SP-100 DYNAMIC POWER AND LITHIUM-PROPELLANT MPD NUCLEAR ELECTRIC PROPULSION TECHNOLOGY REQUIREMENTS

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Abstract

The objective of this study was to evaluate the requirements (including system integration, design, test requirements, and schedule) for the propulsion and power conversion systems of a nuclear electric propulsion (NEP) vehicle using an SP-100 reactor with a dynamic power conversion system, Li-propellant magnetoplasmadynamic (MPD) thrusters, Li-propellant storage and feed systems, and the power conditioning electronics required to convert the power output from the power system to the form (voltage, current) needed by the thrusters. Potassium-Rankine power conversion systems have the potential for the greatest mission benefit in terms of minimum mass and volume (as compared to Brayton or Stirling power conversion systems), but they require the most development. High-current, low-voltage turboalternators are needed for the MPD thruster system envisioned here, although one alternative would be to use more near-term high-voltage alternators at the potential cost of higher rectifier losses or added transformer mass. Power processing is not expected to be a major technology driver, but development of high-current, low-voltage space- and radiation-qualified components is needed. Finally, increases in MPD thruster life would reduce mass, system complexity, and packaging constraints; similarly, higher thruster efficiencies are desirable to reduce trip time.

INTRODUCTION

The focus of this study was to address the technology readiness and development requirements of the dynamic power conversion, power processing, and magnetoplasmadynamic (MPD) thruster systems of a nuclear electric propulsion (NEP) vehicle designed for a Mars cargo mission (Frisbee and Hoffman 1993). The overall vehicle configuration shown in Figure 1 is based on the use of three 500-kW_e power modules each consisting of an SP-100 nuclear reactor and a dynamic power conversion system. A potassium (K) Rankine power conversion system had previously been found (Frisbee and Hoffman 1993) to have the greatest mission benefit in terms of minimum mass and volume, as compared to a Brayton or Stirling power conversion system, and is the system evaluated here.

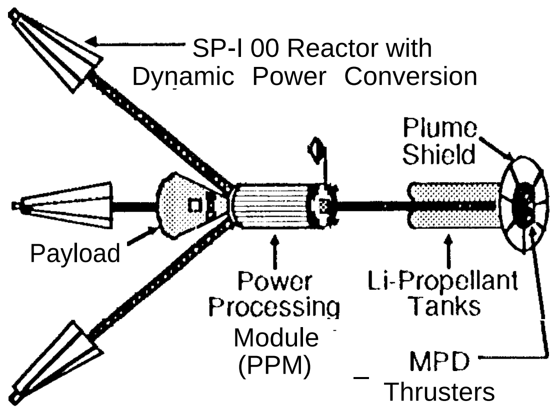

FIGURE 1. Megawatt-Class Nuclear Electric Propulsion (NEP) Vehicle with Li-Propellant MPD Thrusters.

The total 1500 kW_e of "bus" electric power is divided between two 750-kW_e MPD thrusters. Lithium-propellant MPD thrusters were selected for characterization in this study based on their demonstrated megawatt-level power processing capability. We selected Li-propellant, applied-field MPD thrusters because of their projected good efficiency at relatively low specific impulse (I_{sp}). By contrast, a self-field MPD thruster has a lower projected efficiency and lower operating voltage than a corresponding applied-field MPD thruster (Frisbee and Hoffman 1993). MPD thruster lifetimes are projected to be about 3,000 hours (1/3 year); thus, for a roughly 2-year Mars cargo mission, at least 6 pairs of thrusters must be run in series. (A pair of gimballed thrusters are used to provide 3-axis spacecraft attitude control.) Additional thrusters are added for redundancy. Finally, the MPD thrusters can be throttled to accommodate reactor-out or other less-than-nominal power situations.

The payload (the Mars Lander Module) and the power processing module (PPM), which contains the power processing unit (PPU) electronics as well as the other spacecraft systems (chemical orbit raising and attitude control propulsion system, guidance, navigation, control, telecommunications, and so on), are kept at a 24-m distance from the reactor and power conversion systems to minimize the radiation and thermal effects of the power system on the PPM and payload. Similarly, a 25-m distance is used between the PPM and the lithium-propellant MPD thrusters in order to minimize the potential for contamination of the payload or the PPM radiator with condensable lithium from the thrusters' exhaust plumes. The overall vehicle configuration is also driven by the need to package the various components within a launch vehicle; we assumed the use of an Energia launch vehicle, which can transport a 100 metric tonne payload to low Earth orbit in a 5.5-m diameter by 37-m long payload envelope (Isokowitz 1991 and Bayer 1993). With these assumptions, it is possible to package the PPM, thruster clusters, Li propellant tanks, deployable plume shield, and reactor-to-PPM and PPM-to-thruster cluster booms in one Energia launch, the three reactor and power conversion modules in a second launch, and the payload in a third launch.

