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Overview of Space Propulsion Systems for Identifying Nondestructive Evaluation and Health Monitoring Opportunities

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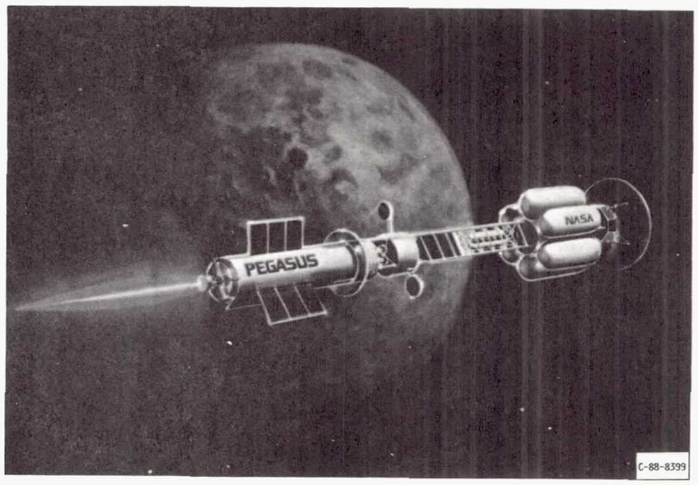

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OVERVIEW OF SPACE PROPULSION SYSTEMS FOR IDENTIFYING NONDESTRUCTIVE EVALUATION AND HEALTH MONITORING OPPORTUNITIES

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SUMMARY

The next generation of space propulsion systems will be designed to incorporate advanced health monitoring and nondestructive inspection capabilities. As a guide to help the nondestructive evaluation (NDE) community impact the development of these space propulsion systems, several questions should be addressed. This report provides an overview of background and current information on space propulsion systems at both the programmatic and technical levels. It provides a framework that will assist the NDE community in addressing key questions raised during the 2-5 April 1990 meeting of the Joint Army-Navy-NASA-Air Force (JANNAF) Nondestructive Evaluation Subcommittee (NDES).

INTRODUCTION

The next generation of space propulsion systems will be designed to incorporate advanced health monitoring and nondestructive inspection capabilities. As a guide to help the nondestructive evaluation (NDE) community affect the development of these space propulsion systems, several questions should be addressed. The following key questions were raised during the 2-5 April 1990 meeting of the Joint Army-Navy-NASA-Air Force (JANNAF) Nondestructive Evaluation Subcommittee (NDES):

(1) What types of space propulsion systems are being considered?

(2) What are the principles of operation of these systems?

(3) Who is developing and/or researching space propulsion systems?

(4) How are inspections and reliability assessments performed on the ground and in orbit?

(5) Do the space propulsion systems require health monitoring?

(6) What are the possible failure modes for these systems?

(7) Have the reliabilities of these space propulsion systems been determined?

This report describes technological driver missions supporting space programs that are developing chemical, electric and nuclear propulsion systems. The types of propulsion systems being considered, their principles of operation and known failure modes, and the developers are identified. The propulsion systems characteristics are described in sufficient detail to identify life-limiting features and opportunities for nondestructive testing and health monitoring. However, the reader should be aware that not all aspects of the propulsion system that required health monitoring and nondestructive evaluation are covered. For example, the failure modes of space-based nuclear generators or solar panels that supply power in the form of electric energy for electric propulsion systems are not discussed. Space propulsion systems are at various stages of development; therefore, some questions, such as those concerned with reliability and failure modes, remain unanswered. The key references provided will assist researchers in developing their particular area of interest in space propulsion NDE and health monitoring.

TRANSPORTATION FOR FUTURE SPACE SCIENCE MISSIONS

The actual vehicles and propulsion systems that are to be used for future space missions have, in most cases, not been determined. The specific propulsion system and vehicle being considered for a particular mission changes as the mission develops and matures. Therefore, these propulsion systems are not predetermined and fixed but are essentially moving targets. Before the NDE community can assist and affect the development of these advanced propulsion systems, they must latch onto these moving targets by understanding the programmatic thrusts, the path of the development, and current status of these systems. Technological challenges have been identified (ref. 1) that are driving the development of advanced space propulsion systems. The following set of missions presents technological challenges that must be addressed to meet national space transportation needs:

(1) Modern expendable launch systems of small and medium capacity

- Payload weight: 20 000 to 50 000 lb low earth orbit (LEO)
- High reliability
- Low cost
- Improved payload-to-lift mass

(2) Unmanned heavy-lift launch capability to LEO

- Payload weight: greater than 100 000 lb
- Payload envelop: as unrestricted as feasible
- Cost: substantial reduction over current systems (full or partial reusability will be determined by economic tradeoffs)

