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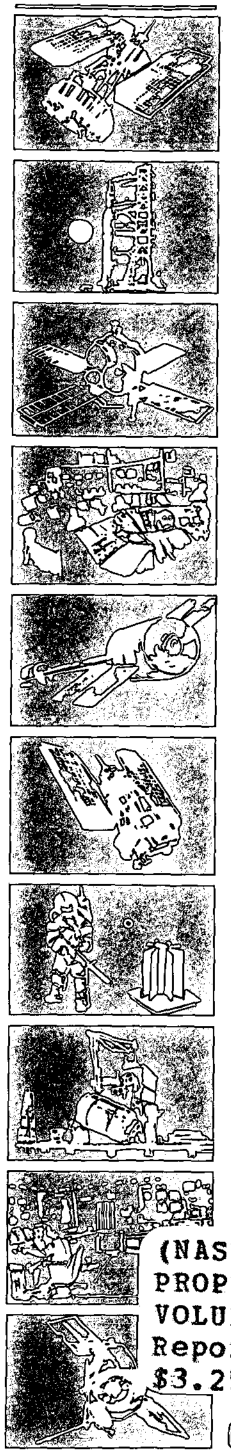

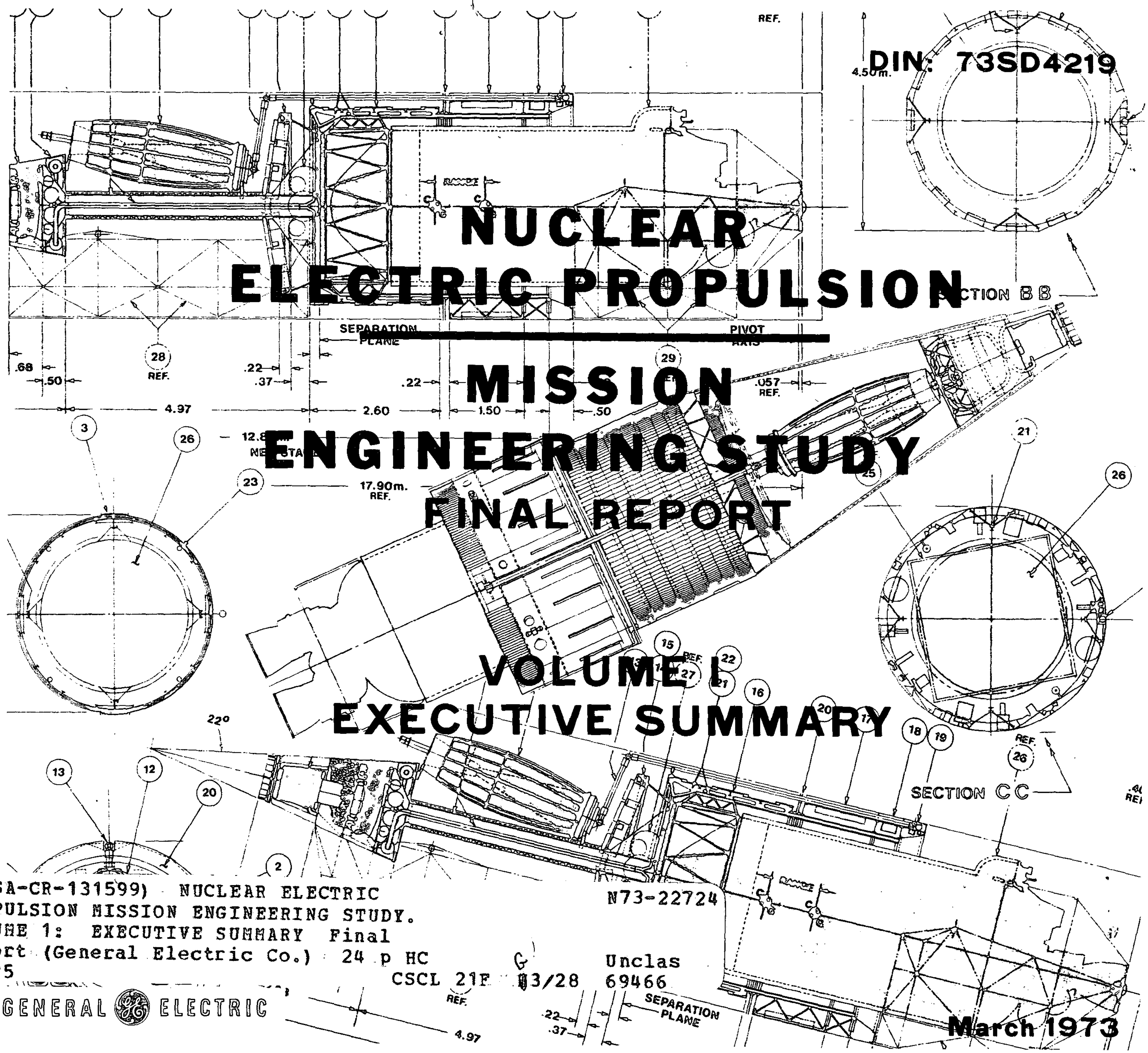

NUCLEAR ELECTRIC PROPULSION

MISSION ENGINEERING STUDY

FINAL REPORT

VOLUME I
EXECUTIVE SUMMARY

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March 1973

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FINAL REPORT
NUCLEAR ELECTRIC PROPULSION MISSION ENGINEERING STUDY

COVERING THE PERIOD APRIL 1971 TO JANUARY 1973

VOLUME I - EXECUTIVE SUMMARY

PERFORMED UNDER
CONTRACT NO. JPL 953104

FOR

THERMIONIC REACTOR SYSTEMS PROJECT
PROPULSION RESEARCH AND ADVANCED CONCEPTS SECTION

JET PROPULSION LABORATORY
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ABSTRACT

This document summarizes the results of a mission engineering analysis of nuclear-thermionic electric propulsion spacecraft for unmanned interplanetary and geocentric missions. Critical technologies assessed are associated with the development of Nuclear Electric Propulsion (NEP), and the impact of its availability on future space programs. Specific areas of investigation include outer planet and comet rendezvous mission analysis, NEP Stage design for geocentric and interplanetary missions, NEP system development cost and unit costs, and technology requirements for NEP Stage development. A multi-mission NEP Stage can be developed to perform both multiple geocentric and interplanetary missions. Development program costs for a 1983 launch would be of the order of $275 M, including hardware and reactor development, flight system hardware, and mission support. Recurring unit costs for flight NEP systems would be of the order of $25 M for a 120 kWe NEP Stage. Identified pacing NEP technology requirements are the development of 20,000 full power hour ion thrusters and thermionic reactor, and the development of related power conditioning. The resulting NEP Stage design provides both inherent reliability and high payload mass capability. High payload mass capability can be translated into both low payload cost and high payload reliability. NEP Stage and payload integration is compatible with the Space Shuttle.