Finally, in evaluating the power conversion system, we assumed that the SP-100 reactor system would follow its previously planned development; thus, the SP-100 reactor subsystem was not treated in any detail. In the remainder of the paper, we will first review the current status and technology readiness level of the various systems, and conclude with an outline of the development and testing/qualification schedule for these systems.

REVIEW OF THE CURRENT STATE-OF-THE-ART TECHNOLOGY READINESS LEVELS AND DEVELOPMENT REQUIREMENTS

The current state-of-the-art, technology readiness, and needed research and development in each area of subsystem technology were determined by evaluating past work and accomplishments (Rocketdyne 1989, NASA Lewis Research Center 1992, Myers 1993, Polk and Pivirotto 1993, Harty 1992, Ewald and Vito 1993, and Temple 1993), and by assessing the future development requirements. The different components were assigned a National Aeronautics and Space Administration (NASA) technology readiness level, which is defined in Figure 2. The results for each of the components in the power conversion, power processing, and MPD thruster system are given in Tables 1 to 4.

LEVEL 1	BASIC PRINCIPLES OBSERVED AND REPORTED	TECHNOLOGY DEVELOPMENT
LEVEL 2	CONCEPTUAL DESIGN FORMULATED	
LEVEL 3	CONCEPTUAL DESIGN TESTED ANALYTICALLY OR EXPERIMENTALLY	
LEVEL 4	CRITICAL FUNCTION / CHARACTERISTIC DEMONSTRATED	
LEVEL 5	COMPONENT /BRASSBOARD TESTED IN RELEVANT ENVIRONMENT	ADVANCED DEVELOPMENT
LEVEL 6	PROTOTYPE /ENGINEERING MODEL TESTED IN RELEVANT ENVIRONMENT	
LEVEL 7	ENGINEERING MODEL TESTED IN SPACE	
LEVEL 8	"FLIGHT QUALIFIED" SYSTEM	FLIGHT SYSTEMS
LEVEL 9	"FLIGHT PROVEN" SYSTEM	

FIGURE 2. NASA Technology Readiness Levels.

TABLE 1. K-Rankine Power Conversion System Technology Assessment.

Item	State-of-the-Art Assessment	NASA Technology Readiness Level	Needed Research / Development
Piping	• Nb-1%Zr commercially available,	4	• Liquid metal mass transfer research
Boiler / Reheater	• Li-heated K boiler demonstrated in ORNL and NASA experiments	3	• Potassium boiling research • Single tube boiling experiments
Boiler Feed Turbopump	• Potassium turbopump has been tested at 1100 K for 2500 hours	4	• Lifetime testing in K
Rotary Fluid Management Device (RFMD)	• Small-scale RFMDs tested on Space Station Freedom and Boost Surveillance & Tracking Satellite (BSTS) programs using organic working fluid • Successful KC-135 tests	4	• RFMD performance with K
Valves	• Conventional design, Nb-1%Zr commercially available	3	• Reliability in K at operating temp.
Accumulator	• Similar accumulator used on SNAP programs	4	• Scale-up to full size
Bearing Supply Cooler & Recuperator	• Conventional design, Nb-1%Zr commercially available	3	• Detailed design and integration
Turbine	• Successful performance of K turbine tests • Moisture removal methods demonstrated • Acceptable blade erosion	4	• Characterization of turbine blade erosion
Bearings and Seals	• Short-term tests of K bearings in proper temp. range successful	4	• Stability testing of rotor / bearing system
Alternator	• Low-voltage alternator needs to be developed	2	• High-current, low-voltage alternator windings

Technology Readiness Levels

Most of the components are at Level 3 (Conceptual Design Tested Analytically or Experimentally) or Level 4 (Critical Function/ Characteristic Demonstrated). However, the low-voltage, high-current alternator, the potassium shear flow condenser, and the main power system niobium-coated carbon-carbon (C-C) heat pipes were identified as being only at Level 2 (Conceptual Design Formulated).