(3) Reusable orbital transfer system to raise payloads from LEO to higher altitude, sun-synchronous or geostationary orbit and to return them

- Geostationary payload weight: greater than 20 000 lb
- Payload envelope: as unrestricted as feasible
- Robotics: capable of interfacing with intelligent front-end for routine servicing operations

(4) Advanced space transportation system to replace the space shuttle after the turn of the century

- LEO payload weight: from 20 000 lb to potentially greater than 100 000 lb
- Payload envelope: as unrestricted as feasible

- Automation and robotics: used to reduce turnaround time and mission costs, with special emphasis on self diagnostics
- Tradeoffs will be made between "Shuttle II" and the transatmospheric Aerospace Plane

(5) High-energy interplanetary transfer system to meet objectives of the National Commission on Space

- High specific impulse, high-thrust, long-life propulsion systems to minimize duration of trips to Mars (e.g., 10 000 lb (44 000 N) or greater thrust, 800-sec specific impulse)
- High specific impulse, long-life propulsion systems for planetary scientific missions (e.g., very low thrust, greater than 1000-sec specific impulse)
- Nuclear-electric or direct thrust engines are candidates for these missions
- Hybrid power and propulsion systems are another attractive option

Some of the specific technology-driver missions for space science for the mid-1990's follow:

The Earth Observing System (EOS) (fig. 1), with three EOS platforms in sun-synchronous orbits, is designed to study the Earth's atmosphere. It is believed that automated or robotic servicing will be required at the operational altitude of the platform during its 20-yr life.

The Large Deployable Array (LDR) (fig. 2) is an astronomical observatory design that will operate in the 30-to 1000-μm range.

It is expected that maintenance will occur on a 3-yr schedule.

During a Mars Sample Return Mission (MSR) (fig. 3), samples at several depths and at widely dispersed sites on the Martian surface will be obtained and returned to Earth in a pristine condition.

SPACE EXPLORATION INITIATIVE

On February 16, 1990, President Bush approved policy for the Space Exploration Initiative. The goal of this initiative (ref. 2) is to place Americans on Mars by the year 2019. The initiative includes both lunar and Mars program elements, as well as robotic science missions. The near-term focus will be on technology development. This will be done by searching for new and innovative approaches and technology, and by investing in high-leverage, innovative technologies with potential to make major impact on cost, schedule, and performance. Mission, concept, and analysis studies will be done in parallel with the technology development.

A baseline program architecture will be selected after several years of defining two or more reference architectures while developing and demonstrating broad technologies (refs. 3 and 4). NASA will be the principle implementing agency, whereas the Department of Defense and Department of Energy will have major roles in technology development and concept definition. Some of the space programs discussed below have been absorbed or replaced by this Space Exploration Initiative.

SPACE PROGRAMS

The National Aeronautic and Space Administration (NASA) has several programs that require advanced, space-based propulsion systems. These propulsion systems may be quite different from those used in Earth-to-orbit launch vehicles. Each program has a different set of mission requirements that drives the development of different space propulsion systems (refs. 5 to 7). For example, the propulsion system used to keep the Space Station Freedom (fig. 4) in orbit will be quite different from that used for a manned Mars mission. To answer the questions presented earlier, we must examine the NASA space programs that have advanced space propulsion needs. Each program identifies specific mission requirements to be met by the propulsion system (ref. 8).

During the development of a space transportation system, propulsion studies and vehicle studies must be iterated until the propulsion requirements are defined for the vehicle. Following the definition of the propulsion requirements, mission-focused propulsion system studies identify the specific required propulsion system. Depending on the acceptable mission scenario, very different propulsion systems and vehicles can result in successful space transfer. However, since studies have not matured sufficiently, we are unable to specify what propulsion system will be used for an actual mission. Mission scenario studies indicate that advanced, reliable, long life, low weight, efficient, high power, and variable-thrust space propulsion systems are needed.

Space propulsion systems may be based on electrical, chemical, or nuclear processes (table I). The design, operation, maintainability, reliability, failure modes, health monitoring, and mission requirements for these propulsion

TABLE I. - SPACE PROPULSION SYSTEMS

Engine type	Principle of operation	Propulsion system
Chemical	Recomposition	Liquid oxygen/liquid hydrogen (LOX/H_2) thruster
	Decomposition	Hydrazine thruster
Electrical	Electrostatic	Ion thruster
	Electrothermal	Resistojet, arcjet, microwave thruster
	Electromagnetic	Magnetoplasmadynamic
Nuclear	Nuclear fission	Solid core rocket Gas core rocket

systems will vary considerably. Therefore, it is natural to examine each of these systems on the basis of the physical process used to produce thrust. Before the types of propulsion systems being considered, developed, or used are described, it is appropriate to identify the programs that support the development of these propulsion systems.

