systems engineers and integrators to understand all of the NP system details, functions, and limits. The engineer's fundamental understanding of the system must extend to normal and abnormal operations and must include development strategies from start up to emergency recoveries. Control schemes, incorporating signal verification and validation, must be developed. Figure 8.14 is an illustration of the "Structure of an Autonomous Controller"[2], showing the implementation of signal verification and validation and how supervisory control is used. The application of new computer control technology to a remotely controlled NEP vehicle will be required.

I&C engineers and technology developers will consider other issues on their way to designing control systems:

- cold restart capability
- load-following between reactor and thruster
- cutbacks instead of scrams
- built in automated diagnosis to assure performance and safety
- loss of coolant
- emergency shutdown .

8.7 FUELS AND MATERIALS

Material requirements for NEP systems cut across all subsystems as highlighted in previous subsections. Fuel requirements are reactor specific and are highlighted below. NEP fuel and material requirements also relate closely to requirements for NTP systems, and tend to define critical technology development areas for all nuclear propulsion systems.

The panel worked with the Fuels and Materials Technology panel to define NEP fuels and materials needs while not dictating how best to meet those needs. The Fuels and Materials Technology Panel provided more detailed technology assessments and developmental approaches for both fuels and materials[3]. This subsection summarizes the input provided by the NEP panel to the Fuels and Materials Technology panel.

While NEP and NTP systems share certain similarities in fuels and materials requirements, most notably high temperatures and low mass, there are also significant differences. NEP systems must operate for years with high reliability. NEP fuels require high burnup. NEP fuels and materials operate at generally more conservative power and temperature levels. Ramp rates for NEP systems are nominal. NEP fuels and material needs are driven by mission power, mass, and lifetime requirements.

A simple, robust, long life fuel form needs to be tested for the NEP reactor environment. Candidates include the present day SP-100 fuel (Uranium Nitride (UN) - with Nb 1Zr cladding), advanced pin-type fuels (UN with ASTAR-811C, T-111, or W-Re cladding), Cermet fuels (UN or Uranium Dioxide), or Carbide/composite fuels (UC-ZrC) in particle or prismatic form.

The SP-100 program is currently qualifying a seven-year core with a 1400 K cladding temperature and relatively low power. The fuel pin irradiation program (86 fuel pins to date) has primarily used accelerated burnup and high power testing in order to provide early data points to the SP-100 effort. Such high power testing may be prototypical to a two-year (single-use piloted) NEP concept requiring a peak fuel pin temperature of 1500 K. Although most of the testing to date has concentrated on 1400 K cladding temperature, some fuel pins have been irradiated at 1500 K. At higher temperatures one can expect more fuel swelling, more gas released from pellet to plenum, more migration of nongaseous fission products, and more aggressive corrosion of cladding and liner. Although the literature and the data have pointed these expectations in a general way, further analysis, examination, and testing is required. A qualification effort for a two-year core would concentrate on analysis of existing data, examination of 1500 K pins currently under irradiation, and potential new irradiations of 1500 K fuel pins.

For the development of other potential fuel forms, an evolutionary fuels strategy is recommended (Figure 8.15). This figure defines the major activities associated with the qualification of any new fuel, namely fabrication, capsule irradiation, and fuel element irradiation, before a full reactor performance/ functional test. The figure also shows the priorities for new nuclear fuel development for NEP, with the highest priority being the advanced pin fuels, and lowest priority being the Carbide/composite fuels. This judgement is based solely on each fuel's current level of development for high power, long life applications, and not on its projected performance.

Advanced pin fuels promise extended life at operating temperatures of 1500 K or higher. Their development would require screening of advanced cladding materials such as ASTAR-811C, T-111, or W-Re and fuel fabrication, as well as irradiation testing, but substantial fabrication infrastructure already exists which could be employed in their development. Cermet fuels having operating conditions from 1500 K (LMC application) to 2000 K (HTGC application) require identical development milestones, but would require a larger investment in material (refractory metal matrix) and coating characterization and fuel fabrication. Carbide/composite fuels operating at up to 2000 K might take the form of separate coated particles or a prismatic element comprised of UC-ZrC bead dispersed in a matrix. The coated particle has much aesthetic appeal, the potential to be the most rugged fuel form, high surface area for heat transfer relative to volume, and may be optimum for manufacturing. Coatings for these particles, containment during operation, and control of coolant flow remain as issues that be addressed in the use of particles, but these appear to be engineerable. Progenitors of carbide/ composite fuel forms were extensively developed under the NERVA/Rover program, but much work has to be done qualifying them for long life applications. It is recommended that the technology work for particle/composite fuels performed during the early years under the NTP Technology project should be closely tracked for its applicability to NEP.

The need for improved materials exits for all NEP subsystems. Many of these needs have been mentioned in earlier subsections.

One focus area not previously mentioned is that of materials for electric thrusters. Thruster lifetimes of up to 10,000 hours are required. Ion and MPD thrusters are the primary candidates for NEP missions. Cathode lifetime and sputter-resistant materials are the critical materials issues. Temperature requirements are as follows:

Thruster Temperature Regimes

Thruster	Cathode Type	Temperature Range (°C)
MPD	Thoriated Tungsten	2500 - 3000
	Low work function materials	1000 - 2000
	Hollow Cathode	1000 - 2000
Ion	Hollow Cathode	1000 - 1500

In summary, fuels and materials are critical areas of NEP technology. The major drivers are high reliability, five to ten year lifetimes, high temperature capability and low specific mass. To meet these requirements will require dedication to fuel and materials issues strictly.◆