Technology Assessments and Major Development Needs

The assessment of the current state-of-the-art and the major research and development issues for the various subsystems are discussed next

Potassium-Rankine Power Conversion Systems

Considerable research and development was performed on K-Rankine systems in the U.S. in the 1960s. This included power reactor experiments that demonstrated successful operation of various components and subsystems, and over 16,000 hours of testing of the boiler and other components in the SNAP-50 system. Researchers in Russia are currently engaged in K-Rankine component testing including two-phase. potassium boiling experiments. However, development in the U.S. has not gone beyond the component level.

TABLE 2. Heat Rejection System Technology Assessment.

Item	State-of-the-Art Assessment	NASA Technology Readiness Level	Needed Research / Development
Shear Flow Condenser	• Design methods have been validated on organic Rankine cycle program • KC-135 tests have verified performance in zero-G	2	• Operation with potassium
Main Radiator	• Heat-pipe operation in zero-G has been demonstrated generically • Fabrication of C-C shapes has been demonstrated • Nb-1%Zr commercially available	2	• Fabrication of Nb-coated C-C heat pipes
Alternator and Bearing Cooling Radiator	• Same as main radiator	2	• Sam as main radiator

TABLE 3. Power Conditioning System Technology Assessment.

Item	State-of-the-Art Assessment	NASA Technology Readiness Level	Needed Research / Development
Rectifier	• Three-phase silicon controlled rectifier (SCR) assembly commercially available	4	• Interface with cooling system
Cable	• High-current aluminium or copper extrusions commonly used on ships and electric submarines	4	• Verification of thermal management and structural design
Switches	• Electronically operated non-load break switches designed for space usage up to 1500 Amps	3	• Development of higher current switches up to 5000 Amps
Ballast Resistor	• High-power (1.5 MWC) resistors available commercially	4	• Verification of thermal management
Rectifier Cooling Radiator	• Low-temp. (298 K) heat pipe radiators of 5 kg/m² available with current technology	4	• None

Techniques for two-phase flow management have been developed in support of organic Rankine systems for Space Station Freedom and for dynamic isotope power systems. Also, operation of rotary fluid management devices (RFMDs) have been demonstrated in short-duration KC-135 zero-G tests.

Development requirements for K-Rankine systems include the development and testing of complete systems, evaluation of turbine erosion and long-term creep behavior, characterization of potassium two-phase flow and fluid management in zero-G, lifetime testing of components, fabrication and demonstration of carbon-carbon heat-pipe radiators, and low-voltage, high-current alternators. Finally, although not uniquely associated with the K-Rankine system, there will be a general requirement for development of spacecraft "assembly" or "docking" hardware (such as connectors and the like) and techniques because of the modular nature of the vehicle. For the power system, this will include the need for low-voltage, high-current devices.

'1'A}H,}14. Li-Propellant MPD Thruster Technology Assessment.

Item	State-of-the-Art Assessment	NASA Technology Readiness Level	Needed Research/ Development
Cathode	• Former Soviet Union demonstrated 500 hours with Li propellant • Low-power alkali-metal MPD thrusters demonstrated in U.S. in 1960s & 1970s • Cathode test facility completed at J}>l.	3	• Measure temperature distribution and erosion rates; validate models • Lifetime tests with Li • Scale-up to 750 kW_e
Anode	• Former Soviet Union demonstrated high-power (1 MW_e), high-efficiency, radiation-cooled anode with Li • Low-power, radiation-cooled alkali-metal MPD thrusters demonstrated in U.S. in 1960s & 1970s	3	• Reduction of anode power fraction; geometry optimization; high-temp. material property data; fabrication with high-temp. material
Li-Propellant Feed System	• Design & fabrication of small (100 kW_e MPD) Li feed system completed; testing to begin in '93 • Cs and Hg flow systems have bet.a flown • Vaporize.r similar to liquid metal heat pipes . Ground test experiments in Russia	3	• Operation in zero-G environment • Validate lifetime
insulator	• Materials compatibility testing with yttria and thoria on-going	3	• High-temp. operation in thruster environment
Anode Heat Rejection	• Heat pipe. performance at 1100 K demonstrated • Pumped liquid metal loops developed for space power	3	• Development, fabrication, and testing of integral heat pipe anode
Applied-Field Solenoid	• Low-power, applied-field, Li thrusters have been demonstrated with high efficiency (60%)	3	• Development / validation of codes for applied-field MPDs • Demonstration of applied-field thrusters at high power levels
Thermal Radiation Shield	• Multi-foil shield used on Brayton Dynamic Isotope Power System (DIPS) and other space programs	4	• None.
Plume Shield	• Preliminary analytical modeling of Li-MPD plumes by former Soviet Union	3	• Plume codes and measurements needed for design

The major technology development items are:

- **Development testing of complete systems.** Although extensive testing of potassium Rankine components took place in the U.S. in the 1960s and 1970s, the interaction between components on a system level has not been investigated or demonstrated.