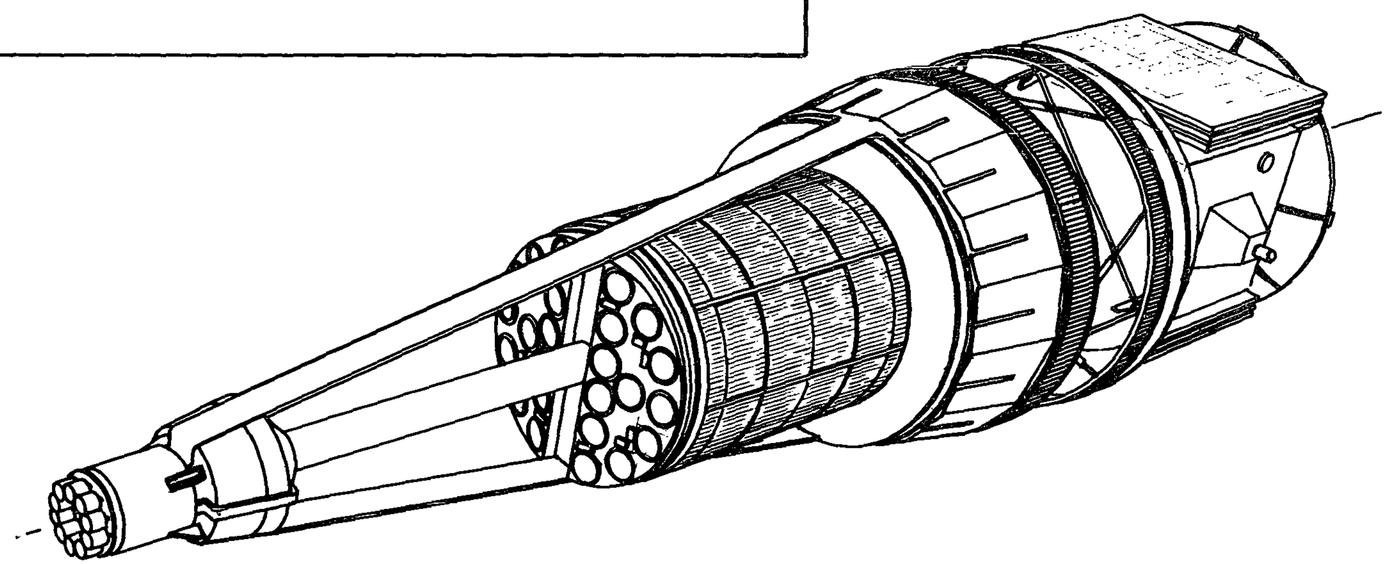

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Table 1. Study Objectives and Ground Rules

STUDY OBJECTIVES

- INVESTIGATE AND DEFINE ALL OPERATIONAL ASPECTS OF A THERMIONIC NUCLEAR ELECTRIC PROPULSION SPACECRAFT OR STAGE
- DEFINE MISSION AND SPACECRAFT INTERACTIONS WITH THE EARTH LAUNCH VEHICLE FACILITIES AND RELATED EQUIPMENT
- DEFINE GROSS PROPULSION SYSTEM DEVELOPMENT PROGRAM
- DEFINE IMPACT OF NUCLEAR ELECTRIC PROPULSION ON SPACE PROGRAM AND TECHNOLOGY REQUIREMENTS

KEY GUIDELINES AND CONSTRAINTS

INTERPLANETARY MISSIONS

- SHUTTLE-CENTAUR D-IT BASELINE LAUNCH VEHICLE
- MAXIMUM USE OF PREVIOUS TRAJECTORY ANALYSES
- HIGH THRUST (CHEMICAL) INJECTION TO EARTH ESCAPE
- LOW THRUST TERMINAL PROPULSION
- COMET HALLEY RENDEZVOUS AND OUTER PLANET EXPLORATION

GEOCENTRIC ORBIT MISSIONS

- SYNCHRONOUS EQUATORIAL EARTH ORBIT BASELINE MISSION
- SHUTTLE/SHUTTLE-CHEMICAL TUG BASELINE LAUNCH VEHICLES

BOTH MISSIONS

- MAXIMUM USE OF PREVIOUS PROPULSION SYSTEM DESIGN STUDIES
- EMPLOY REALISTIC LEVEL OF TECHNOLOGY
- DEFINE MISSION OPERATIONS
- DEFINE GSE AND SUPPORT FACILITIES
- EMPHASIS ON IMPACT OF NUCLEAR ELECTRIC PROPULSION MISSION OPERATIONS

BACKGROUND

Studies on Nuclear Electric Propulsion (NEP) stage design were initiated in February 1969 under the direction of the Jet Propulsion Laboratory (Contract JPL 952381), to assist the AEC in the development of a thermionic reactor compatible with NASA advanced, outer planetary exploration mission requirements and objectives. This effort, completed in Fiscal 1971, supported further evaluation of a 120 kWe NEP Stage to meet these mission requirements.

The subject NEP Mission Engineering Study was therefore initiated in April 1971 to investigate the applicability of the NEP Stage to advanced NASA-OSS upper stage requirements, as well as to further assist the AEC in the development of the thermionic reactor basic to this candidate advanced propulsion stage. This effort focused on the operational and developmental aspects of the NEP Stage, consistent with NASA mission requirements, targeted for the 1980 to 1990 time frame. Initially directed toward outer planet exploration and Comet Halley rendezvous, the scope was expanded to include the application of the NEP Stage to geocentric systems. The assessment of this area was accomplished in 1972.

Evaluation and NEP Stage design definition completed during the past four years has led to the delineation of a true multi-mission NEP Stage, including its preliminary design, operational aspects and performance in the multi-mission role, developmental program definition and development cost, and key NEP Stage technology developments required to assure NEP Stage availability.

OBJECTIVES

The overall program objectives are to perform a mission engineering study of nuclear electric spacecraft for both unmanned interplanetary and geocentric orbit missions to determine the implications of nuclear electric propulsion on future space programs. This effort is also directed toward the definition of a Nuclear Electric Propulsion (NEP) spacecraft with multi-mission capability, its development program definition and development costs, including ground support equipment requirements, and the impact of the availability of a NEP system on the space program. The specific study objectives are listed in Table 1.

KEY GUIDELINES AND CONSTRAINTS

The key guidelines and constraints used in the assessment of nuclear electric propulsion for interplanetary and geocentric earth orbit missions are shown in Table 1. Maximum use is made of previous efforts in the areas of mission analysis and NEP spacecraft design. The Shuttle-Centaur D-1T is the reference launch vehicle for interplanetary missions. The NEP Stage employs high thrust to earth escape, and low thrust electric propulsion for trajectory termination for outer planet missions.

The transportation of operational payloads to and from synchronous equatorial orbit is the baseline mission for geocentric NEP applications. For this mission, the Shuttle/Shuttle-Chemical Tug is the baseline launch vehicle.

Emphasis is placed on multi-mission capability.

Spacecraft design employs maximum utilization of current or near term technology to maximize cost effectiveness and minimize propulsion system development costs. Mission operations, from launch to mission completion, have been investigated, and recommend procedures identified.

KEY TECHNOLOGY AREAS

- 20,000 FULL POWER HOUR LIFETIME
  - THERMIONIC FUEL ELEMENTS
  - ION ENGINES
- POWER CONDITIONING

FUTURE NASA MISSION ENHANCEMENT

- MULTI-MISSION CAPABILITY
- PAYLOAD FLEXIBILITY
  - HIGH MASS DELIVERED
  - STANDARDIZED PAYLOADS
- ACCEPTABLE COSTS

NEP STAGE DESIGN

- IDENTIFIED NEP STAGE DESIGNS PROJECT SPECIFIC MASS OF 36 kG/kWe (INCLUDING AVIONICS MODULE MASS)

NEP STAGE DEVELOPMENT PROGRAM AND COSTS

- NEP SYSTEMS FOR GEOCENTRIC ORBIT AND INTERPLANETARY MISSION APPLICATIONS HAVE COMMON SUBSYSTEMS EXCEPT FOR:
  - ATTITUDE AND THRUST VECTOR CONTROL
  - VAN ALLEN PROTECTION
- GSE AND OPERATIONAL EQUIPMENT ARE BASICALLY COMMON TO ALL IDENTIFIED NEP MISSIONS
- NEP STAGE PROPULSION SYSTEM COSTS ARE INDEPENDENT OF CONFIGURATION AND APPLICATION
- NEP STAGE IOC CONSTRAINED ONLY BY DEVELOPMENT SCHEDULE OF PROPULSION SYSTEM
- NEP STAGE DEVELOPMENT PROGRAM IS OF THE ORDER OF $275M
- FACILITIES AND GROUND SUPPORT EQUIPMENT ARE REQUIRED EARLY ON ALL OPTIONS EVALUATED. THESE COSTS ARE ABOUT $60M
- TOTAL FLIGHT NUCLEAR SAFETY COSTS ARE ABOUT $8M
- AVIONICS MODULE CAN LARGELY BE DEVELOPED FROM CURRENT STATE-OF-THE-ART HARDWARE
  - $30.0M DEVELOPMENT AND QUAL
  - $6.6M RECURRING COSTS
- RECURRING COSTS FOR FLIGHT NEP SYSTEMS COULD APPROACH $25M