MARS PILOTED MISSION

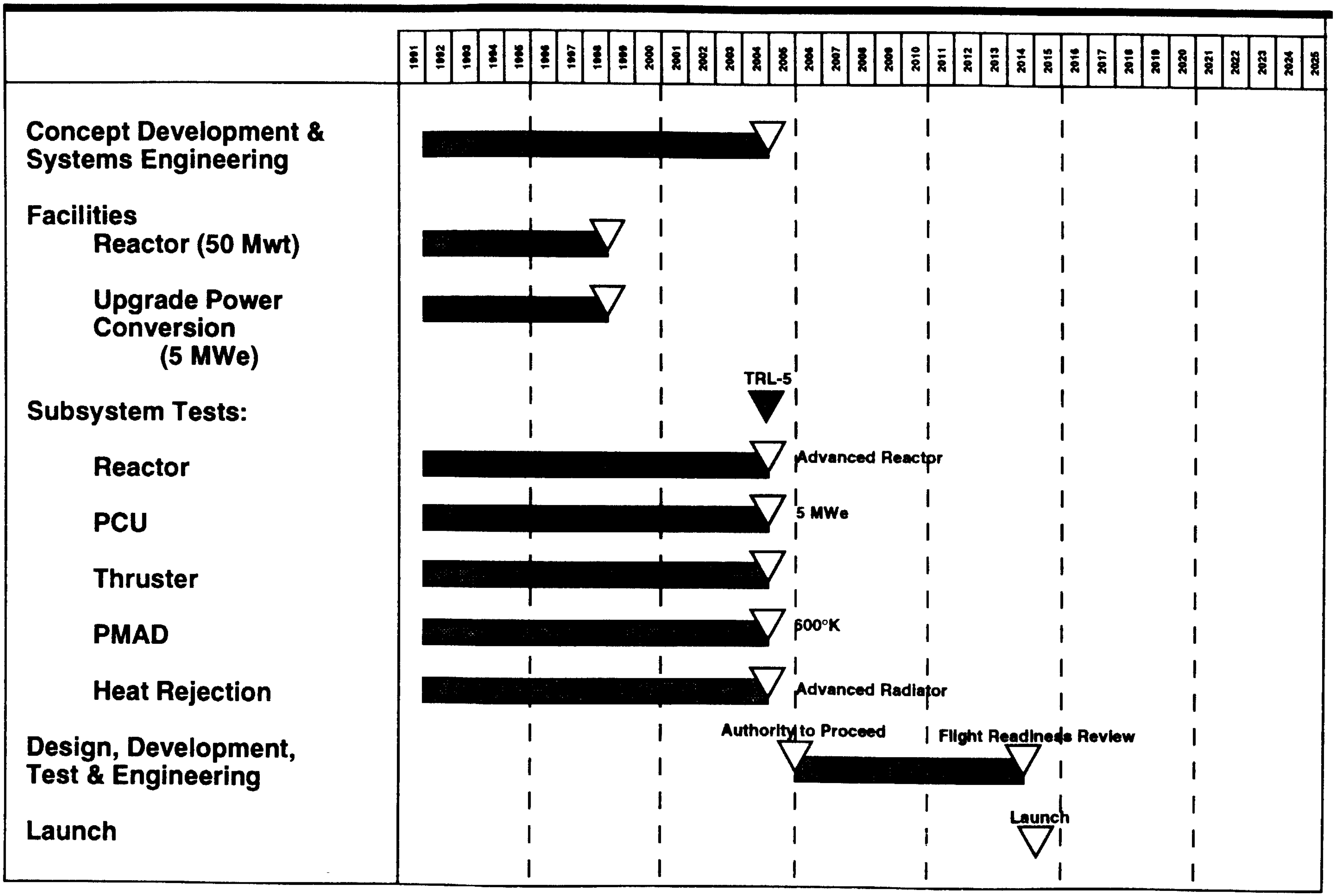

Figure 8.1

LUNAR CARGO, MARS CARGO MISSION

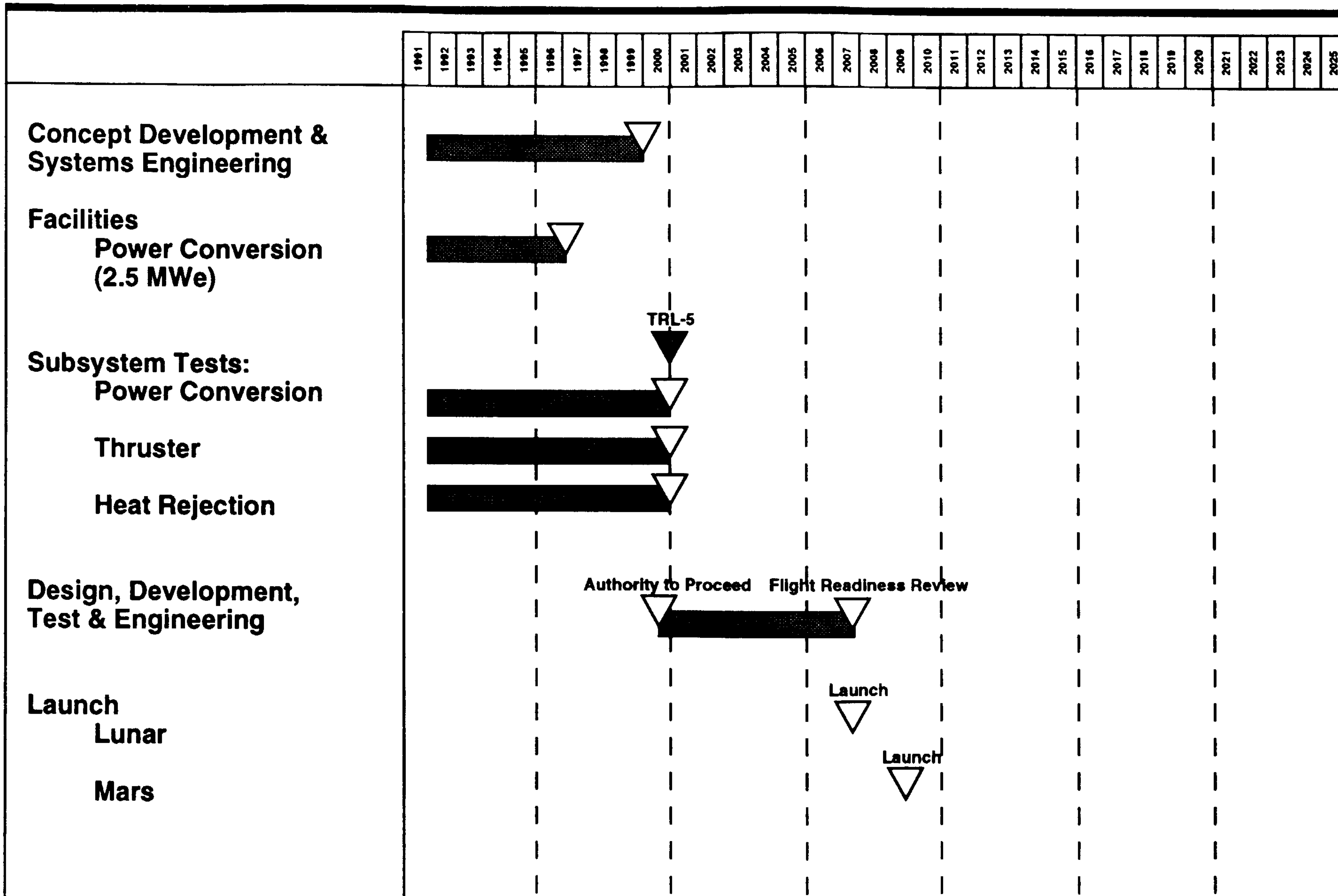

Figure 8.2

INTERPLANETARY ROBOTIC OR NEAR-EARTH ORBIT-RAISING MISSION

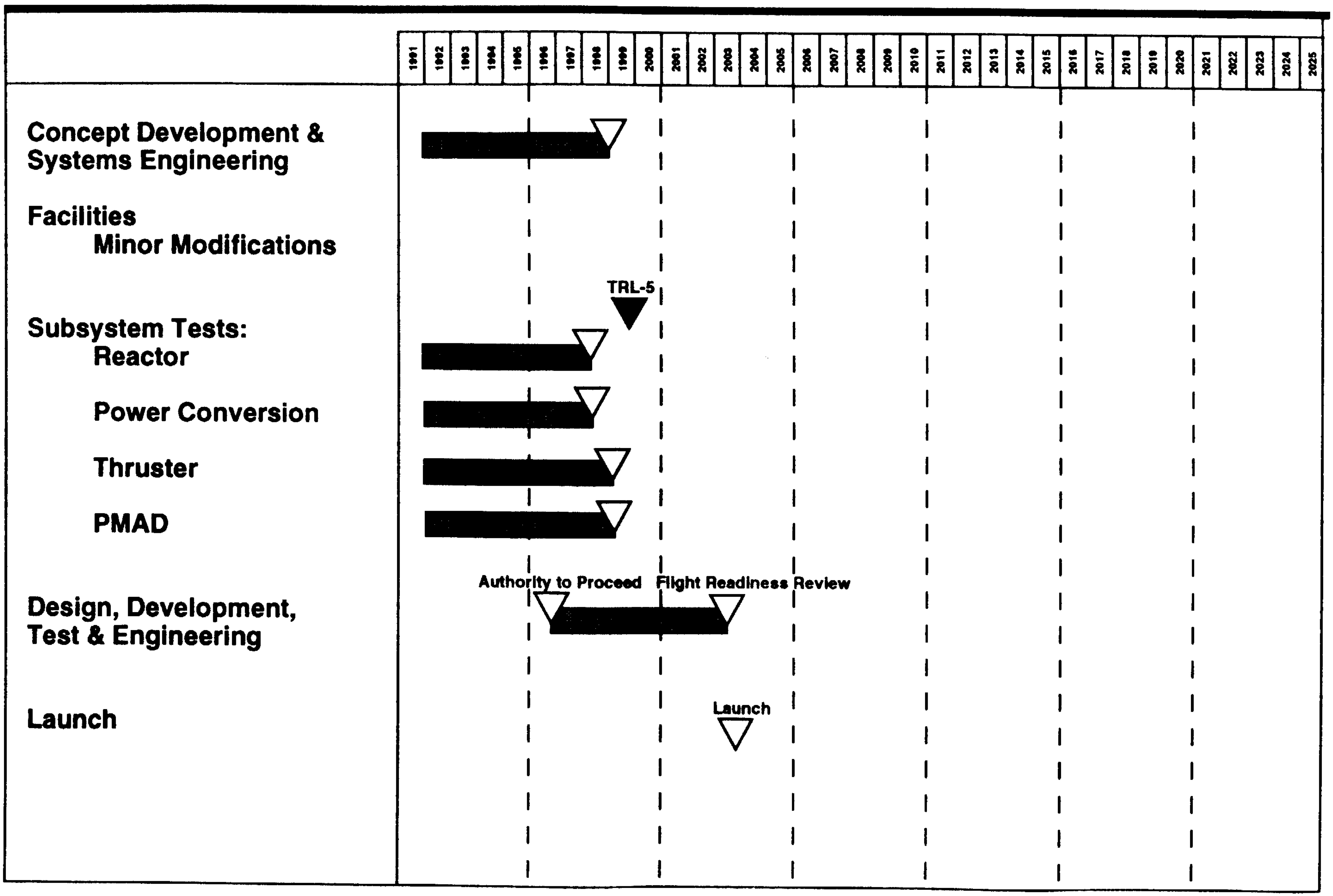

Figure 8.3

ADVANCED PIN TYPE REACTOR DEVELOPMENT PLAN

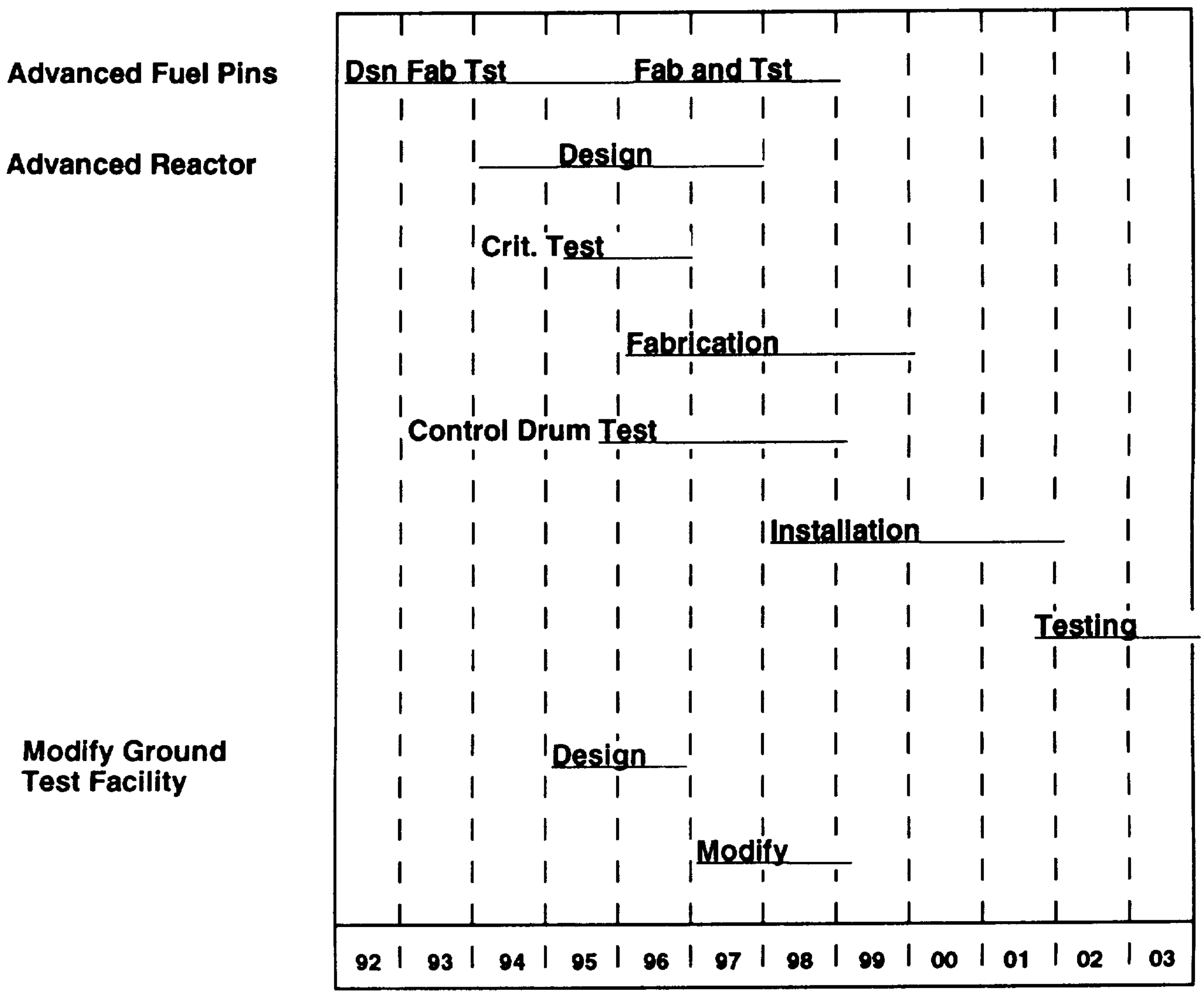

Figure 8.4

DEVELOPMENT SCHEDULE
RANKINE CYCLE POWER CONVERSION SYSTEM

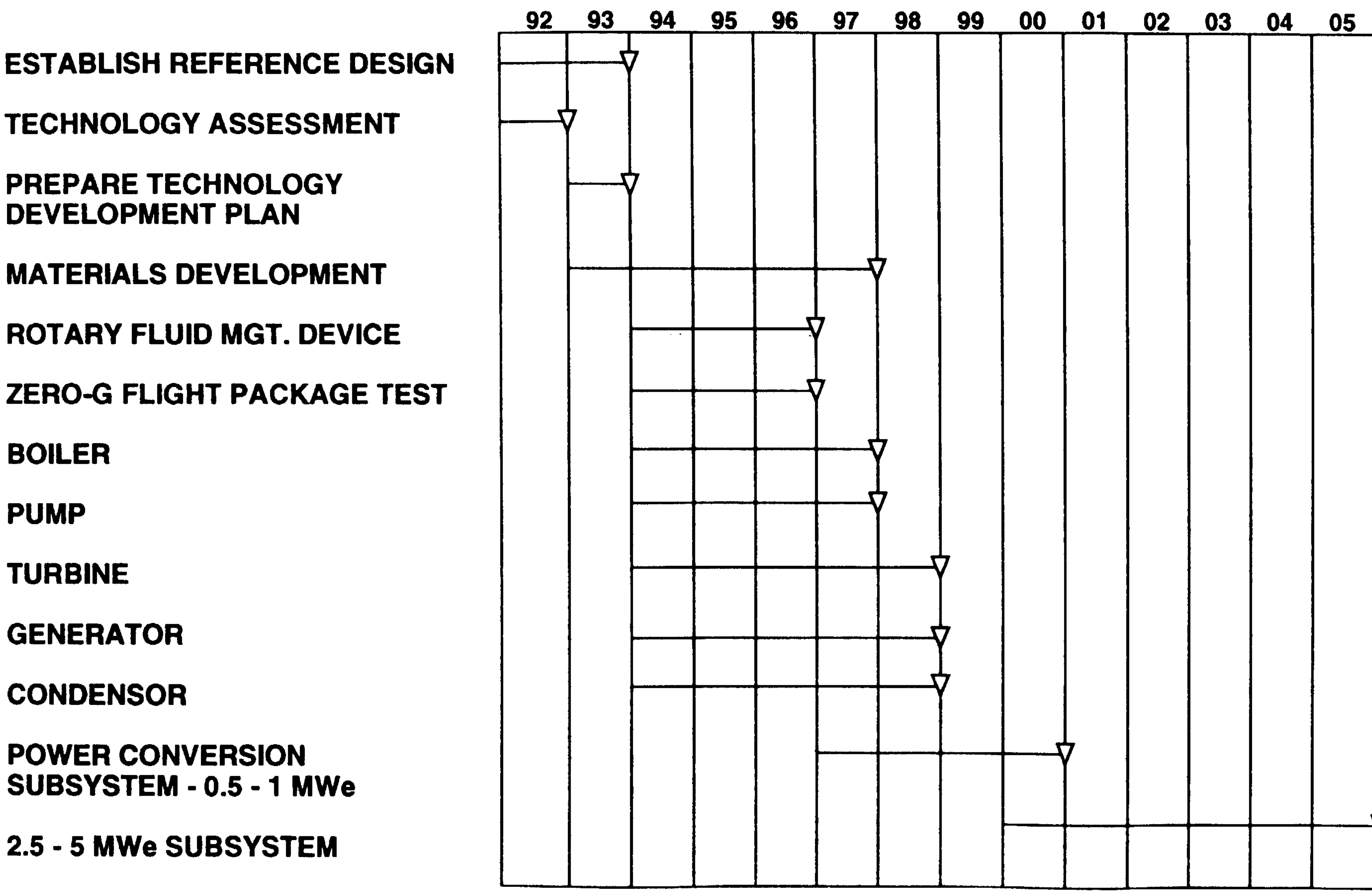

Figure 8.5

AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION

Lewis Research Center

NEP THERMAL MANAGEMENT PROGRAM PLAN

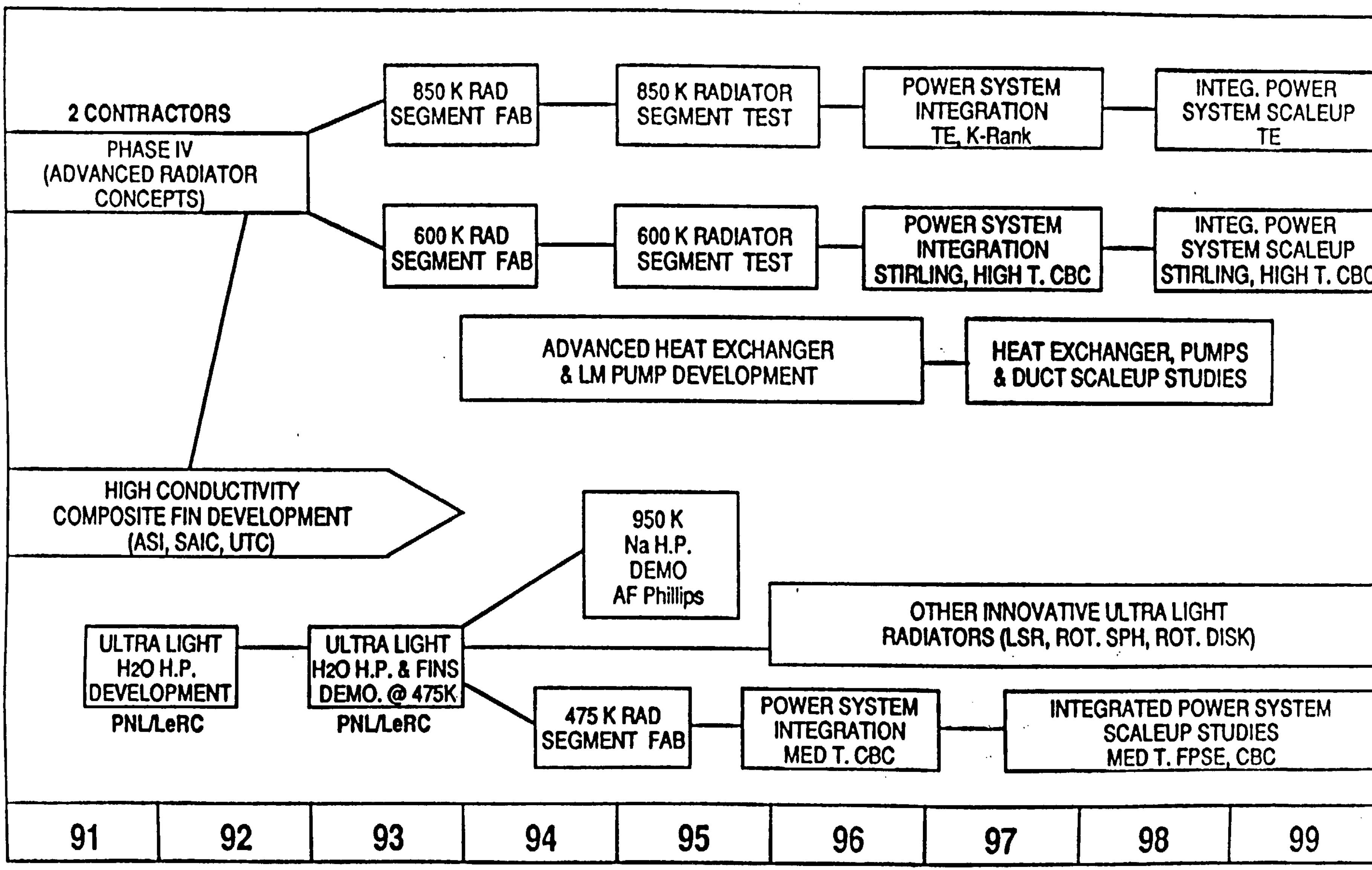

Figure 8.6

NEP POWER SYSTEM RADIATOR TECHNOLOGIES THRUSTS

POWER SYSTEMS (10 MWE)			RADIATOR TECHNOLOGIES			
		HEAT REJECTED MWt	TEMP K	NEAR TERM	MID TERM	FAR TERM