Chemical Propulsion Program

Project Pathfinder (ref. 9) from the NASA Office of Aeronautics and Space Technology[1] (OAST) is a research and technology program designed to make new missions in space exploration possible and strengthen the technology base in support of the civil space program. Pathfinder has a distant horizon that is reached by building on the space shuttle and space station programs. Pathfinder addresses technologies that support a range of space missions including: a return to the Moon to build an outpost (fig. 5), piloted missions to Mars (fig. 6), and continuing exploration of Earth and the other planets.

Project Pathfinder has four major components: (1) Exploration Technology, (2) Space Operations, (3) Humans-in-Space, and (4) Transfer Vehicle Technology. The Exploration Technology, Space Operations, and Humans-in-Space components include planetary rover development, surface power, remote sample acquisition, optical communications, autonomous rendezvous and docking, resource processing, in-space assembly and construction, cryogenic fluid depots, space nuclear power, extravehicular suits, human performance, and closed-loop support systems. The Transfer Vehicle Technology is of particular interest to JANNAF NDES because it supports transportation to and from geostationary Earth orbit, the Moon, Mars, and other planets. Specific goals of the Transfer Vehicle component include significant reduction in the mass that missions require for launch into low Earth orbit and in transit, as well as reductions in the time required for transit. The key elements of the Transfer Vehicle Technology thrust are the chemical transfer propulsion research, cargo vehicle propulsion development, high-energy aerobraking development (fig. 7), autonomous lander development, and fault-tolerant systems.

The Transfer Vehicle Technology thrust led to the initiation of the NASA OAST Pathfinder Chemical Transfer Propulsion Program (refs. 10 and 11). This program was initiated to provide the technology to design and develop highly reliable, reusable cryogenic transfer vehicle engines that are fault tolerant, and have long lives. They will be high-performance, liquid oxygen/liquid hydrogen (LOX/H_2) expander cycle engines for space-based transfer vehicles and Moon and Mars landers.

Electric Propulsion Program

NASA OAST's Propulsion, Power, and Energy Division supports an electric propulsion program (refs. 12 to 15) for a broad class of missions. Three types of electric propulsion systems are being developed (refs. 12 to 29): electrostatic (ion), electrothermal (resistojet, arcjet, microwave, and radiowave), and electromagnetic (magnetoplasmadynamic, or MPD). Resistojets are currently used on geosynchronous communications satellites.

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[1]Now NASA Office of Aeronautics and Exploration Technology (OAET).

Nuclear Propulsion Program

In 1987 the Air Force Systems Command reinitiated a Direct Nuclear Propulsion Program (refs. 1, 30, and 31). The goals of this program are to develop a high-impulse, high-thrust, low-weight propulsion system. This propulsion system would be used for orbital transfer vehicles, fast launch interceptors, intercontinental ballistic missiles, and other missions.

PROPULSION SYSTEM CHARACTERISTICS

The operating characteristics of chemical, electrical and nuclear propulsion systems are quite different (ref. 32). Thrust and specific impulse can be used for making general comparisons between propulsion systems. Table II indicates the range of thrust T and specific impulse I_{sp} for electrical, chemical, and nuclear propulsion systems. Thrust is the amount of force that a propulsion system generates. The greater the thrust, the greater the acceleration of the vehicle. Specific impulse (in seconds) is the thrust (in Newtons) that can be obtained from an equivalent rocket which has a propellant weight flow rate (in Newtons per second) of unity. (Specific impulse is somewhat analogous to the number of miles per gallon of fuel for automobiles.) Electric propulsion systems have lower thrust capabilities than chemical or nuclear propulsion systems do. Chemical propulsion systems yield the highest thrust levels available to date. However, direct nuclear propulsion is expected to yield greater thrust levels than chemical propulsion. The specific impulse for electrical resistojets and arcjets are comparable to chemical LOX/H_2 and hydrazine propulsion systems. The ion, MPD, and nuclear propulsion systems have the