- **Two-phase fluid management in zero-G.** The feasibility of a rotating fluid manage.mcnl device (RFMD) has been demonstrated in zero-G in K~-135 tests. However, development and demonstration of a prototypically sized RFMD for a potassium cycle is needed.

- **Refractory alloy machining/welding.** Capabilities for refractory alloy machining and welding that existed in the U.S. in the 1960s needs to be re-established.

- **Demonstration of lifetime of turbine blades/seals.** Moisture control devices that mitigate potassium turbine erosion were performance tested in the early 1970s, but were not lifetime tested. Hardware that either removes moisture from the low pressure, stages of the. turbine or that can allow moisture without excessive erosion needs to be developed, demonstrated, and life tested.

- **Carbon-carbon brat pipe radiator fabrication and demonstration.** Carbon-carbon composite materials arc good candidate.s for radiators because of their high strength and light weight, Fabrication of carbon-carbon composite into heat pipe shapes, insertion of the metal liner and joining of C-C to Nb - 1 %Zr piping needs to be demonstrated.

- **Low-voltage, high-current alternators.** Typical AC dynamic power conversion system alternators operate at 1000 Volts. The alternator voltage in this study is 100 V AC at 17(KI Amps to provide the required input voltage to the thrusters. Development of this low-voltage alternator is necessary.

- **Spacecraft assembly in orbit.** The spacecraft will be assembled in orbit after the launch of several heavy - lift launch vehicles. It is assumed that the assembly can be accomplished by the simple docking of separate subsystems and booms, with no welding required. These connections require design/development.

Power Precessing Systems

'1'here arc a number of advanced power-contro] technologies that will be required to implement high-power PPUs for megawatt-class NEP vehicles using MPD thrusters. These range from relatively common near-term technologies requiring only the modest advancements in state-of-the-art, to totally new devices that must be uniquely developed for a megawatt-cla.ss electric propulsion PPU applicat ion, For example, space-qualified electromechanical non-load break switches rated at 1.5 kiloamps arc available commercially, and high-power semiconductors arc currently under development for terrestrial applications. However, development of radial ion- and space-qualified equipment and devices (such as high-frequency magnetic materials and power semiconductors including power integrated circuits) will require significant improvements.

The major technology development item is:

- **Low-voltage, high-current, space-qualified and radiation-qualified semiconductors.** High-power *semiconductors* arc *in development* al the GE Corp. R&D Center and at Harris Semiconductor Corp. (Temple 1993). Additional development of these devices will be nccdcd to qualify them for the thermal and radiation environments of the NEP vehicle. Also, devices designed to operate at higher temperatures would simplify the power processing unit's rad iator requirements and design.

Lithium-Propellant MPD Thrusters

Quasi-steady-state MPD thrusters have been flown in space by the Japanese. }high-power (500 kW_e), high-efficiency (60%) self-field s[cady-state MPD thrusters have been demonstrated by Russia in ground tests. Shori-term tests (tens of minutes) at power levels up to 1 MW_e have been achieved for self-field, radiatiml-cooled Li-MPD thrusters. Various test facilities exist for 100-kW_e class MPD thrusters; however, large.r test facilities will be required for loJ~g-term testing at megawatt power levels. Finally, computer mode.ls arc. being developed to predict performance and lifetime ford ifferent geometries and operation cond i lions.

Development requirements for MPD thrusters include evaluation of cathode lifetimes, fabrication of refractory metal components, validat ion of anode, thermal management schcmcs, and demonstration of applied-field M PD thruster performance at megawatt power levels, For the Li-MPD thruster, there will also be the need for development Of test facil ities for high-power Li-MPD thrusters, high- temperature electrical insulation materials compatible with lithium, and zero-G lithium vaporizers and feed systems. Finally, the issue of Li plume contamination, including detailed measurements, modeling, and engineering solutions (such as plume shields, standoff distance, and so on), will need to bc resolved.