THERMIONIC	η_t = .15 η_t = .20	57.0 40.0	1000 1050	SS/Na HP 10 kg/m^2	CC/Na HP 5 kg/m^2	LSR, Fiber HP 2 kg/m^2
LIQUID METAL RANKINE	η_t = .18	45.5	950	10 kg/m^2 SS/Na HP	5.0 kg/m^2 C-C/Na HP	2 kg/m^2 LSR, Electrostatic 3 kg/m^2
THERMOELECTRIC	η_t = .05	190.0	850	9 kg/m^2 Nb Zr/K HP	5.0 kg/m^2 Ti-SiC/K HP	C-C HP 3 kg/m^2
CLOSED BRAYTON	η_t = .30	23.3	800 - 400	10 - 15 kg/m^2 MP Loop Mixed HP	Mixed HP Ti, C-C 5 kg/m^2	Fiber Fabric/H_2O 1-2 kg/m^2
STIRLING - FPSE	η_t = .33	20.0	500 - 450	10 kg/m^2 MP Loop Hg HP	Li-NaK Loop 5 kg/m^2	Fiber Fabric/H_2O 1-2 kg/m^2

Figure 8.7

ION PROPULSION DEVELOPMENT STATUS

HUGHES

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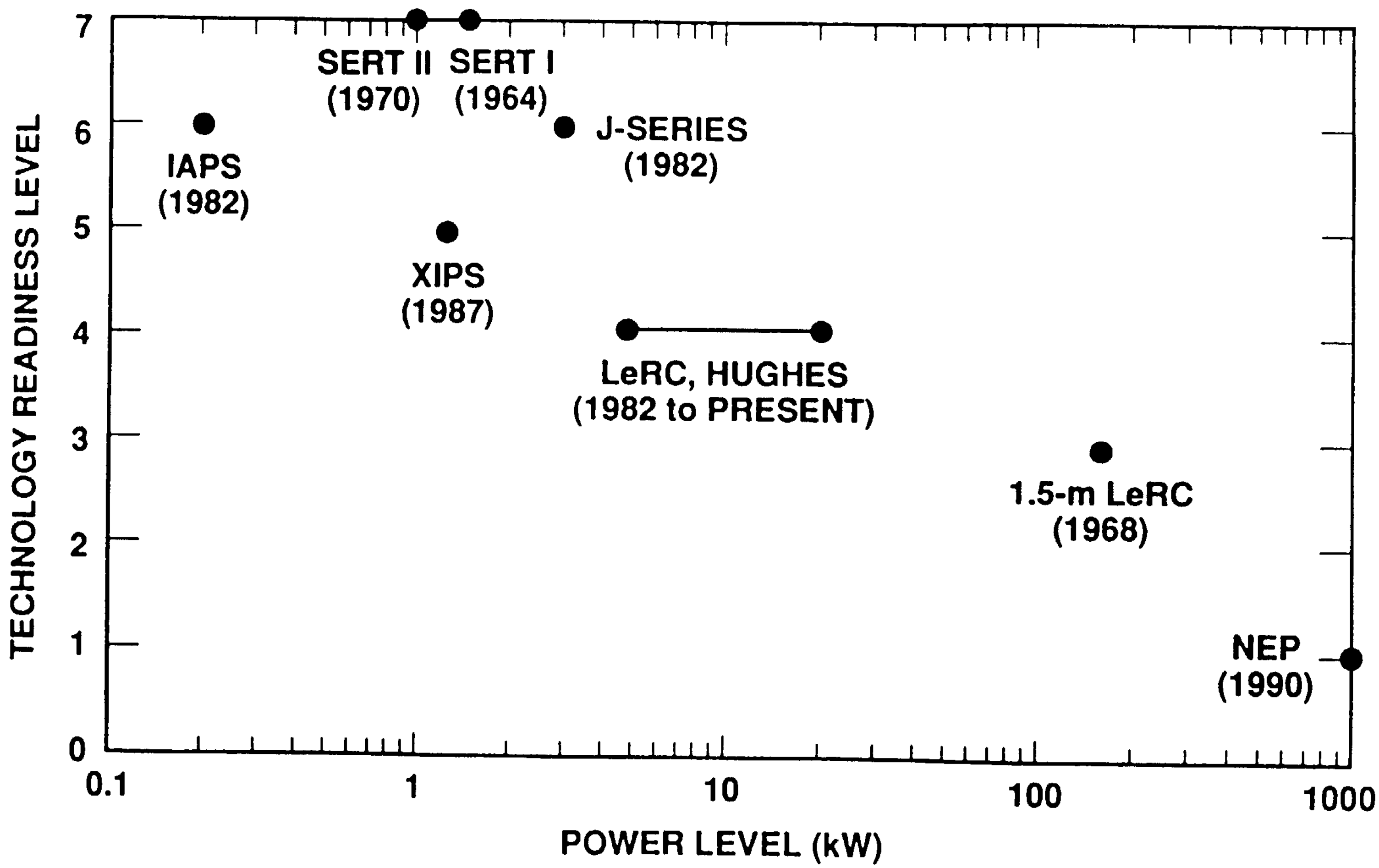


Figure 8.8

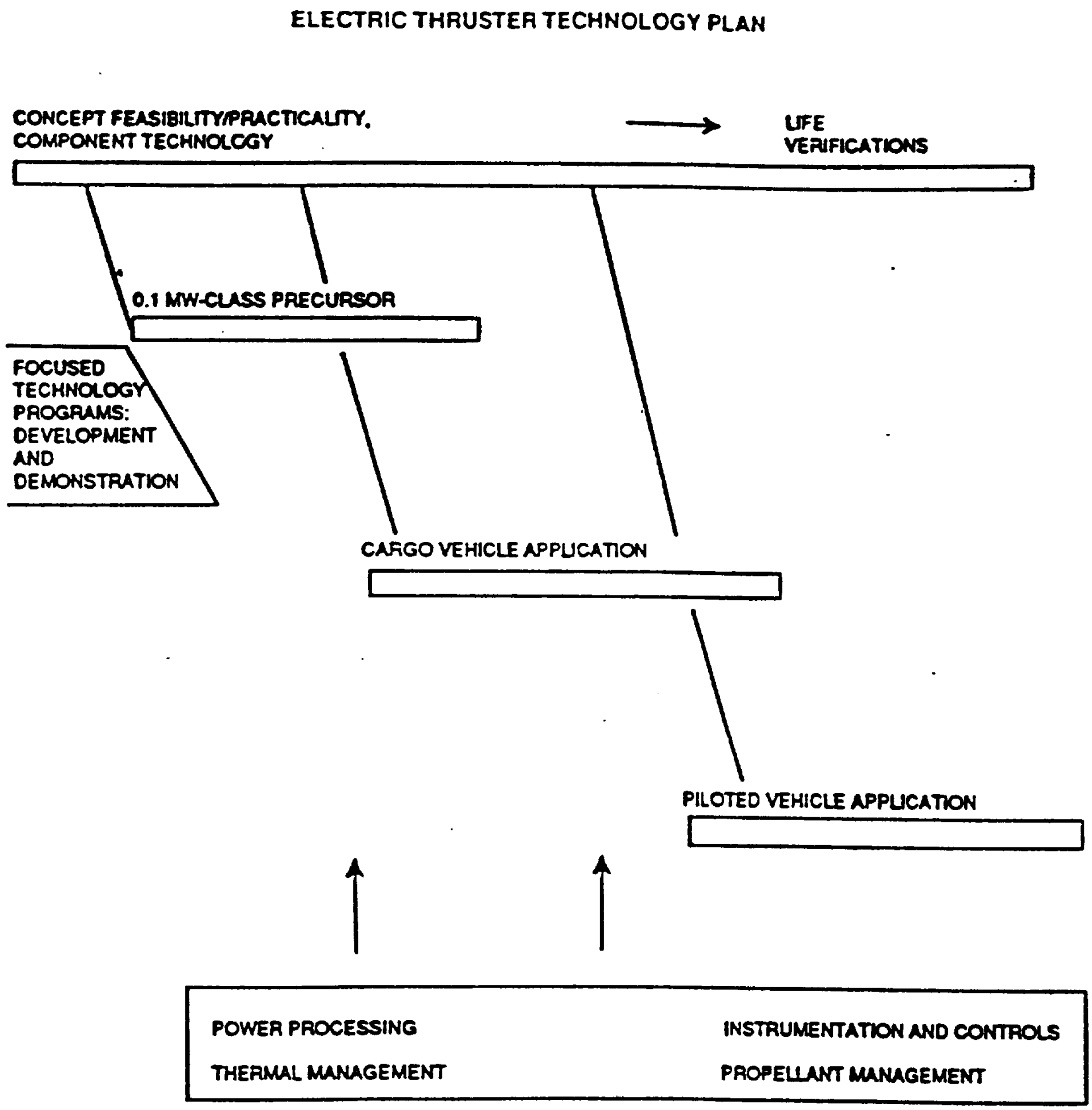
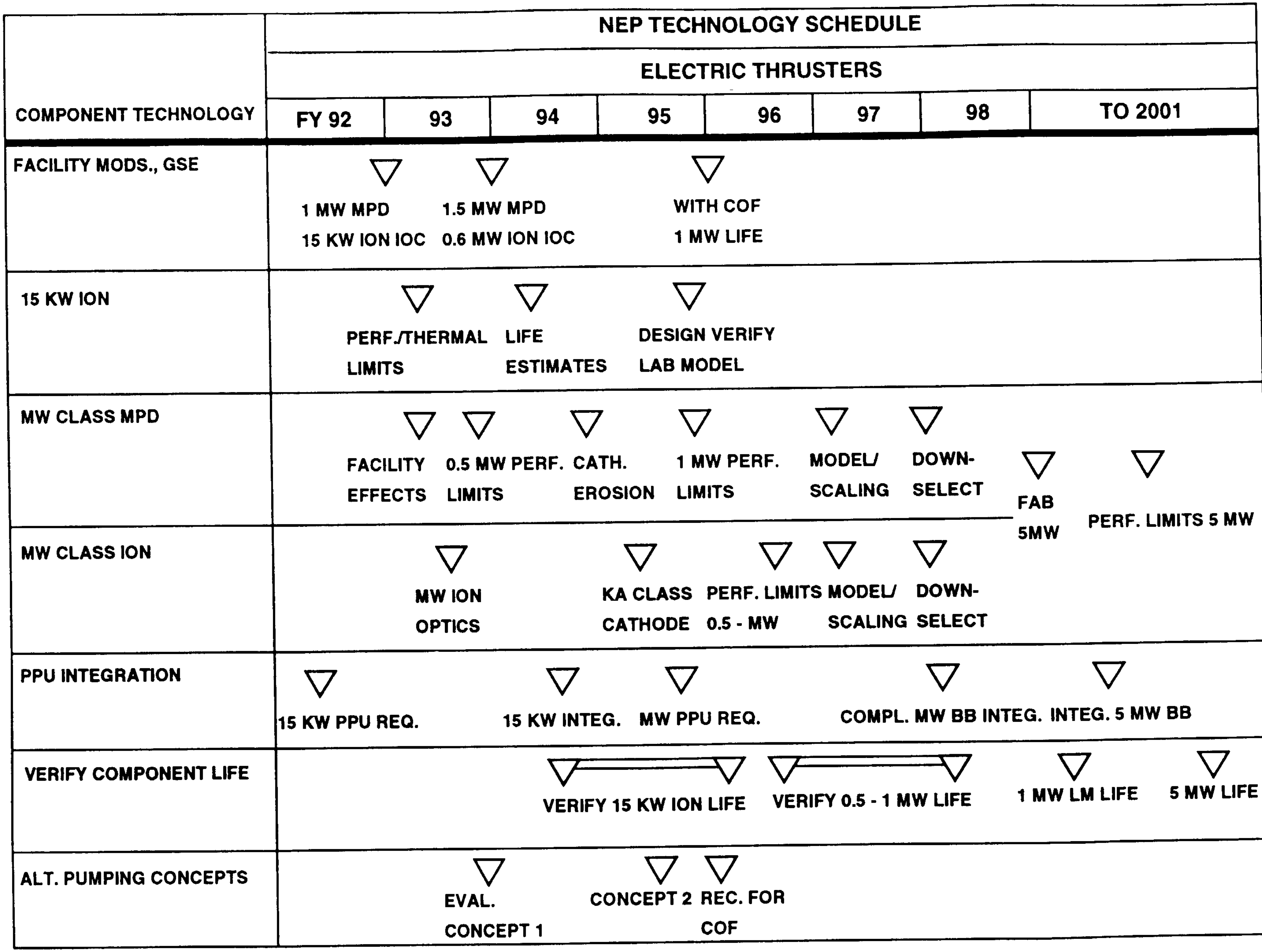