TABLE II. - THRUST AND SPECIFIC IMPUSLE

Engine type	Propulsion system	Specific impulse, I_{sp}, seconds	Thrust, T, Newtons
Chemical	LOX/H_2 thruster	300 to 500	$(0.110 \text{ to } 2222)\times10^{3}$
	Hydrazine thruster	280 to 300	$(180 \text{ to } 360)\times10^{-3}$
Electrical	Ion thruster	3500	$(65 \text{ to } 510)\times10^{-3}$
	Resistojet	290 to 380	$(180 \text{ to } 490)\times10^{-3}$
	Arcjet	400 to 1100	$(10 \text{ to } 212)\times10^{-3}$
	Microwave thruster	200 to 600	
	Magnetoplasma-dynamic (MPD)	1500 to 8000	50 to 200
Nuclear	Nuclear thermal rocket (NTR)	800 to 1200	$(333 \text{ to } 1000)\times10^{3}$

highest specific impulses, and they can exceed those of other systems by an order of magnitude.

Classes of propulsion systems that will be needed to meet mission requirements can be identified from table II and from preliminary mission propulsion requirements. High specific impulse engines, such as ion, MPD, and nuclear propulsion systems, will be needed for interplanetary transfer. Low thrust engines, such as resistojet, arcjet, and hydrazine engines, are needed for station keeping and drag makeup for orbiting systems and for manned maneuvering units. High-thrust engines are needed for cargo orbit and orbital maneuvering vehicles (fig. 8).

BASIC PRINCIPLES OF SPACE PROPULSION SYSTEMS

In this section, each of the candidate propulsion systems is discussed, the operating principles and current developmental status of each system are indicated, and any system features that limit the useful lifetime of these propulsion systems are highlighted. The specific researchers that are developing these systems can be identified in the references quoted.

Chemical Propulsion

Hydrogen/oxygen thruster. - The hydrogen/oxygen (LOX/H_2) thruster uses chemical recomposition to produce thrust. Hydrogen and oxygen are injected, mixed and ignited in the combustion chamber (fig. 9, refs. 33 to 40). The ignited mixture burns to form hot gaseous reaction products that are accelerated via the throat and nozzle assembly to produce thrust. The RL10A-3-3A engine, which is the only upper-stage, LOX/H_2 thruster in operation, was designed to be expendable. Life-limiting failure modes have not been observed for reusable, space-based, gaseous O/H thrusters (fig. 10), therefore, the lifetimes are not known.

Hydrazine thruster. - The hydrazine thruster is based on the principle of chemical decomposition (fig. 11). The propellant, hydrazine, is injected into the catalyst bed (refs. 41 to 46), and the catalyst causes the hydrazine to spontaneously decompose into NH_3, N_2, and H_2 gases. The gases are exhausted via the nozzle to produce thrust. In an augmented hydrazine thruster (fig. 12), the gases are heated further before exiting. The service life of these thrusters is limited by the useful life of the catalyst bed. The failure is due to a break down of the catalyst into fine particles that are eliminated via the exhaust.

Electric Propulsion

Resistojet. - A schematic diagram of a resistojet is shown in figure 13. Propellant is heated via a resistively heated heat exchanger. The heated propellant (1400 °C) is expanded and exhausted via the nozzle to produce thrust (refs. 47 to 66). The propellant may be introduced to create a vortex flow pattern within the heat exchanger. The candidate propellants are CO_2 (carbon dioxide), CH_4 (methane), H_2 (hydrogen), NH_3 (ammonia), N_2 (nitrogen), steam, and N_2H_4 (hydrazine). State-of-the-art resistojets are shown in figures 14 to 18. Heater mass, and material surface changes, and grain growth rates affect the life of these systems. The thruster life also depends on the propellant used.

Arcjet. - The arcjet (fig. 19) uses an electric arc to heat the propellant directly. Here the propellant is passed between two electrodes while an arc is struck and maintained to heat and expand the propellant. Then the heated propellant (hydrazine, hydrogen, or ammonia) is exhausted through the nozzle to produce thrust (refs. 67 to 89). Several designs using different materials have been studied (figs. 20 to 23).

The lifetime of an arcjet is limited by electrode, nozzle, and injector wear. The electrode wear may be in the form of spalling due to thermal shocks or localized melting from high current densities. Electrode wear may also occur when there are chemical incompatibilities. The arcjet reliability is not known; however, the starting reliability indicates that a large number of starts does not affect the steady state performance.

Microwave thrusters. - Microwave and radiowave thrusters heat the propellant without the use of electrodes (refs. 90 to 96). The microwaves heat the propellant (argon, nitrogen, or helium) in the discharge chamber (fig. 24), and the heated propellant (2000 K) exits via the nozzle to produce thrust. Nozzle melting and erosion have limited the thruster life.