MISSION OPERATIONS

- MISSION OPERATION ARE COMMON BETWEEN OUTER PLANET MISSIONS EVALUATED AND BETWEEN GEOCENTRIC MISSIONS EVALUATED, BUT NOT BETWEEN OUTER PLANET AND GEOCENTRIC MISSIONS
- ALL OUTER PLANET MISSIONS EVALUATED CAN BE PERFORMED WITH LESS THAN 10,000 FULL POWER HOURS; COMET HALLEY RENDEZVOUS REQUIRES UP TO 20,000 FULL POWER HOURS
- IMPACT OF SHUTTLE INTEGRATION REDUCED BY USING TRANSFER MODULE; SAFETY AND HANDLING IMPROVED
- NO SPECIAL RADIATION PROTECTION REQUIRED WITH PRE-OPERATIONAL REACTOR
- IN-ORBIT REFUELING, WHICH COULD BE REQUIRED FOR GEOCENTRIC MISSIONS, REPRESENTS ONLY UNIQUE HARDWARE DEVELOPMENT RELATIVE TO BOTH MISSION CLASSES INVESTIGATED
- SHUTTLE LAUNCH COSTS ($10.4M) ARE MAJOR CONTRIBUTOR TO INITIAL DEPLOYMENT AND OPERATIONAL COSTS

Key study conclusions are categorized under five principle areas:

- Technology
- Mission Enhancement
- NEP Stage Design
- Development and Costs
- Mission Operations

Key Technology Areas identified are the development and qualification of mercury ion engines and Thermionic Fuel Elements (TFE) with a 20,000 full-power-hour life. Although an interim NEP Stage design with 10,000 hour life components can be utilized to perform geocentric and most of the outer planet missions, the improved 20,000 hour capability is necessary to perform the more difficult outer space missions, such as comet rendezvous. The longer life capability also reduces mission operational costs for geocentric applications since the total payload delivered to earth orbit during the life of a single NEP Stage is increased.

Power conditioning development at low specific mass is required in order to validate study performance calculations. Power conditioning efficiencies are critical to NEP Stage specific mass. High efficiencies of 90 percent or more, at 20 Volts DC power input (or less) are desirable to simplify the thermionic reactor development. Lower PC efficiencies can have a significant adverse effect on NEP Stage specific mass.

All other technologies required for the NEP Stage, such as shielding, liquid metal systems, and propellant feed system are either current state of the art, or will be developed as a part of solar electric propulsion.

Future NASA Mission performance can be enhanced by the development of NEP. The NEP stage has a multi-mission capability for both outer planet and geocentric applications. The NEP Stage can deliver high payload mass, up to about 8000 kg to synchronous orbit in about 200 days, and 1000 kg to 2000 kg to the vicinity of outer planets in time periods of the order of three years. The NEP Stage can also provide up to 100 kWe power to the payload after delivery. The NEP Stage can deliver payloads to synchronous earth orbit at costs as low as $ 2000/kg of payload, including shuttle support costs.

The NEP Stage Design identified in this study has evolved over the past four years to meet both changing and more stringent mission requirements. The present multi-mission NEP Stage identified has a specific mass of 36 kg/kWe at a power of 120 kWe delivered to the thrust subsystem.

NEP Stage Development Costs are of the order of $ 275 M for the 120 kWe system. These costs will increase by about 30 percent if the power level is increased to 240 kWe. In addition, about $35 M will be required for facilities. The avionics module development cost are about $30 M (guidance, communications and control). NEP Stage unit costs (120 kWe) are estimated at $31.6 M, including $6.6M for the avionics module, assuming that ten or more identical units are built at the rate of about one per year.

These costs are essentially independent of the NEP Stage Configuration.

Mission Operations are common to all outer planet missions evaluated. Mission operations are not necessarily common between outer planet and geocentric missions.

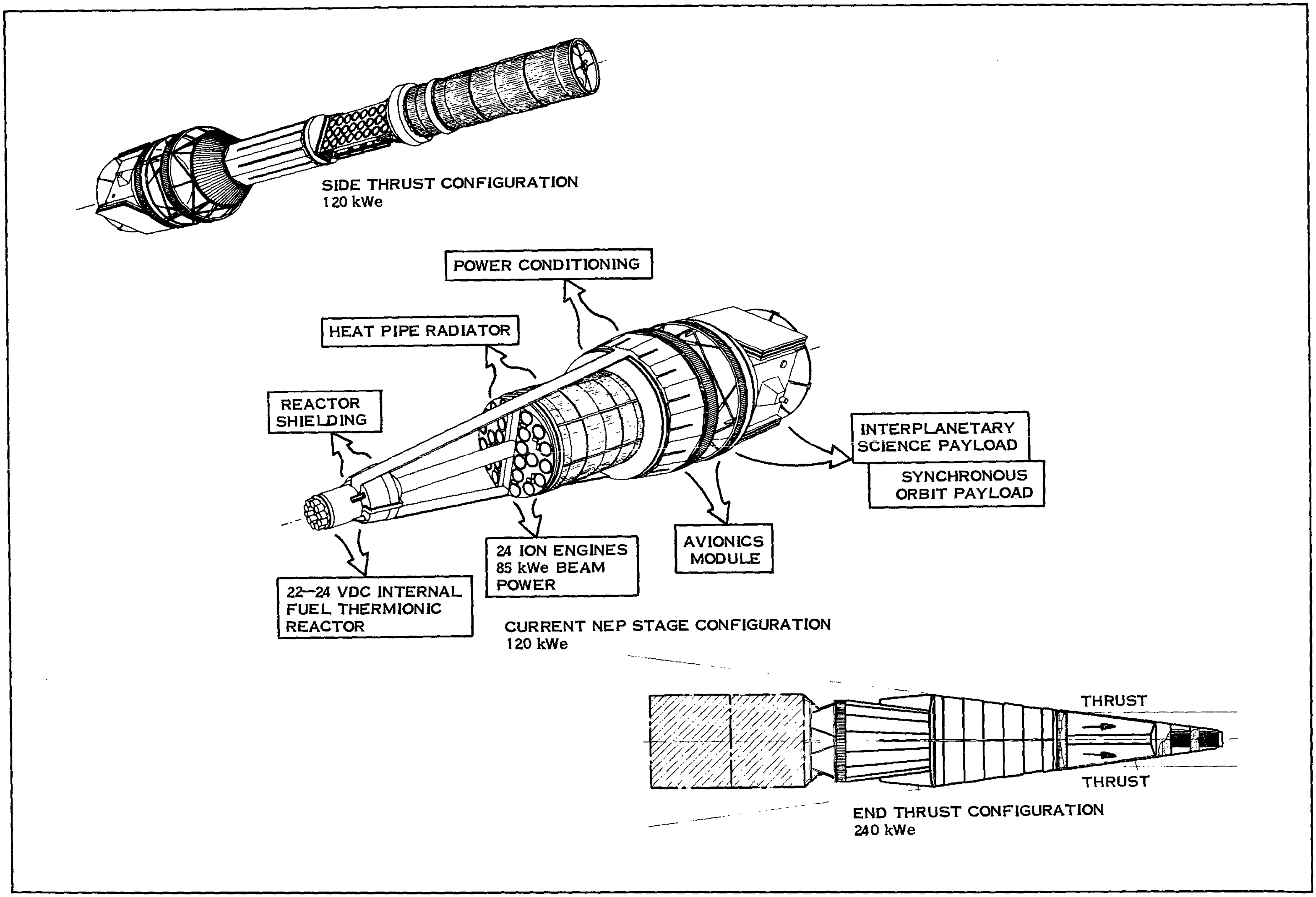

Figure 1. NEP Stage Evolution

NEP STAGE DESCRIPTION

The reference end thrust NEP Stage is basically a conical configuration with a cylindrical heat pipe primary radiator (Figure 1). The reactor is boomed to minimize shielding weight and ion engine interactions, with minimum low voltage cable losses. The thruster array is composed of 24-30 cm mercury electron bombardment ion engines, including 20 percent spares. The thermionic reactor also incorporates a 20 percent redundancy in power. The overall dimensions of the NEP Stage are 12.8 m long and a maximum diameter of 4.6 m. The 55 cm thick LiH neutron shield is conical in shape with a mean diameter of 1.5 m. The mercury propellant tank, 0.36 m in axial thickness, is located forward of the LiH neutron shield. The stored liquid mercury serves as the primary gamma shield. A capton-clad titanium cylindrical structure houses the NaK lines that go to the primary radiator and the mercury feed lines that supply mercury propellant to the ion thrusters.