'J "he. major technolog y development items arc:

- **Cathode lifetime.** Testing to date has shown that cathode erosion can cause thruster failure after relatively short operating times in gaseous-feel MPD thrusters. The maximum demonstrated lifetime in the U.S. has been 30 hours for a 60-kW_e thruster with argon propellant. The Russians have. tc.sled a lithium MPD thruster for 500 hours at 500 kW_e. The projected thruster lifetime for the Mars cargo mission is 3,000 hours.

- **Demonstration of steady-slate applied-field Li-MPD thrusters at high power levels.** Applied-field thrusters have been demonstrated only at low power levels (10 -30 kW_e). Efforts are underway to develop successful analytical models of applied-fic.ld thrusters, from which design improvements and higher power level designs can be based.

- **High temperature electrical insulator' compatibility with lithium.** The insulating material between the anode and cathode must be compatible with lithium, have a low electrical conductivity, and operate at a high temperature. Materials currently being investigated include yttria and thoria.

- **Plume contamination reduction/elimination.** Preliminary results have shown that the ionized thruster effluent is carried in magnetic field lines back toward the space vehicle prior to recombination. A condensable effluent such as lithium may deposit on the space vehicle surfaces, with the most vulnerable component being the low-temperature (~3 00 K) PPU radiators on the PPM. Deposition of lithium could severely diminish the emissivity of the radiators, reducing their performance. Experiments must be performed to determine the. extent of the plume contamination phenomenon, dependency on thruster design, and methods to reduce or eliminate the condensation on spacecraft surfaces.

- **Fabrication of refractory metal components.** The MPD thruster will operate at temperatures beyond the range of conventional materials (> 1100 K). Refractory metals have. been developed, and components fabricated as part of the space nuclear power programs in the 19 60s and 1970s. Nb-1%Zr is commercially available., and higher temperature materials (ASTAR-811C and ASTAR-1511C) arc available. in pilot-plant quantities.

- **Anode thermal management.** The MPD thruster subjects the. anode electrode to significant heat fluxes. The anode can be cooled either with active cooling using a liquid metal coolant, or with a heal pipe radiator. Thermal management techniques need to be further developed once anode geometries are specified and mate.rials arc selected.

- **Facility development for high-power Li-MPD thrusters.** Vacuum test facilities arc available for testing 1 00-k W_e class Li-MPD thrusters. Larger facilities need to be built, or existing facilities modified, to accommodate M W_e class Li-MPD thrusters. Because lithium is a condensable mate.rial, vacuum pumping requirements arc not significant; however, safe.ty issues and methods for cleaning/removing lithium effluent from the chamber need to be examined. The test chamber must be large enough to explore plume contamination effects.

- **Zero-G vaporizers for lithium feed systems.** The design and fabrication of a 100-kW_e size lithium feed system at the Jet Propulsion Laboratory (JPL) has been completed, and testing will begin in 1993. The design is similar to a liquid metal heat pipe, in which a reservoir is heated and feeds liquid to a wick. The Li is vaporized at the wick surface and flows through a heated line to the thruster cathode. Verification of operation in zero-G is required.

DEVELOPME' ' TESTS

SP- 00 Reactor Subsystem

In March 1983, the United State.s initiated the S1'-1 ()() program to develop a space reactor power system capable of providing the increased power levels required for space exploration and national security in space. The program was recently canceled along with most of the space nuclear power programs in the U.S. At the time of the cancellation, the program was in the detailed design and component development phase. Extensive testing of the power system's critical components was underway. Liquid metal testing of the heat transport, energy conversion and heat rejection components and subsystems, and testing of the Nuclear Assembly (reactor, shield, and controls) were planned for future years.

The Mars Cargo mission requires development testing of the components as well as a nuclear assembly test to establish performance of the nuclear reactor and 10 verify form, fit and function of the various components making up the reactor subsystem in a nuclear environment.

Potassium-Rankine Power Conversion Subsystem

Suhsyslcrn-level development of the potassium-Rankine system will consist of an assembly of prototype components, including boiler/rchcatcr, turbine,feed pump, condenser, radiators and rotary fluid management device. The boiler/rchcatcr would be fed with electrically heated lithium. Three of the four tube bundles in the boiler would be dummy bundles, as only one of the four power conversion units would be tested, All performance tests must be conducted in a vacuum environment, bc.cause of the corrosion of refractory metals by ox ygen at operating temperatures.