Ion thruster. - An ion thruster is shown in figure 25. Xenon or mercury vapor is ionized in an ionization chamber, and the positively charged particles are accelerated via the accelerator grid. Then, neutralizer injects electrons to neutralize the accelerated, positively charged particles. This accelerated, neutralized mass produces the thrust (refs. 97 to 124). The magnets, the screen, and accelerator grids make up the ion optic system (figs. 26 and 27) that collimates the accelerated particles. The typical path that the ions follow is also shown in figure 25. Unexpected extinctions of the discharge are due to thermal design and lack of ignition control. Sputter erosion of the discharge chamber, screen, baffle, and cathode limits the life of ion thrusters. Metallic flakes, which form as a result of this sputter erosion, may spall and short out the ion optics by bridging the gap between the screen and accelerator grids. The cathode tubes also oxidize and deform during thruster operation.

Magnetoplasmadynamic (MPD) thruster. - The magnetoplasmadynamic thruster (figs. 28 to 31) looks similar to the arcjet; however, the principles of operation are quite different. The MPD thruster is based on electromagnetic principle as opposed to the arcjet, which is based on electrothermal principle. The propellant is ionized by the current flow between the anode and cathode. This current flow induces a magnetic field that causes expansion of the arc and acceleration of the ionized gas to produce thrust (refs. 125 to 136). The propellants used are xenon, argon, hydrogen, helium, ammonia, neon, nitrogen, and lithium. The lifetimes of these propulsion systems are limited by erosion of the cathode and insulator.

Nuclear Propulsion

Two types of nuclear propulsion systems are being developed: a nuclear thermal propulsion (NTP) system and a nuclear electric propulsion (NEP) system (refs. 102 and 136). The NEP system uses a nuclear reactor to provided electric power to an electric propulsion system (e.g., an MPD or ion thruster). The NTP systems may use either a solid core reactor (SCR) or a gas core reactor (GCR).

Solid core nuclear thermal rocket. - A solid core nuclear propulsion system (refs. 137 to 146) uses fissioning solid uranium carbide particles to heat hydrogen (figs. 32 to 36). The hydrogen is heated as it flows down the coolant tubes of the fuel elements. Then it is accelerated via the nozzle to produce thrust. Both fuel and support elements are used in forming the SCR. The rate of reaction in the SCR is controlled by the graphite matrix supporting the uranium carbide particles that make up the fuel elements and by ZrH moderators contained in the support elements. Corrosion of the graphite moderator/heat exchanger by hot hydrogen limits the life of the SCR propulsion systems.

Gas core nuclear thermal rocket. - Gas core nuclear propulsion systems (refs. 147 to 152) use fissioning uranium gas/plasma to heat hydrogen. Two types of gas core (open- and closed-cycle) rockets are being considered. An open
cycle, porous wall, spherical gas core rocket engine uses the nuclear thermal energy of the fission gas/plasma to heat an envelope of hydrogen propellant (fig. 37). The hydrogen expands and flows out of the nozzle to produce thrust. Both uranium and hydrogen are exhausted in this open-cycle system. A closed-cycle nuclear light bulb (NLB) rocket heats hydrogen that is behind thermally transparent and cooled SiO or BeO walls (figs. 38 to 40). This arrangement isolates the uranium fuel and fission products from the propellant exhaust.

DISCUSSION AND SUMMARY

There are many space propulsion systems that are being developed. The principles of operation vary considerably between systems. Each system has its own particular types of failure modes. However, it is clear that material losses and material microstructural changes are the dominant mechanisms that affect the lifetimes of these advanced systems. These material variations are identified as mass losses due to electrical sputter erosion, oxidation or chemical erosion, and microstructural changes such as melting and grain growth. Therefore the NDE and health monitoring researchers may want to direct their attention to nondestructive evaluation and monitoring of surface and bulk material changes.

The difference between past propulsion systems and the next generation of space propulsion systems will be the incorporation of health monitoring strategies. Lifetime estimates have been obtained for some of these space propulsion systems. However, nonintrusive methods for monitoring and verifying the propulsion system's "age" and health need to be developed. In addition, the reliabilities for most of these propulsion systems remain in question, and methods of determining these reliabilities at a reasonable cost have not been developed.

These space-based propulsion systems provide a rich field of opportunity for nondestructive evaluation and health monitoring researchers. These researchers must become intimately aware of the current status and future directions of propulsion research. Nondestructive evaluation and health monitoring researchers will impact the development of space propulsion systems when they actively participate in the development of future directions.