ELECTRIC THRUSTER TECHNOLOGY PLAN
CONCEPT FEASIBILITY/PRACTICALITY, COMPONENT TECHNOLOGY
LIFE VERIFICATIONS
0.1 MW-CLASS PRECURSOR
FOCUSED TECHNOLOGY PROGRAMS: DEVELOPMENT AND DEMONSTRATION
CARGO VEHICLE APPLICATION
PILOTED VEHICLE APPLICATION
POWER PROCESSING
THERMAL MANAGEMENT
INSTRUMENTATION AND CONTROLS
PROPELLANT MANAGEMENT

Figure 8.9


NEP TECHNOLOGY SCHEDULE
ELECTRIC THRUSTERS
COMPONENT TECHNOLOGY
FY 92
93
94
95
96
97
98
TO 2001
FACILITY MODS., GSE
1 MW MPD
15 KW ION IOC
1.5 MW MPD
0.6 MW ION IOC
WITH COF
1 MW LIFE
15 KW ION
PERF./THERMAL
LIMITS
LIFE
ESTIMATES
DESIGN VERIFY
LAB MODEL
MW CLASS MPD
FACILITY
EFFECTS
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LIMITS
CATH.
EROSION
1 MW PERF.
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SCALING
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FAB
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PERF. LIMITS 5 MW
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PPU INTEGRATION
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15 KW INTEG.
MW PPU REQ.
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INTEG. 5 MW BB
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VERIFY 15 KW ION LIFE
VERIFY 0.5 - 1 MW LIFE
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ALT. PUMPING CONCEPTS
EVAL.
CONCEPT 1
CONCEPT 2
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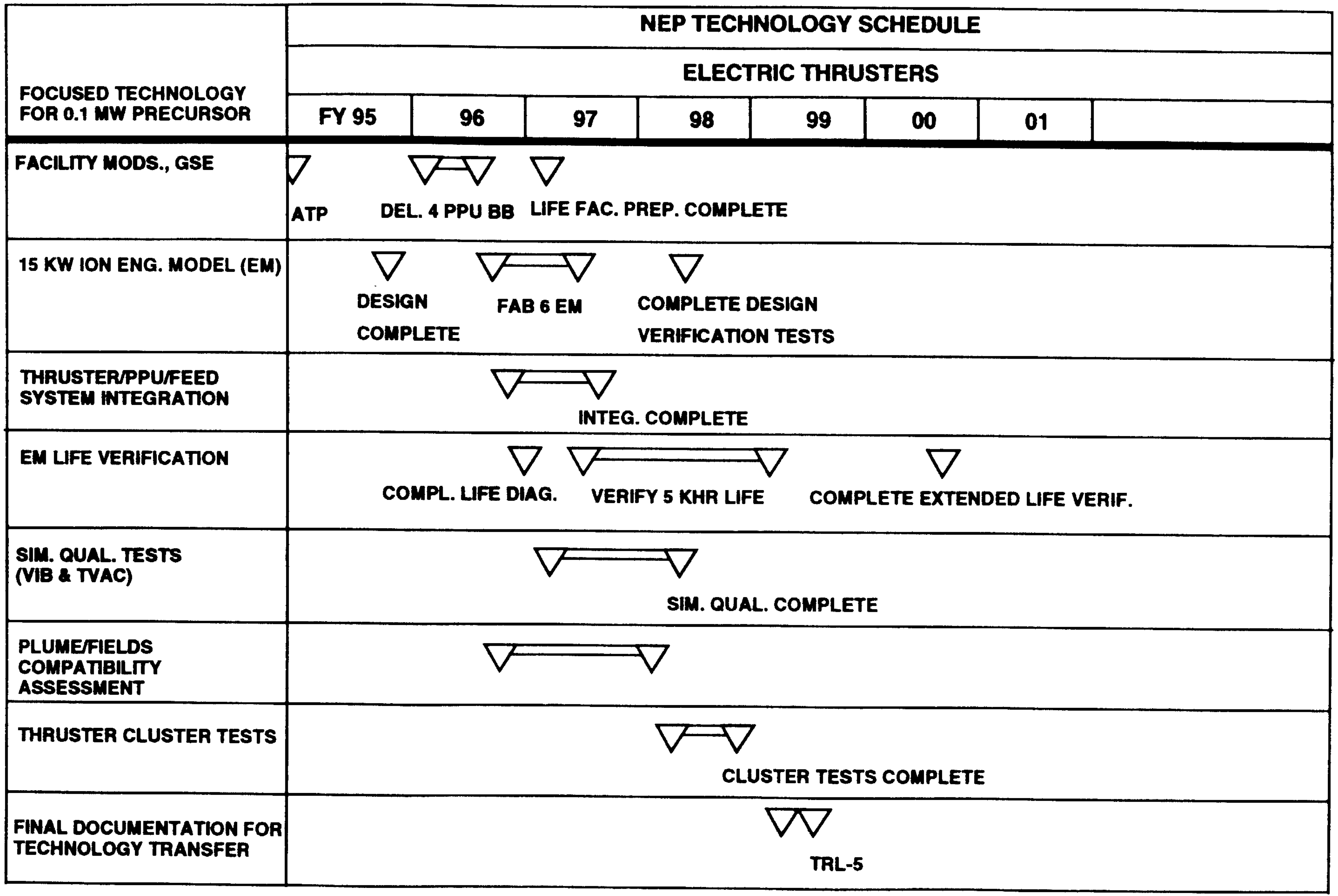
COF

Figure 8.10


NEP TECHNOLOGY SCHEDULE
ELECTRIC THRUSTERS
FOCUSED TECHNOLOGY FOR 0.1 MW PRECURSOR
FY 95
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FACILITY MODS., GSE
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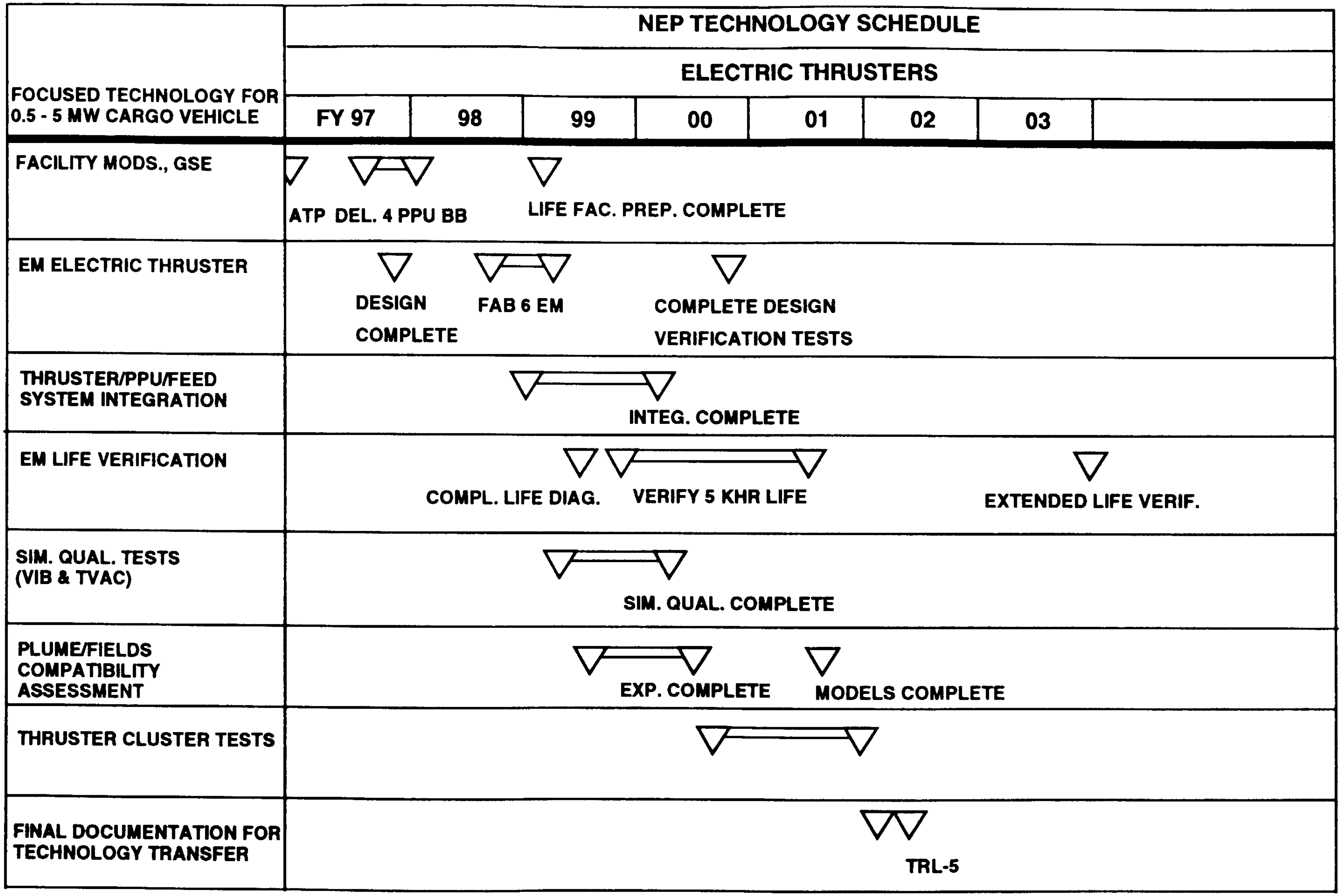
DEL. 4 PPU BB
LIFE FAC. PREP. COMPLETE
15 KW ION ENG. MODEL (EM)
DESIGN COMPLETE
FAB 6 EM
COMPLETE DESIGN VERIFICATION TESTS
THRUSTER/PPU/FEED SYSTEM INTEGRATION
INTEG. COMPLETE
EM LIFE VERIFICATION
COMPL. LIFE DIAG.
VERIFY 5 KHR LIFE
COMPLETE EXTENDED LIFE VERIF.
SIM. QUAL. TESTS (VIB & TVAC)
SIM. QUAL. COMPLETE
PLUME/FIELDS COMPATIBILITY ASSESSMENT
THRUSTER CLUSTER TESTS
CLUSTER TESTS COMPLETE
FINAL DOCUMENTATION FOR TECHNOLOGY TRANSFER
TRL-5