The mercury ion engines are canted out an angle of nine degrees, to reduce mercury impingement on the stage structure. This does result in a one percent loss of effective thrust. Approximately twelve of the ion engines can be gimbaled to provide for roll thrust vector control about the thrust axis and yaw control. The foremost section of the NEP Stage contains the avionics subsystem and the payload docking structure.

Table 2. 120 kWe NEP Stage Mass Summary

SUBSYSTEM	MASS-kg
POWER SUBSYSTEM	3030
THRUST SUBSYSTEM	755
PROPELLANT SUBSYSTEM	
TANKS AND DISTRIBUTION	165
PROPELLANT - OUTER PLANET - TYP.	5000
GEOCENTRIC - TYP.	2500
AVIONICS SUBSYSTEM	460
TOTAL (WITHOUT PROPELLANT)	4410

NEP STAGE PERFORMANCE

As seen from Table 2, the NEP Stage mass exclusive of mercury propellant is 4410 kg. The specific mass is 36 kg/kWe including about 4 Kg/kWe for the avionics subsystem. This value is based on 120 kWe net power delivered to the thrust subsystem. To provide 120 kWe at 23 volts (DC) to the thrust subsystem, the reactor generates 1580 kWt converting 136 kW to electrical power and rejecting the rest as waste heat via the primary radiator. This leads to an overall propulsion system efficiency of 71 percent. For geocentric orbit applications, the NEP Stage operates at a specific impulse of 4000 sec. The specific impulse is increased to 5000 sec for interplanetary missions. The stage is designed for a 20,000 full power operational life, and a 50,000 hour total orbital life.

NEP STAGE EVOLUTION

A propulsion system configuration analysis was performed to arrive at an optimum NEP Stage design. Three "families" of NEP Stage propulsion system configurations were investigated: an end (axial) thrust configuration with a mid-reactor location, an end thrust configuration with the reactor(s) located at the end of the vehicle, and a side thrust (i.e., thrusting perpendicular to spacecraft's major axis) configuration.

In terms of mission performance and overall operational versatility, the 120 kWe end thrust configuration, with end reactor location, is most attractive because of its lowest specific mass (32 kG/kWe, 36 kg/kWe with avionics), ease of Shuttle integration, and multi-mission (geocentric and interplanetary) capability. No significant differences in development and production costs have been identified for the three propulsion system configurations. Based on this assessment, the end thrust NEP Stage configuration with end reactor location was determined to be the best suited configuration for both geocentric and interplanetary missions.

Table 3. Ground Support Equipment and Operational Equipment Requirements

GROUND SUPPORT EQUIPMENT

- FABRICATION AND TEST
  - TFE TEST EQUIPMENT
  - LEAK TEST AND WELD INSPECTION EQUIPMENT
  - NaK CHARGING AND PURIFICATION FACILITY
  - HOT TEST FACILITIES
  - AVIONICS SUBSYSTEM SIMULATOR(S)
  - HIGH POWER, LOW VOLTAGE ELECTRIC POWER SOURCE
  - ION ENGINE ELECTRICAL LOAD SIMULATOR
  - PROPULSION SYSTEM SIMULATOR FOR AVIONICS SUBSYSTEM TEST
  - HANDLING RIGS AND TRANSPORTERS FOR EACH SUBSYSTEM
  - SHIPPING/STORAGE CONTAINERS WITH ENVIRONMENTAL CONTROL PACKAGE FOR EACH SUBSYSTEM
  - SHIPPING CONTAINER FOR ASSEMBLED NEP STAGE
- ARRIVAL AT LAUNCH SITE AND PRELAUNCH
  - NUCLEAR STORAGE AND CHECKOUT FACILITY
  - CHECKOUT EQUIPMENT FOR NEP STAGE SYSTEMS
  - ALKALI METAL HANDLING FACILITY
  - MERCURY PROPELLANT HANDLING FACILITY
  - HANDLING EQUIPMENT
  - TRANSPORTER
  - INERT GAS SUPPLY AND HANDLING FACILITIES
- LAUNCH - MISSION COMPLETION
  - SPACE FLIGHT OPERATIONS FACILITY

OPERATIONAL EQUIPMENT

- NEP STAGE TRANSFER MODULE
- CHEMICAL TUG-SYNCHRONOUS P/L TRANSFER MODULE
- PROPELLANT LOGISTICS DEPOT

GROUND SUPPORT EQUIPMENT AND FACILITIES

Table 3, lists the identified Ground Support Equipment (GSE) and Operational Equipment required to support NEP Stage operations All GSE and Operational Equipment identified are required, whether the mission is interplanetary or geocentric, except for the Centaur support equipment, a Chemical Tug/Synchronous Orbit Payload Transfer Module, and the Propellant Logistics Depot (PLD). The latter two items of Operational Equipment, however, are dependent upon the geocentric orbit mission profile selected, and are not required for other identified NEP geocentric orbit mission modes.

A Nuclear Storage and Checkout Facility provides for remotely controlled environment storage and non-nuclear acceptance testing of the NEP Stage system delivered to the launch site. The NS&C Facility should be capable of supporting more than one nuclear reactor system (and several isotope heat sources) in various stages of assembly, test and storage, in order to provide for growth. The Alkali Metal Handling Facility provides for safe handling of NaK coolant for the NEP Stage power subsystem in the event of a liquid metal leak.

The Mercury Propellant Handling facility provides for storage and handling of the NEP Stage mercury propellant, and for fueling the NEP Stage and the PLD before launch. This building can be very similar to the Alkali Metal Handling Facility.

A shipping container will be designed to maintain an inert, controlled environment for shipping the NEP Stage to the launch site. The shipping container must be equipped to monitor radiation, humidity, temperature and pressure and must provide the necessary inert cover gas environment, fire protection, alarms and warnings.

Safety and handling can be improved, and support requirements imposed on the Shuttle reduced, if a transfer module is used to support the NEP Stage within the cargo bay of the Shuttle.

During flight of the NEP Stage, communications equipment, and data storage and processing equipment are required to monitor and evaluate the progress of the mission. On interplanetary missions, navigation assist can be provided by the radio tracking facilities of the Deep Space Network.