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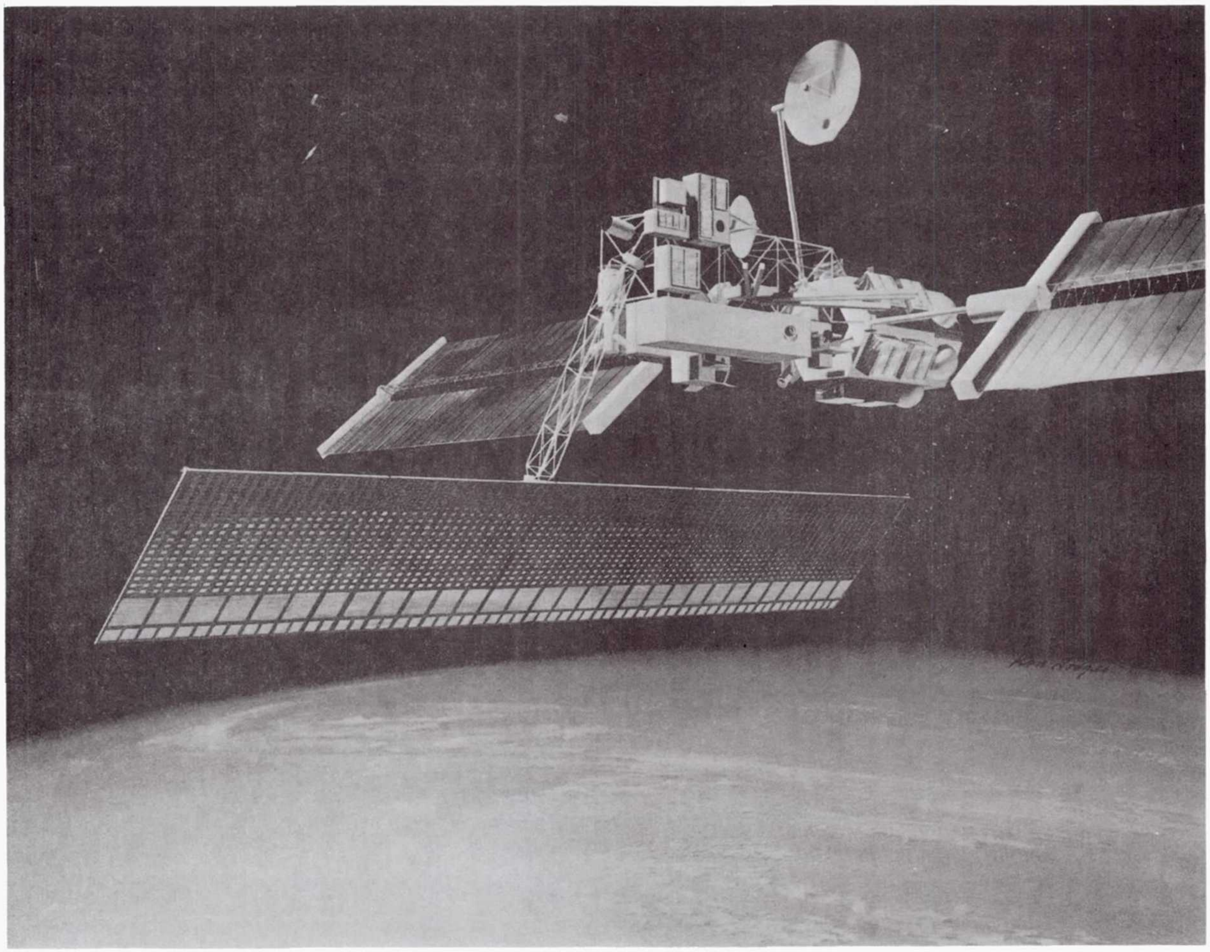


FIGURE 1. - ARTIST'S CONCEPT OF EARTH OBSERVING SYSTEM (EOS) POLAR ORBITING MISSION.