Figure 8.11


NEP TECHNOLOGY SCHEDULE
ELECTRIC THRUSTERS
FOCUSED TECHNOLOGY FOR 0.5 - 5 MW CARGO VEHICLE
FY 97
98
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02
03
FACILITY MODS., GSE
ATP
DEL. 4 PPU BB
LIFE FAC. PREP. COMPLETE
EM ELECTRIC THRUSTER
DESIGN COMPLETE
FAB 6 EM
COMPLETE DESIGN VERIFICATION TESTS
THRUSTER/PPU/FEED SYSTEM INTEGRATION
INTEG. COMPLETE
EM LIFE VERIFICATION
COMPL. LIFE DIAG.
VERIFY 5 KHR LIFE
EXTENDED LIFE VERIF.
SIM. QUAL. TESTS (VIB & TVAC)
SIM. QUAL. COMPLETE
PLUME/FIELDS COMPATIBILITY ASSESSMENT
EXP. COMPLETE
MODELS COMPLETE
THRUSTER CLUSTER TESTS
FINAL DOCUMENTATION FOR TECHNOLOGY TRANSFER
TRL-5

Figure 8.12

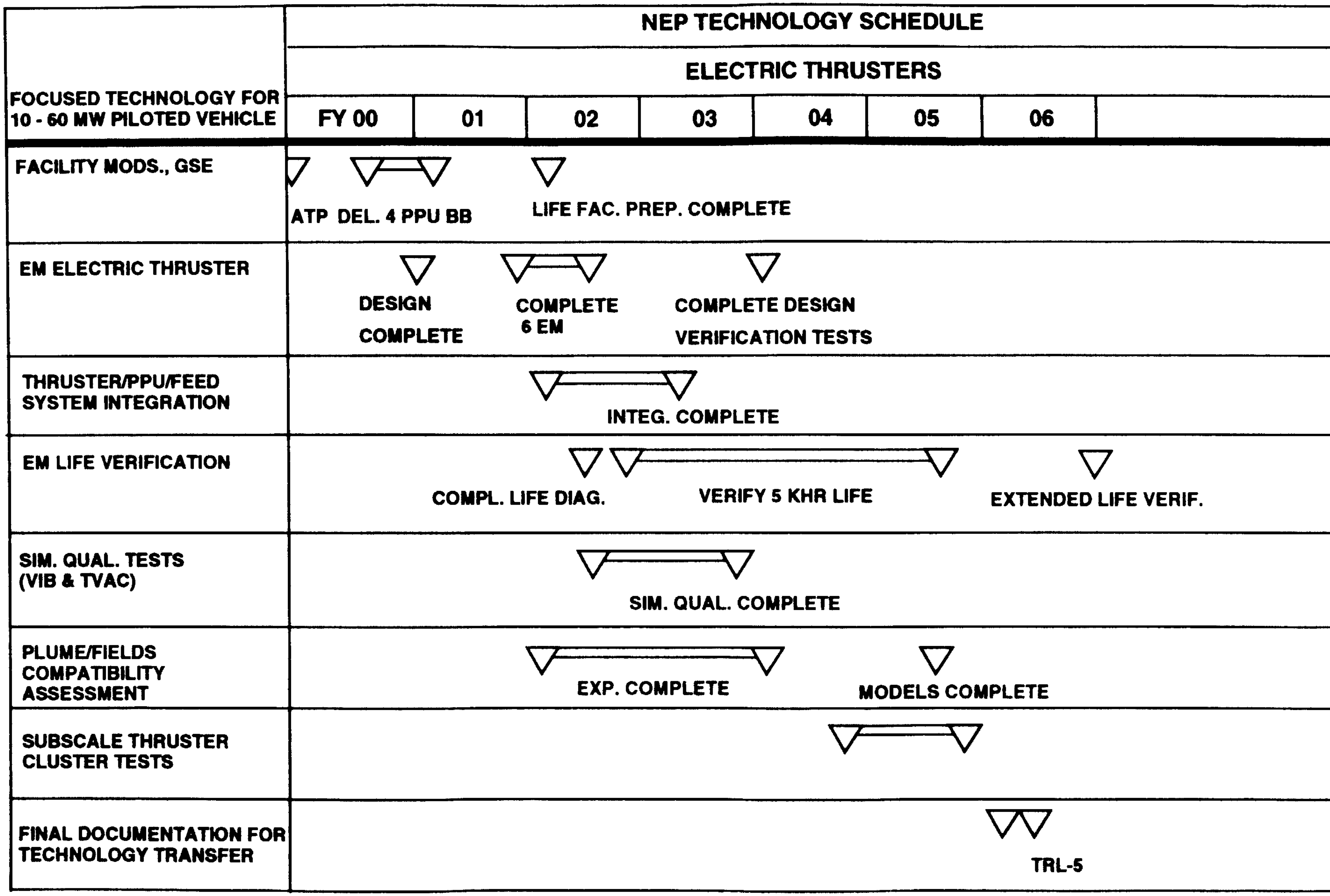

NEP TECHNOLOGY SCHEDULE
ELECTRIC THRUSTERS
FOCUSED TECHNOLOGY FOR 10 - 60 MW PILOTED VEHICLE
FY 00
01
02
03
04
05
06
FACILITY MODS., GSE
ATP
DEL. 4 PPU BB
LIFE FAC. PREP. COMPLETE
EM ELECTRIC THRUSTER
DESIGN COMPLETE
COMPLETE 6 EM
COMPLETE DESIGN VERIFICATION TESTS
THRUSTER/PPU/FEED SYSTEM INTEGRATION
INTEG. COMPLETE
EM LIFE VERIFICATION
COMPL. LIFE DIAG.
VERIFY 5 KHR LIFE
EXTENDED LIFE VERIF.
SIM. QUAL. TESTS (VIB & TVAC)
SIM. QUAL. COMPLETE
PLUME/FIELDS COMPATIBILITY ASSESSMENT
EXP. COMPLETE
MODELS COMPLETE
SUBSCALE THRUSTER CLUSTER TESTS
FINAL DOCUMENTATION FOR TECHNOLOGY TRANSFER
TRL-5