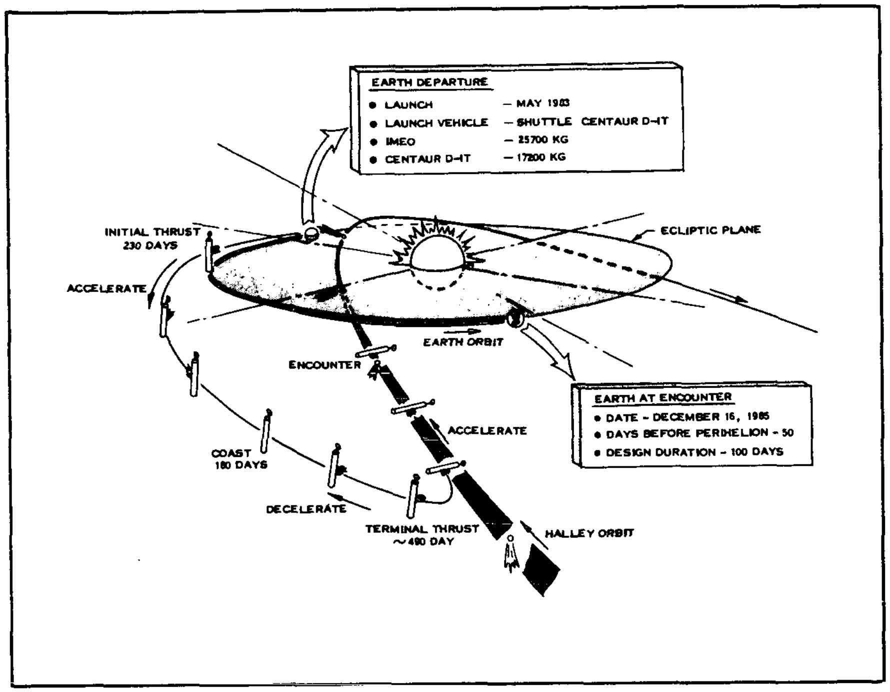

Figure 2. Comet Rendezvous

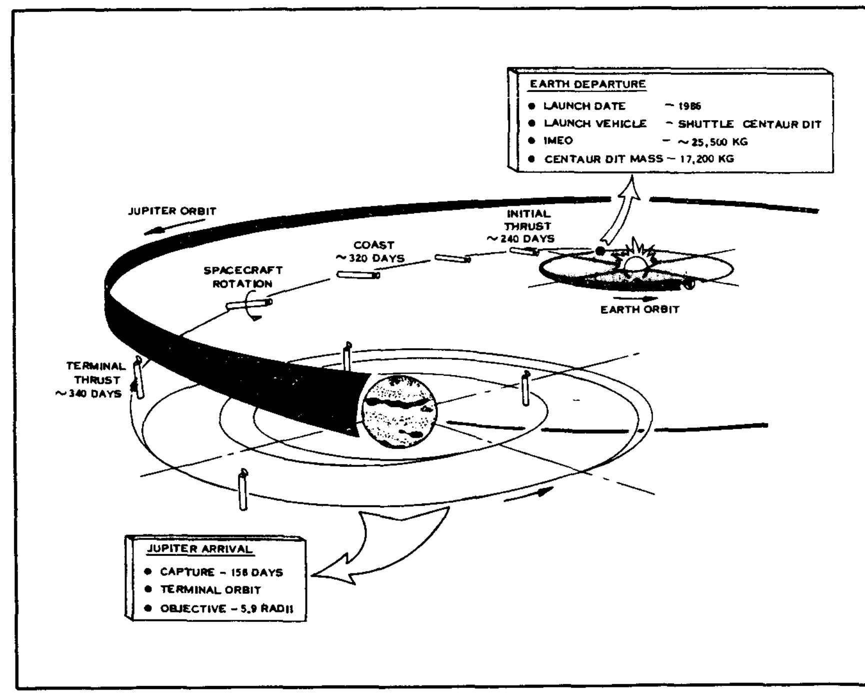

Figure 3. Outer Planet Mission

A single NEP spacecraft design can be defined which will perform multiple outer planet missions, as well as the Comet Halley rendezvous (Table 4). Fixed power level, specific impulse, specific power, and net spacecraft mass identifies the electric propulsion propellant inventory as the only variable that can affect the spacecraft design. The range of propellant inventories shown for these candidate missions can be readily accommodated within a single spacecraft design by sizing the tank system to accommodate the largest mercury inventory required for a family of missions. The tank structure weight penalty necessary to incorporate this feature will be negligible.

The establishment of a fixed 120 kWe power level, rather than the optimum for each mission not only assists in providing the same propulsion system with a multi-mission capability, but improves mission performance. The additional mission energy required for employing an off-optimum propulsion system is obtained from higher specific impulse, which is established at 5000 seconds for the baseline outer planet missions.

Early NEP propulsion systems may be characterized by life limited propulsion systems (Table 5). Therefore, the effect of constraining propulsion times to about 10,000 hours or less for the 120 kWe NEP spacecraft were investigated for the Shuttle, Centaur D-1T launch. Specific impulse decreases to about 4200 seconds. Increased hyperbolic excess velocity assists in decreasing both the trip time and the propulsion time. For the Jupiter orbiter mission of 5.9 radii, the propulsion time is reduced from 14,000 hours to 10,500 hours.

Table 4. Mission Performance of 120 kWe NEP for Outer Planet and Comet Halley Missions

MISSION	COMET HALLEY RENDEZVOUS	JUPITER R = 5.9	SATURN R = 4.9	SATURN R = 20.4	URANUS R = 18.5	NEPTUNE FLYBY
TRIP TIME (DAYS)	900	900	1320	1120	1950	1650
DEPARTURE HYPERBOLIC VELOCITY (KM/SEC)	2.5	2.9	2.9	3.3	2.8	3.6
MERCURY PROPELLANT MASS (KG)	4500	4200	4200	3800	4300	3600
CAPTURE TIME (DAYS)	---	158	95	12	16	---
PROPULSION TIME (HOURS)	18,000	14,000	17,000	15,200	21,000	15,000

CONSTANT MISSION PARAMETERS	
• LAUNCH VEHICLE	SPACE SHUTTLE/CENTAUR D-1T
• POWER TO THRUST SUBSYSTEM, P_e	120 kW_e
• PROPULSION SYSTEM SPECIFIC WEIGHT	27 KG/kW_e
• SPECIFIC IMPULSE	5000 SECONDS
• NET SPACECRAFT, SCIENCE AND AVIONICS	700 KG

Table 5. 10,000 Hour Propulsion Time Constraint Shuttle/Centaur Launched 120 kWe NEP Stage

MISSION	JUPITER R = 5.9	SATURN R = 4.9	SATURN R = 20.4	URANUS R = 18.5	NEPTUNE FLYBY
TRIP TIME (DAYS)	825	1320	1040	2250	1500
SPECIFIC IMPULSE (SEC)	4200	4200	4300	4000	4200
DEPARTURE HYPERBOLIC VELOCITY (KM/SEC)	6.2	6.2	6.5	6.1	6.7
CAPTURE TIME (DAYS)	125	100	11	25	---
PROPULSION TIME (HOURS)	10,500	10,000	10,000	10,000	10,000