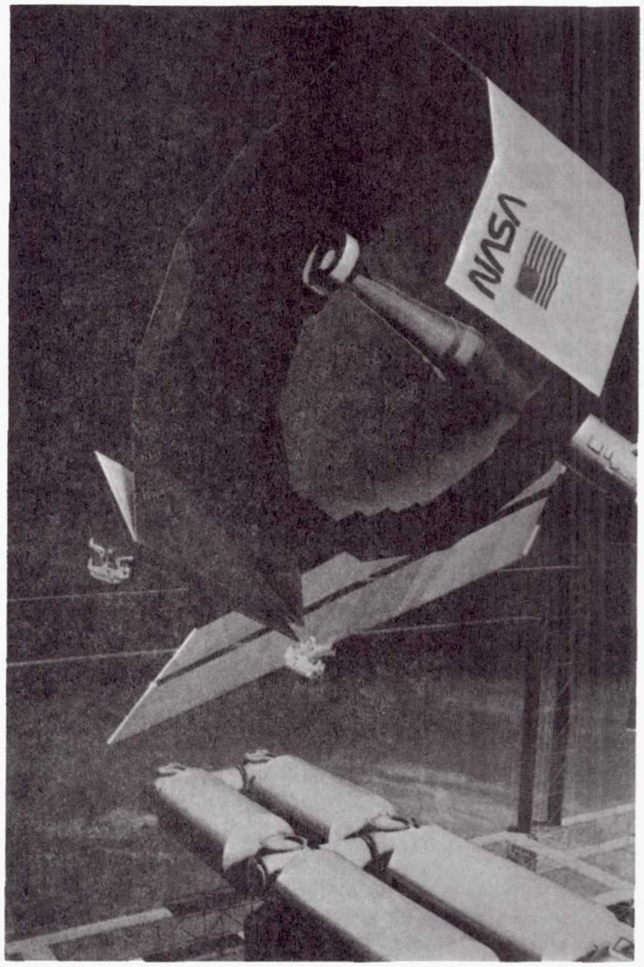


FIGURE 2. - ARTIST'S CONCEPT OF LARGE DEPLOYABLE REFLECTOR.