Figure 8.13

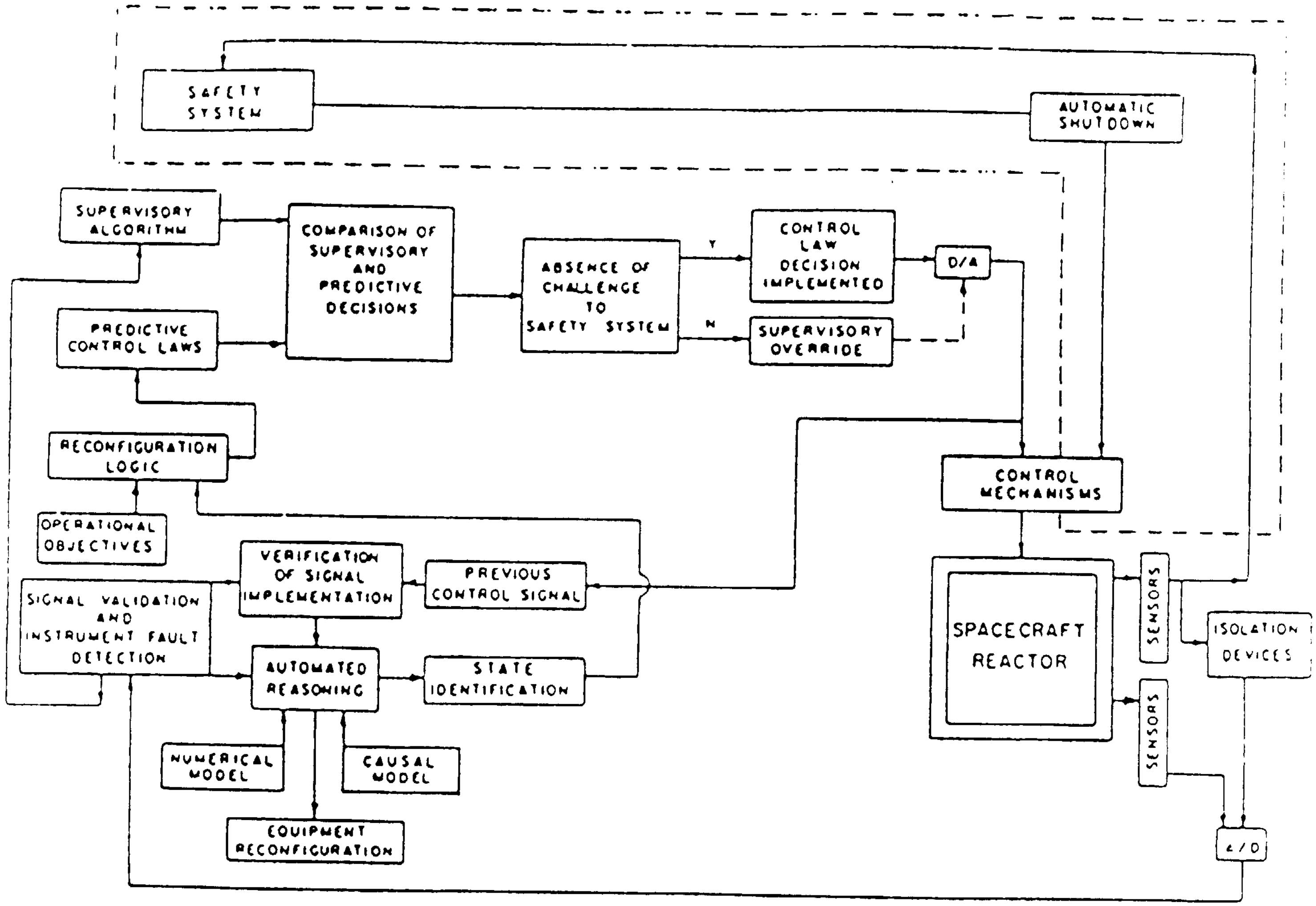


Figure 8.14: Structure of an Autonomous Controller

NEP Evolutionary Fuels Strategy

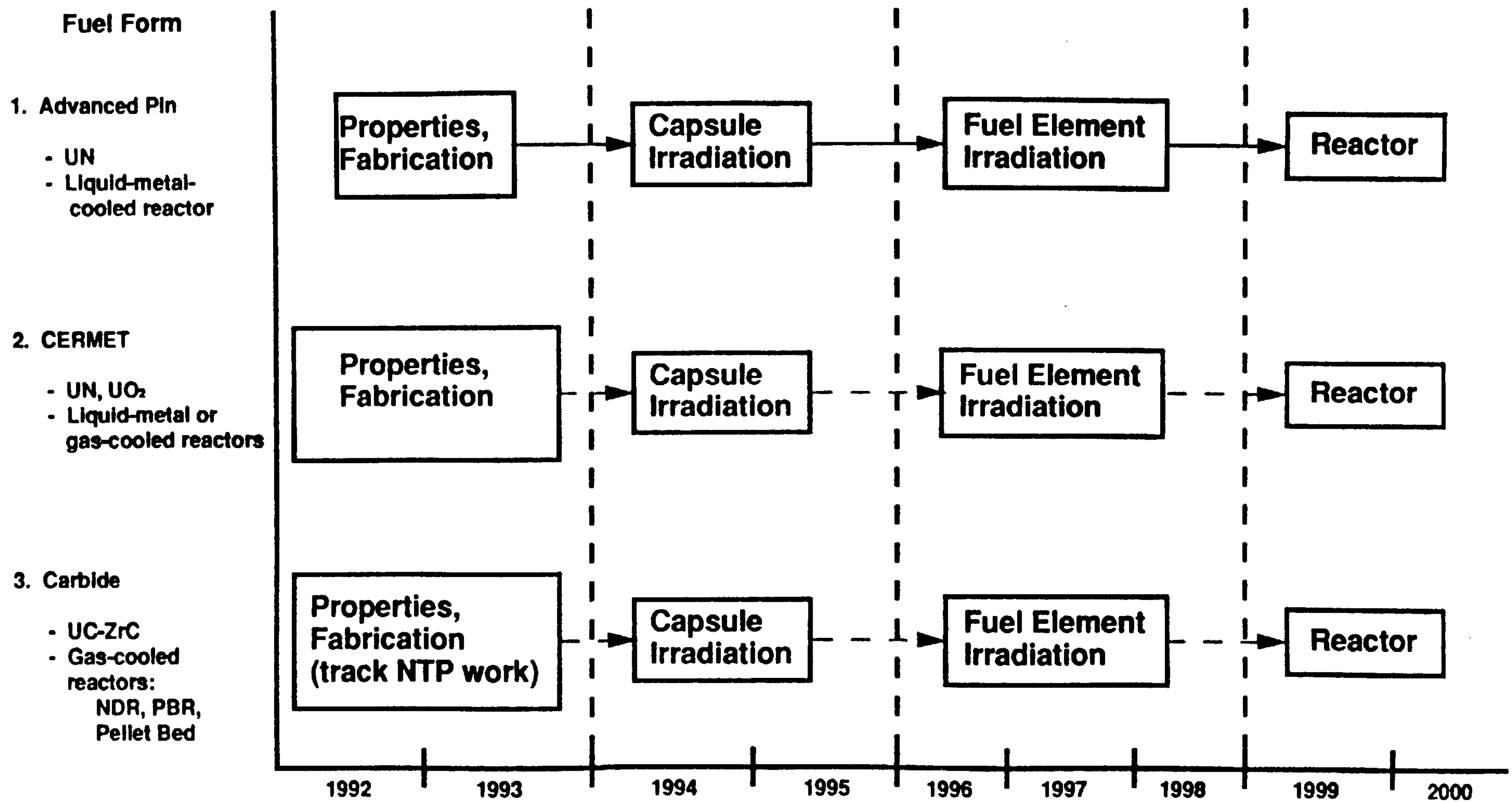


Figure 8.15

9.0 INNOVATIVE TECHNOLOGY

The exigent development of nuclear electric propulsion, from present low power applications to the megawatt level of performance required for piloted missions, will require an aggressive R & D program. As explained in Section 8, the NEP base technology program is designed to address focused technology requirements. Here, each focus embodies the research, development and demonstration necessary to support NEP system concepts which meet specific NEP mission requirements. Furthermore, each focus or mission advances the NEP state-of-the-art in an evolutionary manner. In this way, the base NEP technology program addresses the full spectrum of relevant missions from low power robotic precursor missions of the 100 kWe class to the megawatt cargo and piloted missions.

Within the envisaged base technology program, concepts deemed "most advanced" will be baselined as principal NEP technologies. Here, the term "most advanced" refers to technologies that are considered most likely to meet programmatic milestones without requiring huge "leaps" in scientific understanding or technology development. These baselined technologies will probably embody the greatest foundation of research or developmental history. A selection of baseline technologies, which may require a comprehensive technology trade study, is important in order to focus limited resources on achieving programmatic milestones in a timely manner.

In contrast, and in view of the scientific and engineering breadth necessary to achieve multimegawatt electric propulsion, it is recognized that ultimately the development of NEP cannot afford to prematurely downselect technologies. That is, flexibility between support of the base program and innovative alternatives to the base program is necessary in order to assure programmatic balance. Augmentations to the baselined technologies should be developed that afford higher payoff performance, albeit at an increased programmatic risk.

As envisaged, the NEP innovative technology effort supports two major activities: Concept Improvement research and Advanced Concepts research. Concept Improvement research seeks to improve, in an evolutionary way, the principal technologies that are supported in the base program. These "improvements" may lead to higher mission performance or shorter development time. Concept Improvement research is mainly directed towards augmenting the baseline technologies and exploring the high performance aspects of the base technologies at an earlier date than allowed in the base technology program.

In contrast, Advanced Concepts research seeks to develop, in a revolutionary way, advanced NEP. This research addresses the development of concepts and technologies that are not part of the base program. Therefore, it is limited to concepts that offer a substantial improvement over those in the base program, but with an increased element of perceived risk. In essence, this is the activity area where the high risk, high payoff part of the NEP program is supported. Within the Innovative Technology effort, the Concept Improvement and Advanced Concept activities will be balanced to maintain flexibility in the base program while supporting new, exciting and high benefit/risk ideas.

9.1 CANDIDATE INNOVATIVE TECHNOLOGIES

A variety of concepts exist that augment the baselined technologies discussed in Section 8. These concepts (first presented in Section 6) have the potential to favorably impact the base program in every subsystem of NEP (power generation, conversion, conditioning and propulsion). However, their scientific or technical immaturity precludes them from base technology consideration. The NEP technologies classified as "innovative" are shown in Table 9.1. These technology options are felt to have benefit/risk ratios too low as to expect their development to a Technology Readiness Level 5 (subsystem ground test) by the year 2005. The year 2005 was chosen so that the technologies would be available in time to be considered for the SEI missions.

9.2 PROPOSED EARLY INNOVATIVE TECHNOLOGY EFFORTS

In reviewing the plethora of potential candidates for innovative technologies, it is clear that a criteria for candidate selection must be based on a broad assessment of the technical feasibility and mission benefit of each system proposed. This assessment further serves to prioritize those technologies upon which research and development efforts can be focused most effectively within the prescribed budget. However, in planning for the near term, where the results of this technical assessment are not available, it is prudent to consider concepts that satisfy the NEP innovative criteria and that have some established technical basis and ongoing effort. These identified technologies and their perceived benefit are summarized below.

9.2.1 Vapor Core - MHD - MPD Modeling

Vapor core fission reactors promise not only high thrust, high specific impulse (~2500 seconds) performance for far term nuclear thermal propulsion, but as an ionization source for MHD power conversion for far term NEP. The integration of a gas core reactor with an MHD electrical convertor and high power MPD may provide very low specific mass NEP. A possible early study task would initiate the development of models for vapor core reactor flow, neutronics, and MHD power conversion for use in projecting system feasibility and performance. Phenomena to be modeled include two phase flow, flow separation, neutronics of a flowing uranium vapor/plasma, non-equilibrium fluid flow including fission products induced ionization, and the MHD power conversion processes. Connection with high power MPD thruster modeling should also be included.

9.2.2 Power Conversion - High Temperature Fabric Radiators

Low-mass heat rejection is critical technology for high performance NEP, where low specific mass is crucial. Light weight fabric radiators may provide an efficient, low-mass space based heat rejection technology. Current research shows promise in low temperature (< 500°K) water heat pipes using woven ceramic fiber mantles with metal foil liners. A possible task would extend the ongoing fabric radiator work to alternate, more relevant working fluids (liquid metals) at SEI relevant operating temperatures (> 800°K). As such, it would provide an important extension and assessment of this technology.

9.2.3 Propulsion

Three tasks are proposed for the early-on electric propulsion innovative technology effort: advanced thruster survey, multimegawatt MPD thruster proof-of-concept, and pulsed inductive thruster (PIT) proof-of-concept.

9.2.3.1 Advanced Thruster Survey

A number of advanced thruster concepts have been proposed for future electric propulsion applications. (Most of the concepts are briefly reviewed in Section 6.1.5). In general, very little quantitative understanding has been developed for these concepts. Also, very little quantitative analysis of thruster performance and mission applicability exists.

An analysis of advanced thruster performance is necessary to provide predictions of advanced thruster applicability to future NEP missions. This analysis should form a basis for prioritization of thruster proof-of-concept development. In this task, advanced NEP thrusters would be evaluated by first analyzing the existing experimental database with a view to thruster physics performance. Using this database, modeling and associated theoretical analysis would estimate specific impulse, efficiency, thrust, power rating, and lifetime. These performance estimates would then be utilized to compare projected mission performance of each thruster with the baseline nuclear thermal and nuclear electric technologies. Drawing on these comparisons, the study will provide recommendations on which concepts should proceed to the proof-of-concept level.

9.2.3.2 Multimegawatt MPD Thruster Proof-of-Concept

The propitious application of nuclear electric propulsion to SEI class missions will require the aggressive development of multimegawatt electric (MMWe) propulsion. A proposed task addresses multimegawatt, large scale, quasi-steady-state MPD thruster development at the proof-of-concept level (TRL-3). The study will evaluate the efficacy of MMWe, large scale MPD thrusters and develop a quantitative and benchmarked model of multimegawatt MPD thruster performance scaling. The research, based on an integrated experimental-theoretical approach, utilizes existing high-power capabilities in plasma technology; including facilities, diagnostics, and analytic and computational physics. Included is the application of analytic and numerical plasma theory to understanding and modeling the physical processes inherent in MPD thrusters.

9.2.3.3 Pulsed Inductive Thruster Proof-of-Concept

Receptively pulsed energetic plasma thrusters can exhibit several performance benefits in comparison with steady-state thrusters. These benefits derive from electrodeless operation and the possibility of very high power high specific impulse pulsed operation leading to improved propellant utilization. The Pulsed Inductive Thruster (PIT) exemplifies the potential of pulsed thruster technology. PIT prototypes have been developed in the laboratory at the 5 kJ per pulse level. Performance, in terms of specific impulse and efficiency, look promising. However, an SEI relevant PIT performance assessment will require measurement at appropriate power levels and repetition rates. This task addresses key PIT performance issues such as high fidelity specific impulse and efficiency assessment, as well as the identification of key technical issues associated with PIT operation at high (SEI relevant) rep-rates.◆

NEP TECHNOLOGY OPTIONS

TECHNOLOGIES NOT EXPECTED TO REACH TRL-5 BY YEAR 2005

Boiling Potassium
Vapor Core

Electrochemical
Magnetohydrodynamic

Ceramic Fabric Heat Pipe
Liquid Sheet Radiator
Bubble Membrane

Very high power MPD
Electron Cyclotron Resonance
Ion Cyclotron Resonance
Variable Specific Impulse
Deflagration
Pulsed Plasmoid
Pulsed Inductive

Table 9.1

10.0 FACILITY REQUIREMENTS

Ground testing is an extremely critical activity in the validation of NEP technology to insure readiness of the technologies for flight system development. This section will convey the general approach to ground testing for NEP, present requirements for major facilities for ground testing NEP, and mention candidate facilities for meeting these major facility requirements.

10.1 GENERAL APPROACH TO NEP GROUND TESTING

NEP technology will be validated at the subsystem level (TRL-5). There are two reasons for this. First, because there is only an electrical coupling between NEP power and propulsion subsystems, each subsystem should be capable of being adequately simulated in the testing of the other. That is, an electrical load simulating the electric thruster and power processing subsystems could be used in the NEP power subsystem test, and vice versa. Second, test environments for space power and space propulsion subsystems are very different from one another. Space power subsystems require a clean, static thermal vacuum environment, while the test environment for electric thrusters is characterized by the presence of an effluent. These requirements, in combination with the extreme distances between reactor and thruster subsystems to minimize radiation effects, place severe demands on a facility to test "everything under one roof". Instead, subsystems might be tested alone (e.g., thrusters) or in combination (e.g., a simultaneous test of reactor, power conversion, and heat rejection). Flight system demonstrations from orbit about Earth, first using low power NEP systems for orbit raising missions and planetary missions, and finally MW-class NEP systems for SEI cargo missions would then provide the necessary system and flight experience to assure reliable performance of the piloted NEP system.

The subsystem development for NEP will generally proceed from small-scale feasibility demonstrations and component tests to large scale and lifetime testing.

Associated with feasibility demonstrations, component tests, and similar small-scale operations at the subsystem level will be a variety of test facilities. These "programmatic" facilities will be supported directly by research and development funding. Typical of these will be liquid-metal loops for turbine development, and relatively small vacuum facilities to develop thrusters. The programmatic test facilities are essential to the rapid and successful development of the subsystems required for NEP. Existing facilities may be adaptable but new first-class equipment will be required in many cases to advance the state-of-the-art in critical technologies, and the funding for the facilities is a significant part of that required for the program. The NEP Technology panel, however, did not attempt to identify these requirements in detail; the appropriate process to define such requirements will be through proposal and review procedures associated with the component development process.

Major facilities will be required for full scale (or near full-scale) testing of large components, subsystems, and especially for lifetime testing. The facilities will generally be expensive (many $M), requiring specifically budgeted capital investment, will require a long length of time to establish their readiness for use, and will require dedicated operational teams.

10.2 REQUIREMENTS FOR MAJOR FACILITIES

Performance and schedule requirements for megawatt NEP mandate that requirements for major ground test facilities be defined as early as possible. To identify major facility requirements, the panel considered robotic, cargo, and piloted NEP missions occurring in time periods from 2004 - 2014.