LAUNCH VEHICLE: SHUTTLE/CENTAUR D-1T
NET SPACECRAFT: 700 KG
P_e = 120 kW_e
a = 27 KG/kW_e

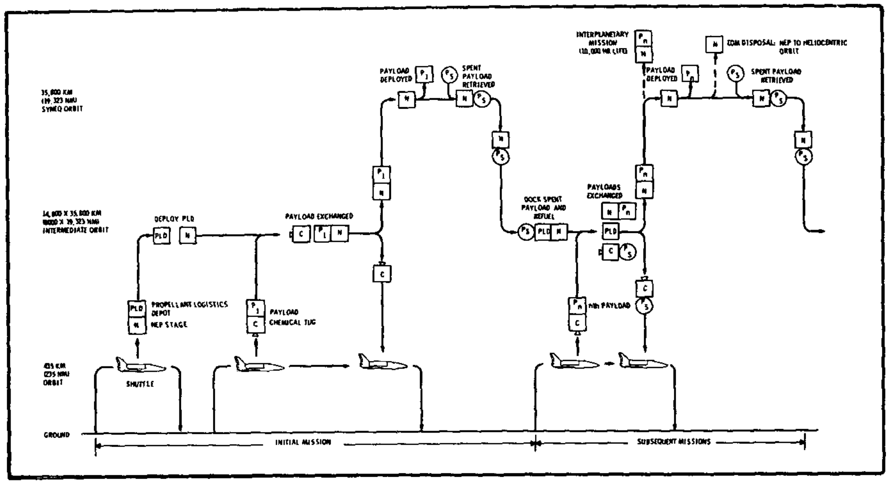

Figure 4. Baseline Geocentric Mission

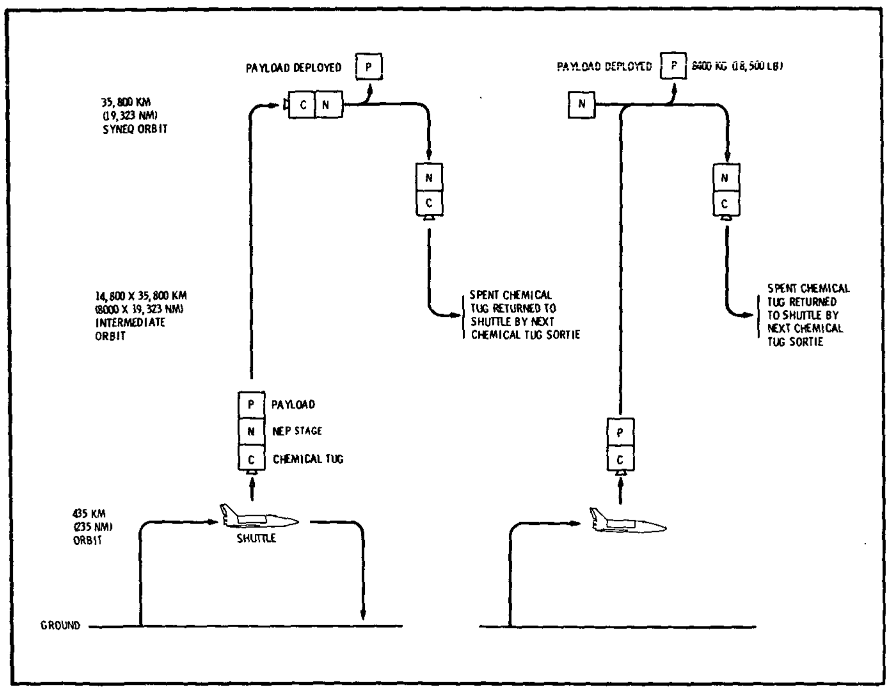

Figure 5. Minimum Time to Orbit Geocentric Mission

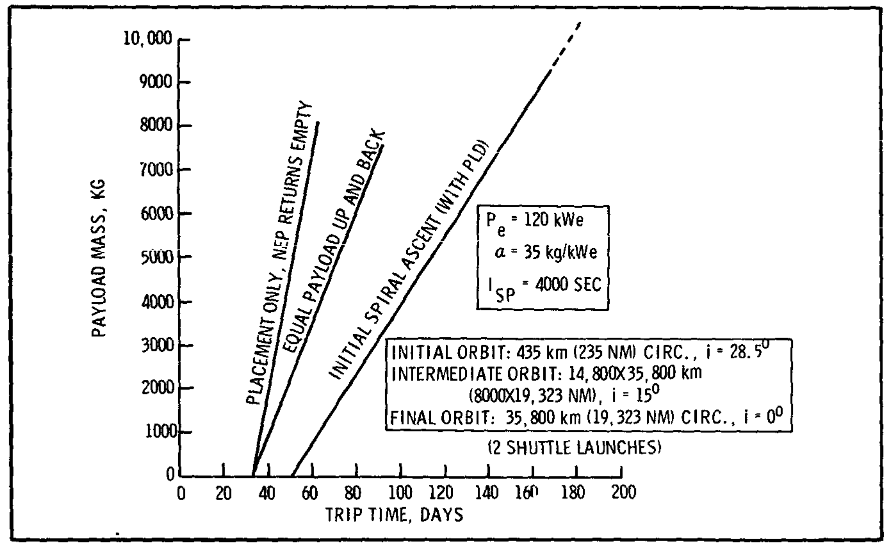

Figure 6. Baseline Geosynchronous Orbit Mission NEP Stage/Chemical Tug Performance

MISSION PERFORMANCE - GEOCENTRIC

The example baseline NEP Stage mission selected for geocentric orbit applications is the transportation of operational payloads to and from synchronous equatorial earth orbit. The mission profile for this application is shown in Figure 4. For missions requiring fast payload deployment (~ 6 hours), two potential mission modes are depicted in Figure 5.

Trip time and payload capability for the baseline NEP Stage geocentric orbit mission are presented in Figure 6. The initial spiral ascent of the NEP plus the Propellant Logistics Depot (PLD) from low earth orbit to the selected intermediate parking orbit will take approximately 140 to 160 days. The baseline geocentric orbit mission includes NEP Stage in-orbit refueling by means of the PLD. At launch the PLD contains sufficient mercury propellant and other consumables to support the NEP Stage for its total 20,000 full power hour life. From the 15 degree inclined intermediate orbit, NEP round trip times are less than 100 days with a maximum payload capability of about 7600 kg for equal payload up and back, and 8100 kg for payload placement only. Maximum payload capabilities of approximately 8700 kg are possible with trip times of about 100 days for equal payload up and back, and about 65 days for payload placement only.

The impact of increased power level on mission performance is illustrated in Figure 7. In the baseline geocentric mission a 240 kWe Stage will reduce the spiral round trip time from 93 days to approximately 65 days (~30 percent reduction); however, the maximum payload capability is also reduced from 8600 to 8300 kg (due in part to be increased mercury propellant requirements for the 240 kWe system).

The impact of higher power level is most noticeable in the mission mode which involves no Chemical Tug assist. In this mode, the NEP Stage travels between low earth orbit and synchronous equatorial with no intermediate orbit. At maximum payload capability the round trip flight time is reduced from ~700 days for the 120 kWe to ~400 days for the 240 kWe Stage with only a 5 percent reduction in payload capability. Therefore, higher power levels (relative to 120 kWe) are required to make the all NEP mission mode attractive. The optimum power level for this application may in fact be greater than 240 kWe.

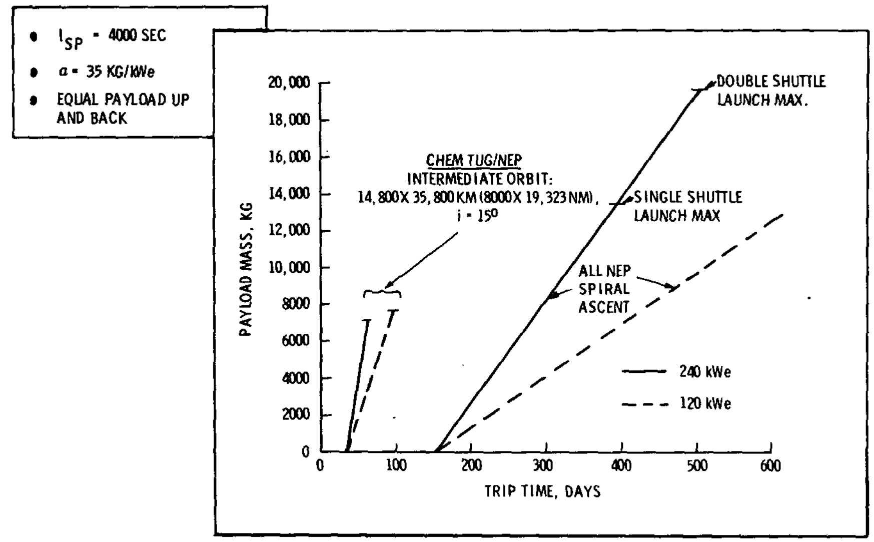

Figure 7. Effect of Higher Power Level on Mission Performance

These missions have assumed a 20,000 hour full power life. The option also exists for the NEP Stage to operate in a dual mode and perform an interplanetary mission after completing up to 10,000 full power hours in geocentric orbit.