Power Processing Subsystem

Component development of the power processing subsystem includes development of high-current alternators and switches. Subsyslcnl-level development includes performance, functional, and electromagnetic interference testing of the complete subsystem, including alternator, switches, rectifiers and cooling radiator. An electrical test that includes the prototype booms would not be practical, duc to the length of the booms. Boom voltage drop and power loss must be simulated for the tests. This test does not need to be conducted in a vacuum environment, bc.cause refractory materials arc not involved.

Li-Propellant MPD Thruster

Development testing of 1.i-propellant MPD thrusters must include experimental measurements of rc.search-t ypc thrusters in order to characterize performance, and to provide input to validation of computer codes. (Wits must be validated for a variety of designs for applied-field sole.noids, anodes, cathodes, and insulators. Subsequently, a prototype can be designed and tested. The lithium feed system and anode heat rejection system must undergo design trade studies and reliability testing. Measurements and modelling arc necessary in order to characterize and find solutions for plume contamination of lilt spacecraft.

Li-propellant MPD thrusters must be tested in a vacuum environment of less than 10-2 Pa (1()-4 Torr). A vacuum facility must be large enough so that there is minimum interference with the plume expansion. For megawatt-class thrusters, a chamber size of at least 6-m diameter and 18-m tong is recommended.

System-Level Development Tests

Because of the size of the Mars Cargo Vehicle, a test of the entire vehicle is not practical. Tests of the various subsystems described above., arc assumed to be adequate.

DEVELOPMENT AND QUALIFICATION TESTING SCHEDULES

Figure 3 summarizes the development/qualification schedules for the Brayton, Stirling, and Rankine power systems, and for the Li-MPD thrusters. Although the Rankine system is preferred from a mass and volume perspective, it has the longest development time requirement of lhc three power system options due to the need to develop and qualify subsystems like the vapor-driven pump, preheater, valves, rotating fluid management device, and so on. Also, experience with Rankine systems is more limited than that with Stirling or Brayton, so more life testing will be required. If a primary driver is the need to minimize program schedule rather than maximize vehicle performance, the Brayton system could be ready approximately five years sooner than the Rankine. The Stirling system is intermediate in schedule and vehicle performance.; its development schedule is longer than lhat of the Brayton duc to the more complex and higher power and temperature of the Stirling engine..

The MPD thruster schedule was designed assuming a similar development period as the Rankine system. If needed, the MPD development schedule could be compressed somewhat. Finally, although the S}'-100 reactor development schedule is not the focus of this study, it should be noted that additional time (1 to 6 years) would need to be added to the reactor's development schedule to recapture technolog y if there is a delay in the S1'- 100 program of more than four years.