For near-term missions, such as interplanetary robotic or near-Earth, the only major facilities required are for thrusters. Reactor, power conversion, and heat rejection subsystem development are expected to use the results of the SP-100 program.

As the development moves beyond the initial stages, additional major facilities are required to meet testing needs for four of the subsystems: reactor, power conversion, heat rejection, and thruster, with the option to upgrade some of these facilities at a later date for even higher power NEP systems.

The resultant major facility requirements for ground testing the NEP subsystem technologies needed for SEI missions are listed in Table 10.1.

For reactor testing, a facility having at least a 25 MWt, but no greater than 50 MWt, capacity will be required. Given also are a vacuum vessel and reactor containment structure. Outlet temperature ranges from 1500 - 2000 K are desired, depending on whether a liquid-metal-cooled or high-temperature-gas-cooled reactor is tested. Some capability to test shielding is required. Liquid metal handling capability might be required.

Redundancy approaches to power conversion imply an initial capability to test only a 2.5 MWe power conversion module and a 10 MWe heat rejection subsystem, meaning that a power conversion/ heat rejection test facility will be required to provide a 2.5 MWe electrical load and a 12.5 MWt heat dump. Again, it might be advantageous to specify a single facility to simultaneously test the reactor, power conversion, and heat rejection subsystems. A facility for power conversion testing should be upgradable to 5 MWe.

No major facilities are anticipated to test PMAD subsystems. Final ground testing of PMAD will be performed simultaneously with a neighboring subsystem.

For the testing of electric thrusters, propellant flow rates of up to 1.2 grams per second will be necessary, which translates into the capability to test thrusters at up to 2.5 MW electrical power rating. Facilities will be required for both performance and life testing.

The ground testing schedule is derived from postulated flight schedules for robotic, cargo, and piloted missions, shown in Figure 10.1 (previously shown in Figures 8.1 through 8.3), implying a range of TRL-5 dates for the required technologies. The earliest TRL-5 date, 1998, should provide technologies in time for a 2004 inter-planetary robotic and near-Earth mission, while the latest TRL-5 date, 2005, would be timely for SEI piloted mission needs. This leaves very little time for bringing the major test facilities on line and carrying out performance and lifetime tests. A Subsystem Major Test Facility schedule is provided as Figure 10.2. The schedule for each facility can be considered as three stages: (1) design, modification, and commissioning, (2) use for development and performance testing for major components, and (3) lifetime testing. As lifetimes of 10,000 hours might be required for subsystems and components, a minimum of two years could be required to achieve (3). Thus, planning and design need to be initiated soon, especially for the reactor which has long lead-time requirements for safety and environmental issues, and for the thruster which needs an initial product as early as 1998.

10.3 LEADING CANDIDATES FOR MAJOR GROUND TEST FACILITIES

Facilities to meet the needs identified above were identified in cooperation with the Nuclear Propulsion Facilities Panel[1]. Most of these facilities have been catalogued into a draft document by the Lewis Research Center[2].

10.3.1 Reactors

The requirements for a reactor for an NEP interplanetary robotic or near-Earth mission will be met by SP-100 technology. For a larger thermal power reactor required for SEI missions, ground test facilities do exist which could be used by the NEP program. The Primary facility is the SP-100 Reactor Ground Test Facility at Hanford. Information on this facility and other potential facilities follows:

Site	Facility	Comments
Hanford	SP-100	Reconfigure for larger reactor
Sandia	Bldg. 6580	

ORNL	Experimental Gas Cooled Reactor	Reactor testing areas in standby
INEL	Contained Test Facility (CTF)	Previously operated as the Loss-of-Fluid Test (LOFT) Facility

10.3.2 Power Conversion

Facilities required for development of the power conversion system for NEP might include:

- Materials Test Facility: Capable of testing 1550°K electric heated refractory metal piping containing lithium coupled to a refractory metal single tube potassium boiler and condenser.
- Subscale Boiler Test Facility: Capable of testing an electric heated lithium heat source coupled to an 800 kWt potassium boiler.
- Quarter-Scale Power Conversion Test Facility: Capable of testing a 500-1000 kWe potassium-generator with an electric heated lithium heat source coupled to a potassium boiler.
- Full-Scale Power Conversion Test Facility: Capable of testing a 2.5-5 MWe potassium generator with an electric heated lithium heat source coupled to a potassium boiler. The facility is expected to be approximately 50 ft. diameter x 50 ft. high.

Existing facilities which could be converted to be used as a power conversion facility are identified as follows:

Site	Facility	Comments
ORNL	Thermal Hydraulic Out-of-Reactor Safety (THORS) Facility	Vacuum or inert gas enclosure needed
AEDC	10V Chamber	Modifications Required
AEDC	J-2A Facility	Modifications Required
AEDC	Mark I Chamber	Modifications Required
LeRC	Space Power Facility	Modifications Required

10.3.3 Thruster

Two facilities are recommended, one to handle up to 1 MWe thrusters and one for up to 5 MWe thrusters. The second of these can serve as a second 1 MWe facility by using only a portion of its (operationally expensive) cryogenic system. Each must be capable of a base pressure better than 10-6 Torr. Preliminary specifications of size would require, respectively, minimum diameters of 5 and 10 meters and lengths of 10 and 30 meters. [16' x 31' and 33' x 98']

Gas flows are nominally 0.5 and 1.2 g/sec, with pumping speeds of 10 and 25 million liters/sec. During the tests, the background neutral pressure must be less than 10-5 Torr for ion thrusters and a factor of $3x10^{-4}$ for MPD thrusters. This requires, roughly, cryopanel surface areas of 200 and 1000 m^2 respectively, and helium refrigeration capacities of 2 and 10 kW (@ 4°K). The panel temperature, either 4°K or 20°K, is determined by the gas to be pumped and is important in sizing the system. Nitrogen refrigeration systems for the cryopanel shrouds are probably needed for long term tests.

For the helium refrigerators there is a choice of a large, closed loop refrigeration system, or large storage dewars to supply liquid during tests, and smaller refrigerators with concomitant long down-times to reliquify the gas for the next test. Using storage will avoid the expense of a large refrigerator but will limit the test time for a given thruster test. This limit, as well as the required time for typical tests, needs to be determined. For the nitrogen system the options are closed-loop refrigerator or batch purchase of N_2. Except for long life (or partial life) test, batch purchase may be the most economical. A closed loop N_2 system is probably required for the 10,000 hour life test.

The energy in the thruster exhaust, either in thermal or directed energy, must be removed in a cooled baffle arrangement before it hits the cryopanels. The sputtered material efflux from beam targets must be controlled so optical properties of thermal control surfaces are not changed. The power level in the exhaust exceeds by a large amount the refrigeration capacity of the cryopanels. An appropriate cooling system must be part of the facility as is the power conditioning for the thruster power.

These requirements are the major cost drivers of the installation. The cryopanel/refrigeration systems are big cost items (given that a variety of large tanks exist around the U.S.) and their specifications need to be evaluated carefully. Regeneration of the cryopanels (by warming them to release the gases frozen to them) during operations is very difficult, but various ideas have been advanced. The need to do so must be established, or else the allowed down-time during lifetest should be determined.

A number of larger vacuum tanks suitable for testing thrusters after (often extensive) modifications, notably at AEDC, LLNL, NASA Lewis, and ORNL, were reviewed. There may be others, but these institutions are characterized not only by having facilities, but in having experience in or directly related to thruster development. Existing facilities which could be adapted for thruster development include:

Facility	Dia/Length (ft)	N2 (kW)	He (kW)	Cryopanels (sq.m.)
AEDC				
Chamber 12V	12/35	90	8	100
Mark I	42/82	90	8	1000
LLNL				
MFTF	36/210	500	11	1000
TMX	12/72	batch (from MFTF)		none
NASA LeRC				
Tank 5	15/63	batch	0.11	41
Tank 6	25/72	batch	0	none
SPF	100/121	batch	0	none

All of the above, with modifications, are candidates for the 1 MWe facility. Several already have substantial refrigeration facilities and cryopanels, but others need these additions. The larger tanks could also be used for 5 MWe facilities.

To better evaluate the costs (and time) needed for modifying these facilities, a better definition of the requirements is necessary, followed by engineering evaluations and estimates. We recommend that this comparison be made.

Proof-of-concept testing can be done in many of the facilities listed in the above table. Typical operation for up to several hours will be followed by a period of regeneration of the cryopanels and reaccumulation of liquid helium. However, lifetime tests and systems tests will require extended test periods (up to 10,000 hours) and can be done only in facilities which have large cryoplants and regeneration capability during operation. The MFTF facility is the only plant with a large enough helium capability at 4°K; regeneration techniques need to be evaluated. In addition, the size of its vacuum vessel and its other capabilities make it the leading candidate for a Lifetime and System Test Facility.

10.4 CONCLUSIONS

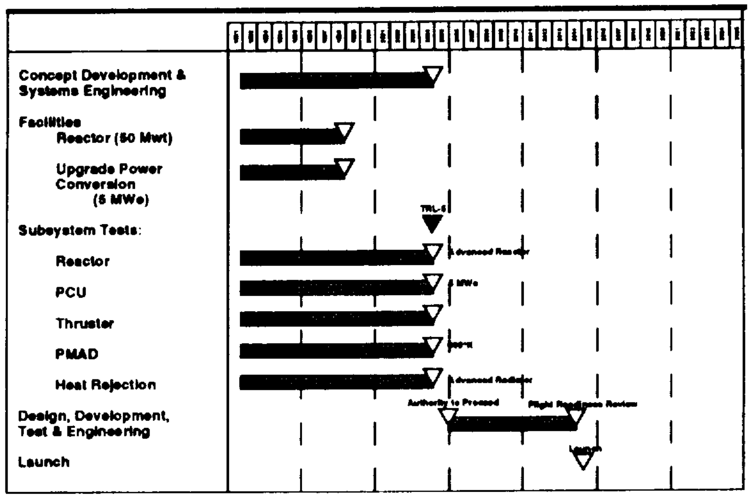
In conclusion, the facility requirements for testing megawatt NEP appear to be met using existing U.S. facilities. Detailed definition of NEP ground testing needs will follow from decisions on readiness need date, subsystem test combinations, and performance and life test requirements, and will enable a greater level of specification of the requirements on major facilities for NEP.◆

MAJOR FACILITY REQUIREMENTS FOR GROUND TESTING NEP SUBSYSTEM TECHNOLOGIES IN A RELEVANT ENVIRONMENT

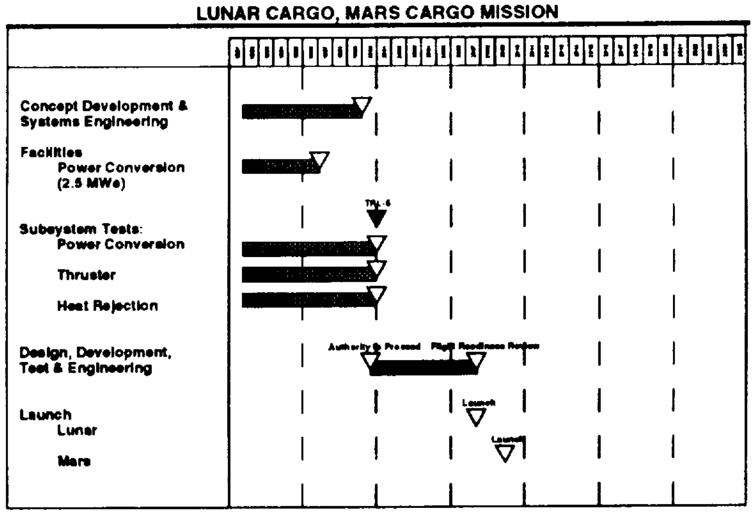
SUBSYSTEM	REQUIREMENT
REACTOR	50 MW heat rejection, Vacuum vessel Reactor containment, Capability to test shielding Outlet temperature = 1500 - 2000°K Liquid metal handling facility Control room; Maintenance, storage, decontamination and disposal facility Lifetime = 5 - 7 years
POWER CONVERSION	2.5 MW (electric load), 12.5 MW (heat source/dump) Vacuum or inert gas insulation, Support facilities Lifetime = 5 - 7 years Upgradable to 5 MW (electric load)
THERMAL MANAGEMENT	10 MW, Upgradable to 20 MW
POWER MANAGEMENT AND DISTRIBUTION	No major facility required
THRUSTER	Up to 1.2 grams per second effluent flowrate 2.5 MW electric power 10 meter (m) diameter by 30 m long tank size