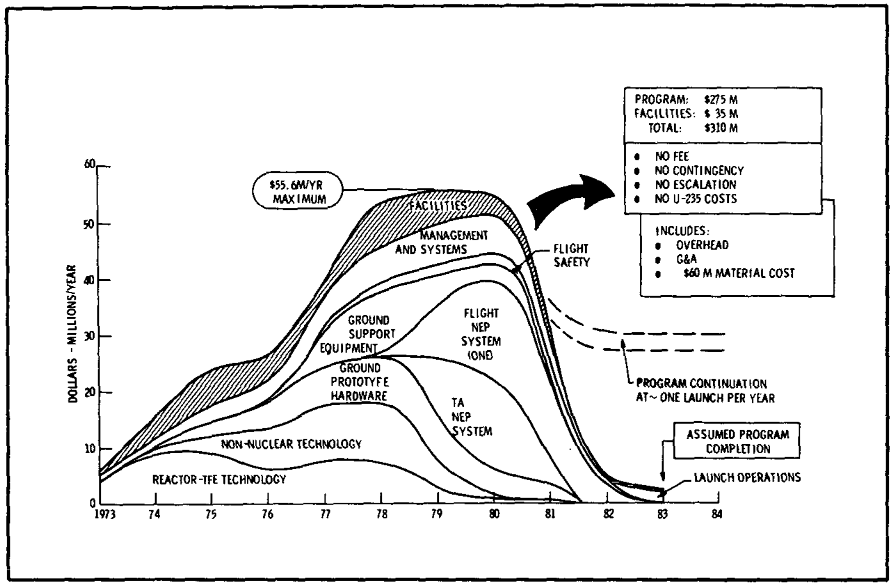

Figure 8. Costs by Program Year Baseline NEP System Program

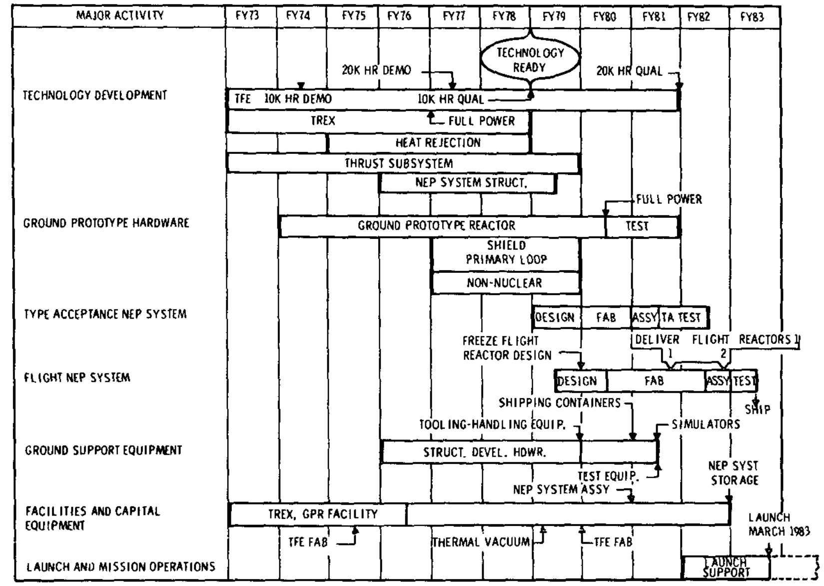

Figure 9. Summary Schedule Baseline NEP System Program

Table 6. Avionics Module Development Costs

SUBSYSTEM	NON-RECURRING COSTS (DEVELOPMENT & QUALITY)
ATTITUDE CONTROL	$ 5.0 M
AUXILIARY PROPULSION	2.5
COMMUNICATION	4.5
VIDEO/LIGHTING PLATFORM	1.5
SCANNING LASER RADAR (SLR)	3.0
VEHICLE	
STRUCTURE	0.4
THERMAL CONTROL	0.4
MECHANISMS	0.4
POWER DISTRIBUTION	0.2
SUBTOTAL	$ 17.9 M
SYSTEM INTEGRATION & TEST, AND PROGRAM MANAGEMENT	12.1
TOTAL	$30.0 M

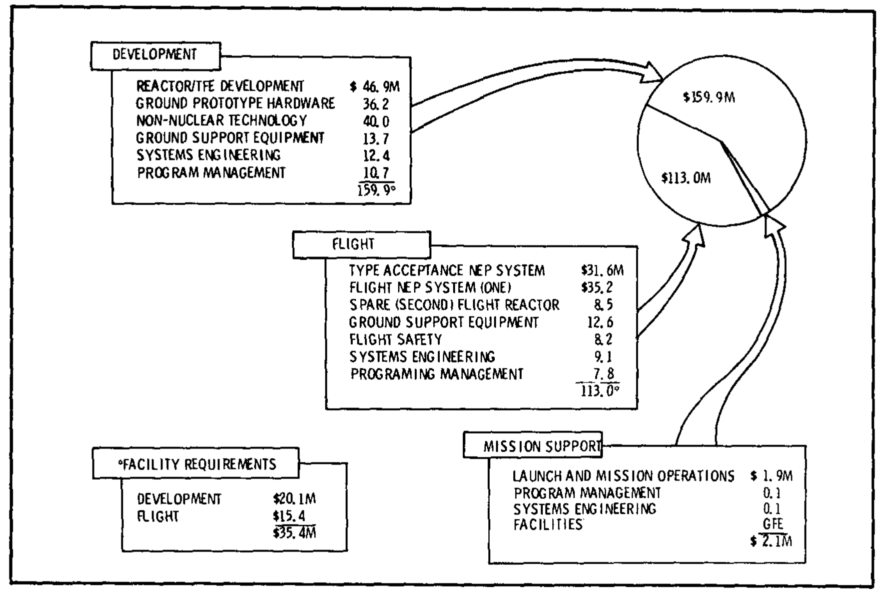

Figure 10. Subsystem Cost Summary Baseline NEP System Program

NEP SYSTEM COSTS - DEVELOPMENT

Figure 8 presents program costs as a function of fiscal year for the $ 275 M baseline NEP system development program. Peak costs of $ 56 M are estimated for Fiscal Year 1979. These costs are based on Fiscal 1972 dollars, and do not include any allowance for contingency, escalation, U-235 fuel costs, and fees.

The contribution of the major task elements are presented. There is a clear flow of funding from technology, to ground prototype hardware, to the Type Acceptance (TA) NEP system, and to the Flight NEP systems. The early requirement for facilities and GSE and their impact on annual program funding requirements is clearly indicated.

The summary schedule is shown in Figure 9. The baseline program is assumed to begin in Fiscal Year 1973 and extend for eleven years to meet an early 1980's launch objective for a 20,000 full power hour NEP system.

Key elements of the baseline program are:

- Inclusion of two ground reactor tests, Thermonic Reactor Experiment (TREX) and a Ground Prototype Reactor (GPR).
- Strong inheritance from SEP technology, although a partial ion engine array development test and a full ion engine array test are included to verify performance in the NEP configuration.
- Early requirements for GSE, particularly structural simulation, and for facilities for reactor tests. The NEP system assembly test and checkout facility is required about three years before launch.
- A TFE design with proven continuous 20,000 life capability is qualified two years before launch.
- Technology ready and preliminary mission approval occur in FY 1978 after demonstration of the feasibility of a 20,000-hour TFE life, and with the qualification of the 10,000-hour life TFE. The Type Acceptance (TA), or qualification NEP system design is initiated at this time.

Figure 10 shows the baseline NEP system development program cost elements grouped to present program costs in terms of basic development, the total flight program, and mission support. The $ 160 M development program represents about 58 percent of the total. The $113 M flight program costs is about 41 percent of the total. The contractor mission support function constitutes less than one percent of the program total. Required facilities will add $35.4 M to these costs. The costs incorporate a $27 M TFE development program. The total cost for the two test reactors, including test operation, is $48 M. Other technology development, including structures and ion engine array, accounts for $48 M. These totals do not include related program management and safety.

Total TA and Flight NEP Systems costs are $76 M. Flight nuclear safety costs are about $8 M. Management and Systems Engineering are $42 M (Launch and Mission Operations are included at $2 M). Total GSE costs are $26 M.

The $30 M Avionics Module development costs, summarized in Table 6, are based on an engineering design and prototype test cycle of thirty months. The subsystem cost estimates include engineering, technician and drafting support necessary to adapt flight proven components to the specific NEP Stage requirements. An experience factor of 68 percent is added to these costs, to cover normal system integration, test and program management.