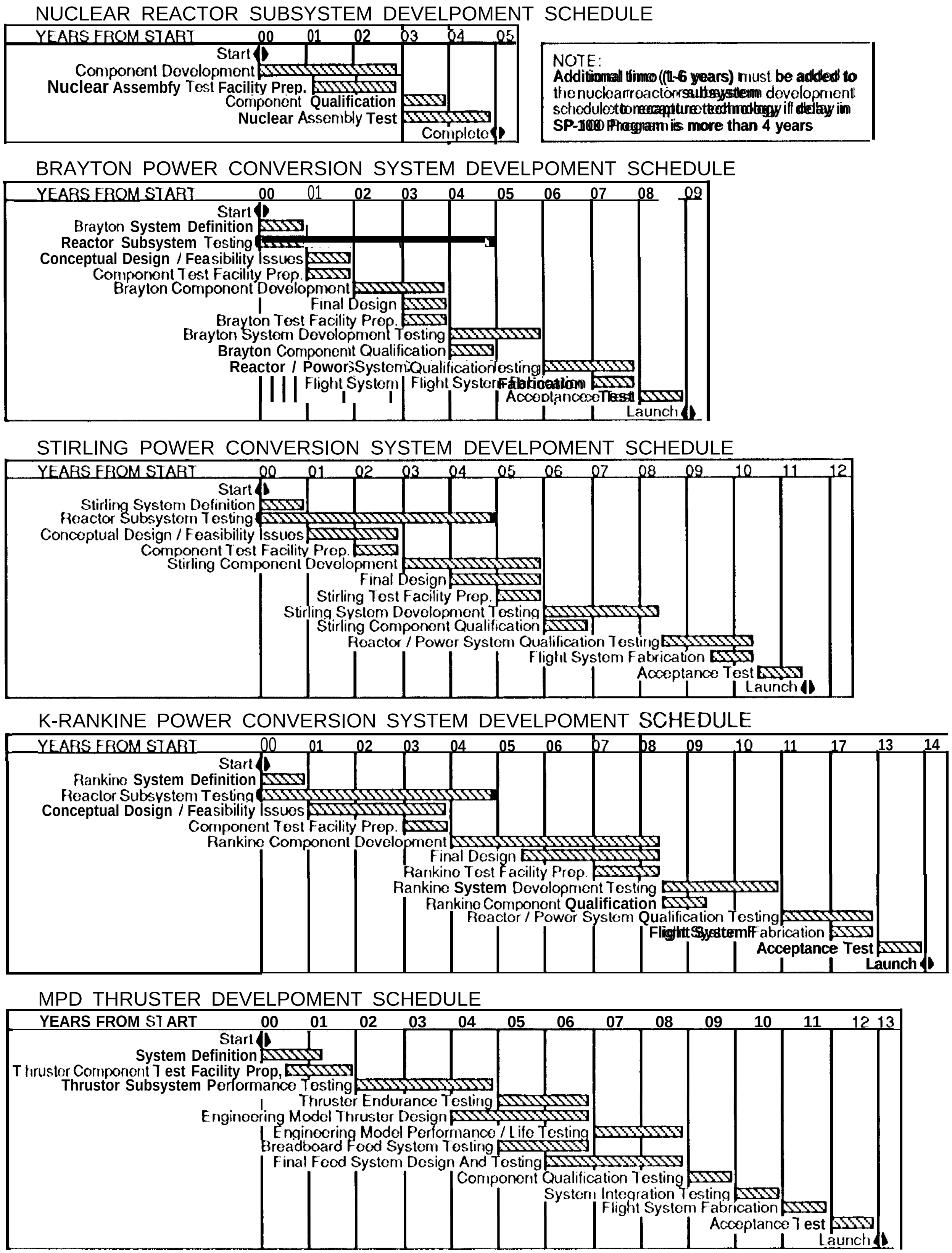

FIGURE 3. Development / Qualification Schedules.

CONCLUSIONS ANI) RECOMMENDATIONS

Near-term SP- 100 reactor, K-Rankine power conversion, and 1,i-propellant MPD thruster technologies and systems arc applicable to a broad range of NEP missions in support of human exploration of the solar system, such as lunar and Mars cargo missions and potentially the piloted portion of Mars missions (Frisbee and Hoffman 1993). Furthermore, S1'- 100 rcacior-based power system technologies arc synergistic with surface base power applications, as well as propulsion applications. However, there is the potential for significant slip in the overall program if SP-10() development is delayed more than four years. Unfortunatel y, as of this writing (September 1993), funding for the S1'- 100 nuclear reactor program in fiscal year (FY) 1994 has been eliminated, leaving only FY'93 funding for close-ou[of the project.

K-Rankine power conversion has the potential for the greatest mission benefit in terms of mass and volume, but it requires the most development. In this regard, it may be possible to make usc of Russian experience in this area. Iligh-current, low-voltage turboalternators arc needed for the MPD thruster system envisioned here, although onc al ternat ive would be to u sc more near- term high-voltage. al ternators at the potential cost of added transformer mass.

Power processing is not expected to be a major technology driver; for example, space-qualified electromechanical non-load break switches rated for kiloamps arc available commerciall y, and high-power scmicond uctors are currentl y under development for terrestrial applications. }lowever, development of radiation - anrt spat.c-qualified equipment and devices, such as high-frequency magnetic materials and power semiconductors including power integrated circuits, will require significant improvements in technology for the NEP application.

A technology push for longer MPD thruster life (>3000 hours) is desirable 10 reduce mass, system complexity, and packaging constraints. MPD thruster I_{sp}s of 391049 kN-s/kg (4,0(K) 105,000 lb_f-s/lb_m) and efficiency of 60% arc needed. Higher thruster efficiencies arc desirable to reduce trip time, although the NEP vehicle performance is only moderatel y sensiti ve to total specific mass or thruster efficiency.

Finally, wc recommend an evaluation of the Russian K-Rankine technology effort, Also, various technology and system design options, such as self-field MPD thrusters or high-voltage alternators, should be evaluated.

Acknowledgments

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