Table 10.1

MARS PILOTED MISSION



LUNAR CARGO, MARS CARGO MISSION



INTERPLANETARY ROBOTIC OR NEAR-EARTH ORBIT-RAISING MISSION

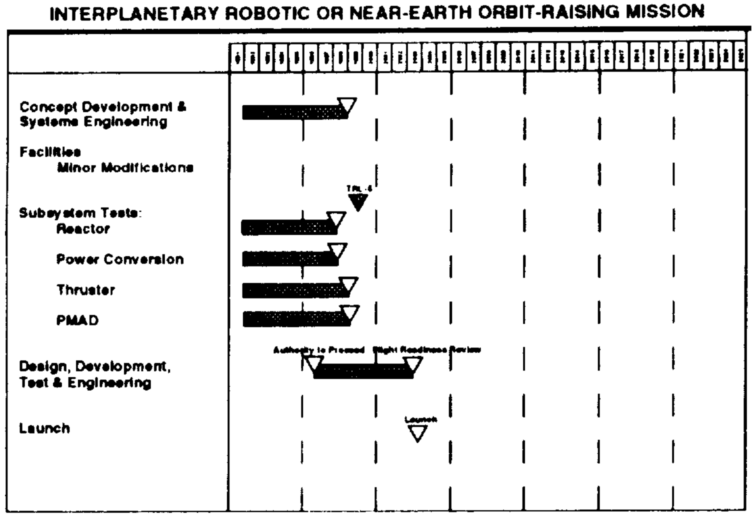


Figure 10.1

SUBSYSTEM MAJOR TEST FACILITY REQUIREMENTS

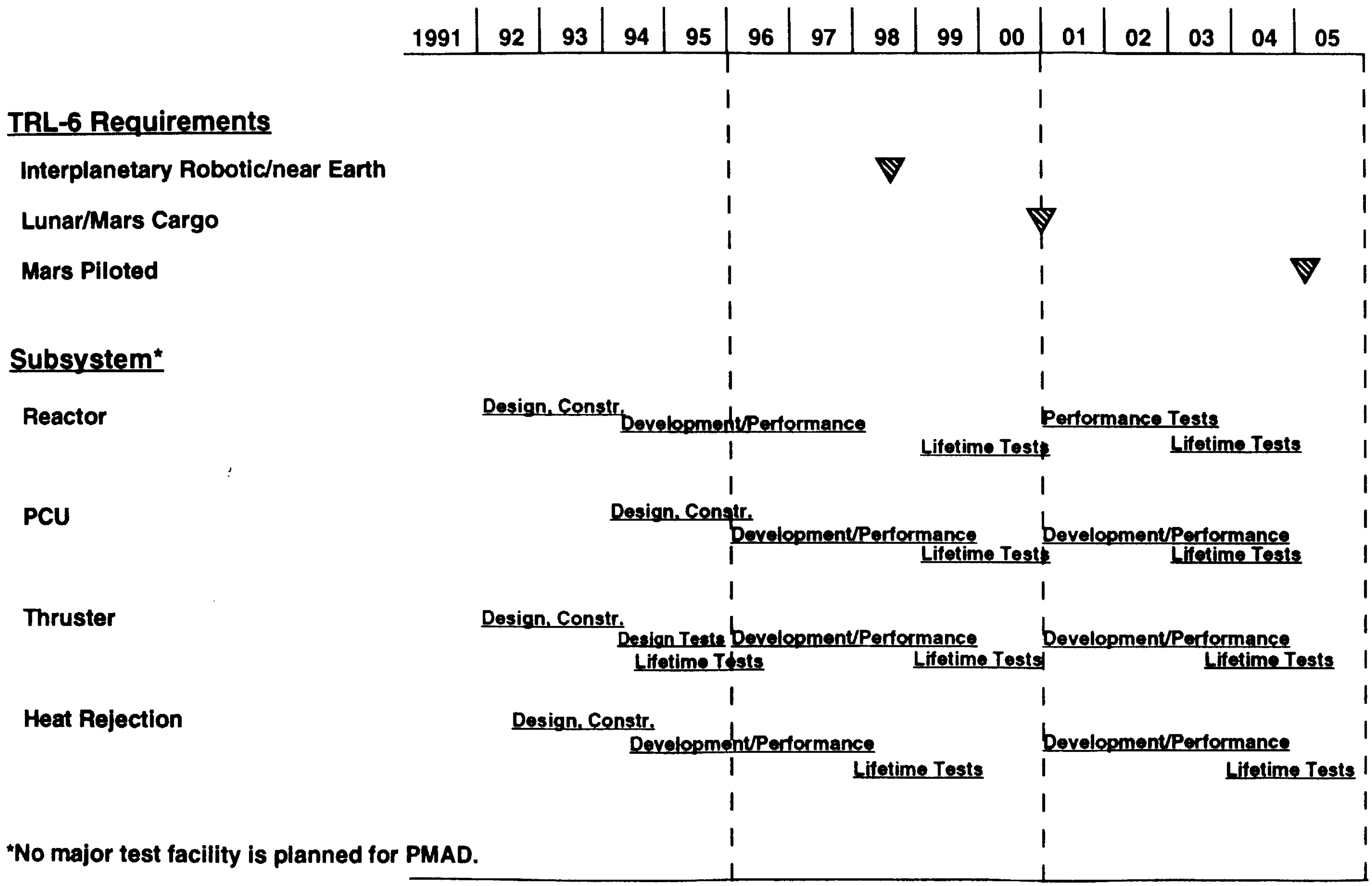


Figure 10.2

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APPENDIX 1: NUCLEAR ELECTRIC PROPULSION FLIGHT TESTING

A1.1 INTRODUCTION

Electric propulsion systems are unique in that they encompass two elements that are traditionally considered systems in themselves: power and propulsion. This characteristic is in contrast to current chemical propulsion systems, in which the rocket is the lowest level of system that can be defined. Electric propulsion is also unique in that the size of the propulsion system is such that the propulsion system design in essence defines the vehicle design. Thus, a piloted Mars mission vehicle using NEP will be defined to a great extent by the radiators and shielding requirements of the NEP system, rather than by the payload. All of these characteristics create testing requirements and options that are unique to electric propulsion.

On one level of detail, an NEP system can be considered to be made up of two subsystems: power and propulsion. These subsystems can also function as systems; for example, a power supply for an NEP vehicle could also be used for surface applications, independent of the thruster system. At a lower level of detail, the NEP subsystems are:

Reactor	(Power)
Shield	(Power)
Power Conversion	(Power)
Radiator	(Power)
Power Conditioning	(Propulsion, Power)
Thrusters	(Propulsion)

To a certain extent, some of these subsystems can be developed independently. For example, the radiator system can be tested using a heat source simulating the power conversion outlet conditions without requiring the use of the actual power conversion loop. Similarly, the thrusters and attendant power processing may be tested using a simulated power supply, rather than requiring a full reactor - power conversion - thruster system. This characteristic of EP systems will be discussed further in later sections.

The size of NEP systems to be developed for SEI missions introduces a potential difficulty in the ground testing of full sized systems. A multimegawatt NEP system would involve a high power reactor, hundreds of square meters of radiator area, and 50 - 100 m separation distances from the reactor to the payload plane. The high vacuum (and therefore pumping) requirements of megawatt electric thrusters introduce stringent facility requirements not necessary for testing of the power systems, while the nuclear power system introduces nuclear safety and containment requirements not necessary for testing thrusters. Similarly, the scale of the overall system imposes large volume requirements not necessary for performance or operation demonstrations prior to flight.

A1.2 BACKGROUND

Electric propulsion systems have been flown in space for more than 20 years. Resistojets are currently in use for station keeping in communications satellites. Pulsed plasma thrusters were flown extensively on Navy satellites for use in attitude control. Mercury ion thrusters were flown and operated successfully on the SERT I and II missions, and the SERT II spacecraft would be operational today if the propellant had not run out. The Solar Electric Propulsion Stage (SEPS) had reached the point of engineering prototype development for a Halley's comet mission prior to cancellation of the mission. These missions were powered by solar photovoltaic panels and batteries. In point of fact, a small cesium ion thruster was included on the only U.S. flight test of a space nuclear power reactor, the SNAP-10A, leaving NEP as the only nuclear propulsion system with flight experience. This foundation in flight testing and operation of electric propulsion systems has led to some general characteristics and flight qualification approaches for electric propulsion.

Past successful flights of EP systems were qualified and tested on the ground using a separable approach. The power systems were assembled and ground tested individually, and the thruster/power processor systems were tested in vacuum independently. The interfaces between these two systems were specified in suitable detail to ensure compatibility. After development and testing of these systems in the appropriate simulated space environments (vacuum, thermal), the assembled satellite vehicle was then flight qualified as any satellite would be (vibration, heating, ...). A valuable lesson learned from this experience is the importance in identifying all subsystem interface requirements, and testing the interfaces to a level suitable for flight qualification and satisfactory operation in space.

A1.3 NEP TESTING/FLIGHT QUALIFICATION APPROACH

NEP systems are anticipated to be developed in an evolutionary fashion over time. Initial systems would be at low (<1 MWe) power levels, performing Earth orbital and robotic interplanetary missions. The next generation systems would operate at 1 - 5 MWe, suitable for Lunar and Mars Cargo vehicles. Finally, systems producing 5 - 10 MWe would be developed for piloted Mars missions. In terms of system demonstration and flight qualification, this evolutionary approach provides, in manageable increments progressive experience in system flight and operational requirements.

As stated previously, the nature of NEP systems precludes full-up ground testing, with the exception perhaps of the first low power systems. Instead, ground testing of subsystems would be done in conjunction with meticulous interface requirements and testing. Subscale ground testing of subsystem assemblies, such as a power conversion unit and radiator panel, could be accomplished where needed. Technologies requiring microgravity environments would be flight tested at the component level. Full system testing takes place in the vacuum and thermal environment of space with the first flight system. All subsystems and components are to be flight qualified prior to the first flight. Due to the evolutionary nature of NEP development, common or similar subsystem technologies could be flight tested in one phase and used over multiple missions. For example, flight qualification and demonstration of a rotary fluid management device at one power level could serve as a basis for later similar components.

An example development/testing program would proceed as follows:

- I. Low Power (100 kWe)
  - A. Sub-systems:
    1. Reactor - SP-100, 2.5 MWt, 1350°K
    2. Power Conversion - Thermoelectric
    3. Radiator - Ref. Metal Heat Pipes
    4. Thruster - Argon Ion
  - B. Testing:
    1. Reactor Ground Test
    2. TE/Liquid Metal Loop Test
    3. TE/Radiator Panel Test
    4. Argon Ion Thruster/Power Processor Test
       - a. Thruster performance, life tests; PPU performance, integration
  - C. Flight Test:
    1. Full up LEO/GEO OTV
- II. Cargo
  - A. Sub-systems:
    1. Reactor - SP-100, 25 MWt, 1350°K
    2. Power Conversion - K Rankine
    3. Radiator - Ref. Metal Heat Pipes
    4. Thruster - Magnetoplasmadynamic
  - B. Testing:
    1. Reactor Ground tests
    2. K-Rankine system tests
    3. K-Rankine/Radiator Panel tests
    4. MPD Thruster/Power Processor tests
       - a. Thruster performance, life tests; PPU performance, integration
  - C. Flight Tests:

1. Zero - g Fluid Management
2. Full up Lunar Mission

III. Piloted (5 - 10 MWe)
   A. Sub-systems:
      1. Reactor - SP-100, 25-50 MWt, Higher Temperature
      2. Power Conversion - K Rankine
      3. Radiator - Carbon-Carbon Composite Heat Pipes
      4. Thruster - Magnetoplasmadynamic
   B. Testing:
      1. Radiator tests
      2. K-Rankine/Radiator Panel tests
      3. MPD Thruster/Power Processor tests - High Temperature PPU
   C. Flight Tests:
      1. Full up Lunar Mission

Some commonality of technology and subsystem can be noted in the above example. In particular, after proving zero-g fluid management capabilities in Phase II, little or no additional component testing may be necessary for Phase III, depending on the similarity in design between phases. In all cases, the full up system tests are performed in space, and capitalize on the growing experience with each phase.

The actual testing scheme will depend upon the results of further mission design and technology development. The above examples are only used to illustrate the possible progression throughout an integrated NEP development program. The key element in such a strategy is the unique qualities of nuclear electric propulsion systems and technologies that enable such a modular approach to testing.◆

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13. ABSTRACT (*Maximum 200 words*)

A project in NEP technology is being established to develop the NEP technologies needed for advanced propulsion systems. A paced approach has been suggested which calls for progressive development of NEP component and subsystem level technologies, leading to major facility testing to achieve TRL-5 for megawatt NEP for SEI mission applications. This approach is designed to validate NEP power and propulsion technologies from kilowatt class rating to megawatt class rating. Such a paced approach would have the benefit of achieving the development, testing, and flight of NEP systems in an evolutionary manner. This approach may have the additional benefit of synergistic application with SEI extraterrestrial surface nuclear power applications, also.

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