Table 7. NEP System Unit Cost Estimates

FIRST NEP FLIGHT SYSTEM	$35.2 M
SECOND FLIGHT NEP SYSTEM AT ~80 PERCENT	$28.2 M
SUBSEQUENT FLIGHT NEP SYSTEMS MAY APPROACH ~70 PERCENT	$24.6 M

Table 8. Avionics Module Cost Estimates

SUBSYSTEM	RECURRING COSTS
ATTITUDE CONTROL	$ 1.2 M
AUXILIARY PROPULSION	0.5
COMMUNICATION	0.4
VIDEO/LIGHTING PLATFORM	0.2
SCANNING LASER RADAR (SLR)	0.3
VEHICLE	
STRUCTURE	0.2
THERMAL CONTROL	0.2
MECHANISMS	0.2
POWER DISTRIBUTION	0.1
SUBTOTAL	$ 3.3 M
SYSTEM INTEGRATION & TEST, AND PROGRAM MANAGEMENT	3.3
TOTAL	$ 6.6 M

UNIT COSTS

Estimated total recurring costs for the Flight NEP System are presented in Table 7. The first Flight NEP System costed for the development program options totals $ 35.2 M. It is estimated that the cost of the second of these two units is about 80 percent of the cost of the first unit, if these two are built consecutively over a two-year period. It is projected that the cost of subsequent units could approach $25 M, or 70 percent of the cost of the first unit.

NEP SYSTEM COSTS - UNIT COSTS

The preliminary unit cost estimates for the Avionics Module are shown in Table 8. The subsystem cost estimates include required engineering technician, and drafting support. The recurring costs are $6.6 M, including normal product revision, system integration and test, and program management during the manufacturing cycle.

Table 9. NEP System Technology Requirements

1973 - 1977

- 20,000 FULL POWER HOUR THERMIONIC REACTOR
- 20,000 FULL POWER HOUR ION ENGINE
- POWER CONDITIONING DEFINITION

1975 - 1979

- FURTHER REACTOR DEVELOPMENT
- POWER CONDITIONING LIFE TESTS
- RADIATION EFFECTS
- ION ENGINE INTERACTIONS

1977 - 1981

- AVIONICS SUBSYSTEM
- DOCKING AND RENDEZVOUS
- UNIQUE GSE

NEP SYSTEM TECHNOLOGY REQUIREMENTS

A review of the study analysis and results identifies area where research and development are required to assure availability of the NEP Stage. Several of the key areas of technology, shown time phased in Table 9, are briefly discussed below.

DEVELOPMENT OF 20,000 HOUR TFE REACTOR

This program would provide for completion of the TFE reactor development, building on the technology developed through Fiscal 1973. To meet the NEP Stage development schedule identified in this study, a 20,000 hour demonstration reactor would be required by fiscal year 1977, and a 20,000 hour qualification test in fiscal year 1981.

ION THRUSTER DEVELOPMENT

Significant mission advantages for NEP applications can be achieved for full power lifetimes up to 20,000 hours. This program would be designed to develop the 30 cm ion engine to provide these long-life capabilities, including hardware demonstration test, by fiscal year 1977. An additional development program task for advanced systems of higher power levels ($\geq$ 240 kWe) would involve investigation and preliminary designs of ion thrusters having higher allowable beam current. These designs could permit weight and engine array area savings.

SELECTION AND DEVELOPMENT OF POWER CONDITIONING APPROACH

Two different schemes for the main power conditioning were considered during the mission engineering study, both of which employ three phase transformers. This study and development program would first make a selection of preferred design approach, including selection rationale. The development phase of the program will then include controls design, three phase transformer development, breadboard models, and fabrication of prototype test hardware for environmental testing.

IMPACT OF ION THRUSTER INTERACTIONS WITH NEP STAGE

Based on the objectives of current space programs, the mission engineering study resulted in the definition of an end thrust NEP Stage with boomed reactor located aft of the thruster array. In this configuration, some uncertainties exist relative to the impact and interactions of mercury and sputtered grid material from the ion engines on stage components aft of the ion engines. The NEP Stage design minimizes such interactions, and currently available data indicate that these are acceptable. However, future effort should be directed toward the identification and characterization of sputter resistant coatings, and the assessment of such interactions with adjacent NEP Stage components. This effort would provide design requirements for improved beam focusing characteristics of 30 cm ion engines.

ASSESSMENT OF RADIATION EFFECTS ON NEP STAGE

During the mission engineering study several areas under the broad category of radiation effects were determined to require further detailed analysis. This detailed study shall provide calculation and specific assessment of mercury shielding effectiveness as the primary gamma shield. This study shall also provide for in-depth calculation of scattered radiation from antennas and other stage components, and an assessment of the effects of this radiation source on electronics performance.

DEVELOPMENT OF MULTI-MISSION AVIONICS SUBSYSTEM

The objective of this program is the design and development of a single avionics subsystem to be utilized with the NEP Stage to perform both geocentric and interplanetary missions. Areas of concentration shall be attitude control sensor design, implementation of data handling hardware, software for the Thrust Vector Control (TVC) System, and communications requirements.

DEVELOPMENT OF STANDARD DOCKING SYSTEM FOR GEOCENTRIC PAYLOADS

To provide cost effectiveness, multi-use of the NEP Stage dictates a requirement for utilization with many geocentric payload configurations. This program would involve design, fabrication, and testing of a standardized docking integration systems, suitable for use with these payload classes.

POTENTIAL IMPACT OF NUCLEAR ELECTRIC PROPULSION ON FUTURE NASA SPACE PROGRAM

- LOW COST
  - HIGH PAYLOAD CAPABILITY PERMITS MULTIPLE OUTER PLANET EXPLORATION BY ONE NEP STAGE
  - HIGH PAYLOAD CAPABILITY PERMITS DELIVERY OF MULTIPLE SPACECRAFT TO EARTH ORBIT BY ONE NEP STAGE
- LOW COST
  - HIGH PAYLOAD CAPABILITY OF NEP STAGE IS COMPATIBLE WITH THE DEVELOPMENT AND UTILIZATION OF HIGH RELIABILITY, LOW COST STANDARDIZED PLANETARY AND GEOCENTRIC PAYLOADS
- LOW COST
  - THE IDENTIFIED CAPABILITY OF ONE NEP STAGE DESIGN TO PERFORM BOTH GEOCENTRIC AND OUTER PLANET MISSIONS PERMITS LOW COST BLOCK BUYS OF NEP STAGE HARDWARE

Low cost is identified as the major area where the availability of nuclear electric propulsion would impact future NASA space programs. This aspect is directly attributed to the multi-mission capability of the NEP Stage, and its capability to deliver multiple payloads during a single mission. The low cost capability is also related to the inherently high reliability potential of an NEP Stage which employs an in-core thermionic reactor.

The high payload capability of the NEP Stage permits the exploration of several outer planet systems during a single mission. Similarly, the same NEP Stage design could deliver multiple payloads to geocentric orbit. For example, multiple communication satellites could be placed in one or several synchronous orbits, during a single mission. The flexibility of the NEP Stage is further demonstrated by its capability to operate in earth orbit for times of the order of 10,000 full power hours, and then complete an outer planet mission requiring similar thrust time duration. These capabilities exist at the 120 kWe power level emphasized in this study, and further improve on the power level increases to 240 kWe and above. The Shuttle payload bay envelope limits the maximum NEP Stage size to the order of 400 kWe.

The NEP Stage is modular in design. At least 20 percent redundancy is designed into all major subsystems, including the reactor, ion engine array, power conditioning, heat rejection radiator, and avionics. Component/subsystem failures up to 20 percent do not compromise the design value of 120 kWe at end-of-mission. Similarly, failures greater than 20 percent, although reducing the power level below 120 kWe, are not expected to result in total loss of power. The probability of mission completion remains very high, although somewhat longer mission times will be required, should the power level fall below 120 kWe. Such degradation is expected to be gradual.

The high payload capability, the NEP Stage flexibility and its inherently high reliability, all contribute to the identified cost effectiveness of the NEP Stage.

The NEP Stage high payload capability is compatible with the development of low cost, long life payloads, where additional weight is employed to reduce costs through standardization, and to increase reliability through increased redundancy. The capability can be implemented for both geocentric and outer planet payloads.

The NEP Stage multi-mission capability eliminates the need to develop and procure separate hardware for different mission classes. (The NEP Stage is also adaptable to inner planet missions, although these may be initially performed by solar electric propulsion stages.) This permits further NEP Stage cost reductions, because block buys of NEP Stage flight hardware can be implemented. It is estimated that a production rate of at least one NEP Stage per year is required to reduce NEP Stage unit costs to $25 M or less.