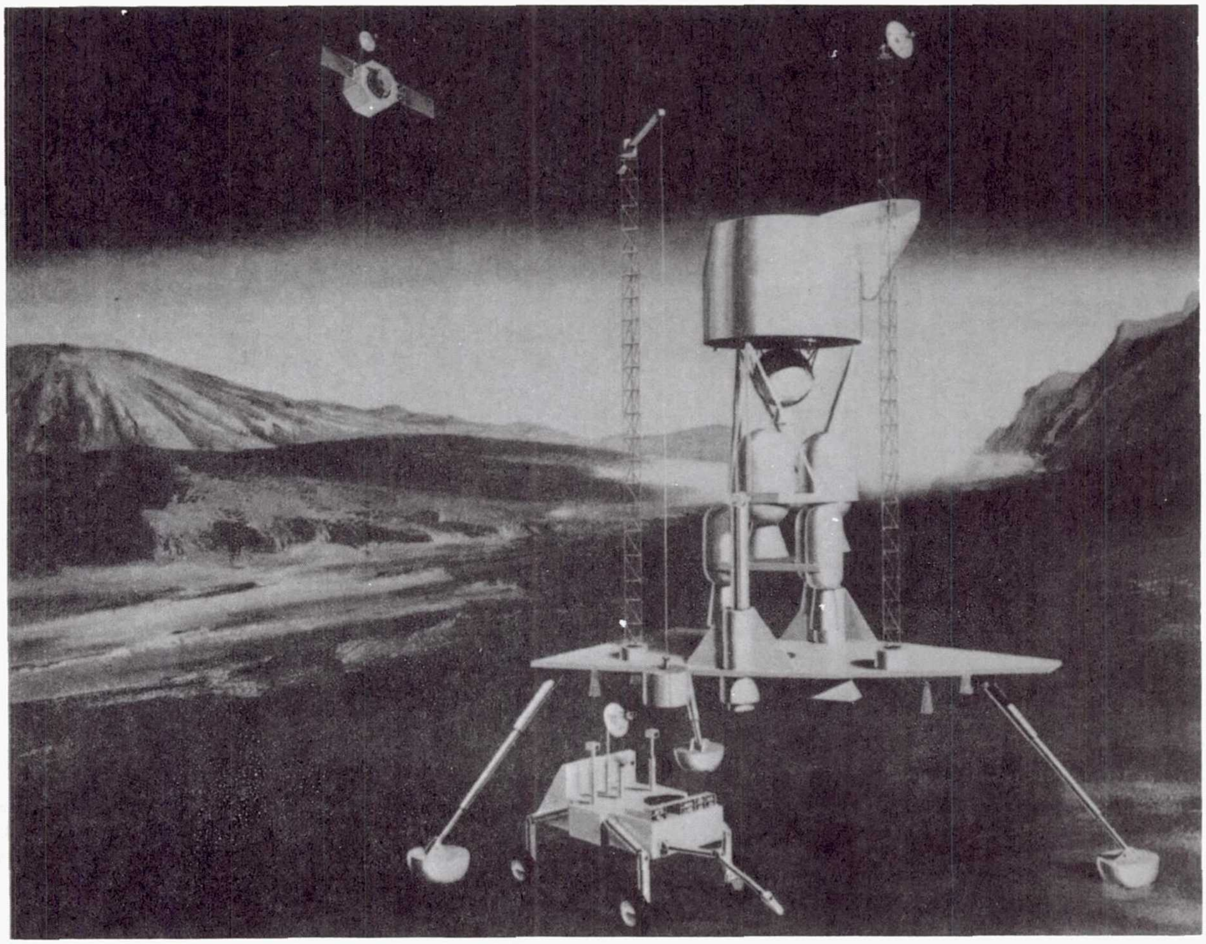


FIGURE 3. - ARTIST'S CONCEPT OF THE LANDER, ROVER, AND COMBINED SAMPLE RETURN SYSTEM AND LAUNCHER ON THE SURFACE OF MARS.

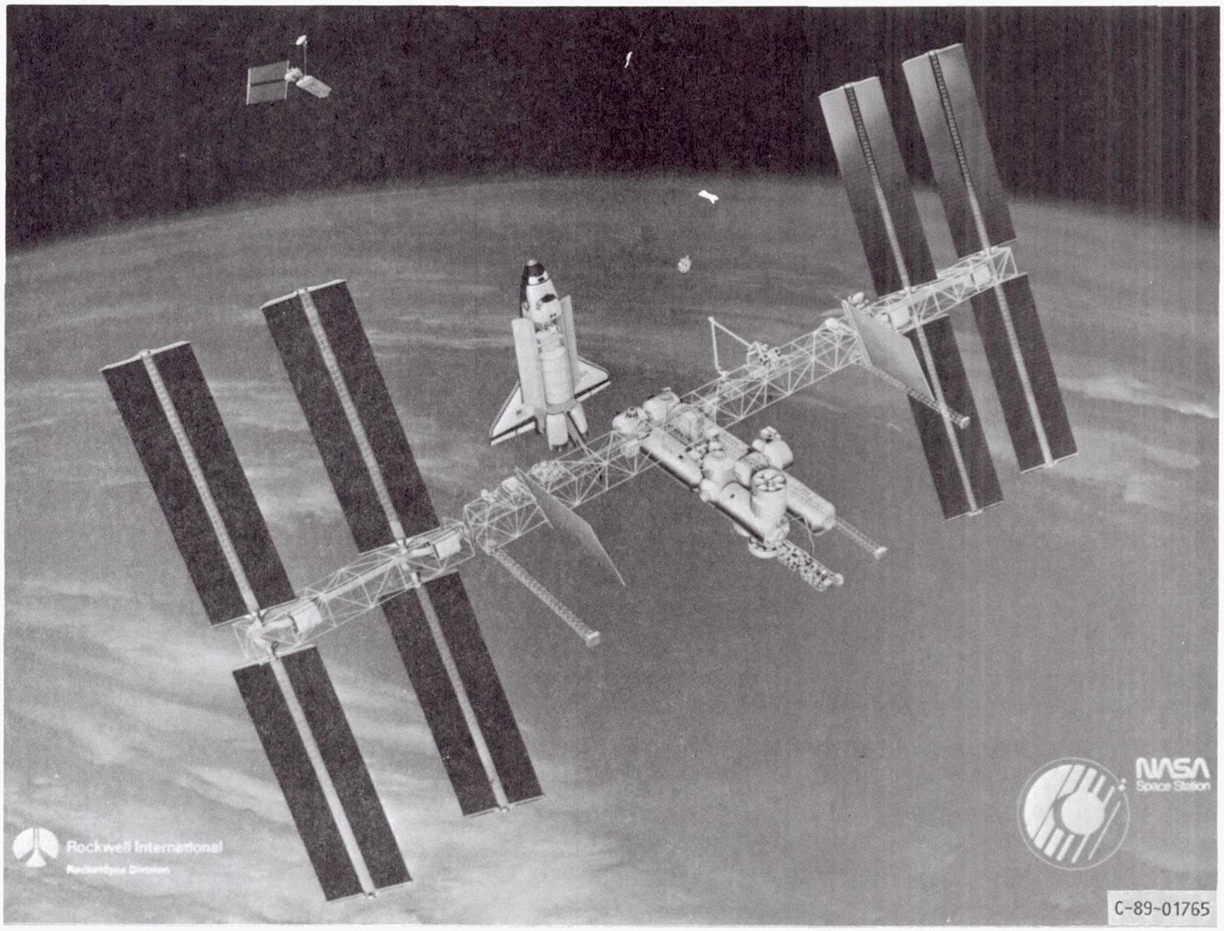


FIGURE 4. - SPACE STATION FREEDOM.

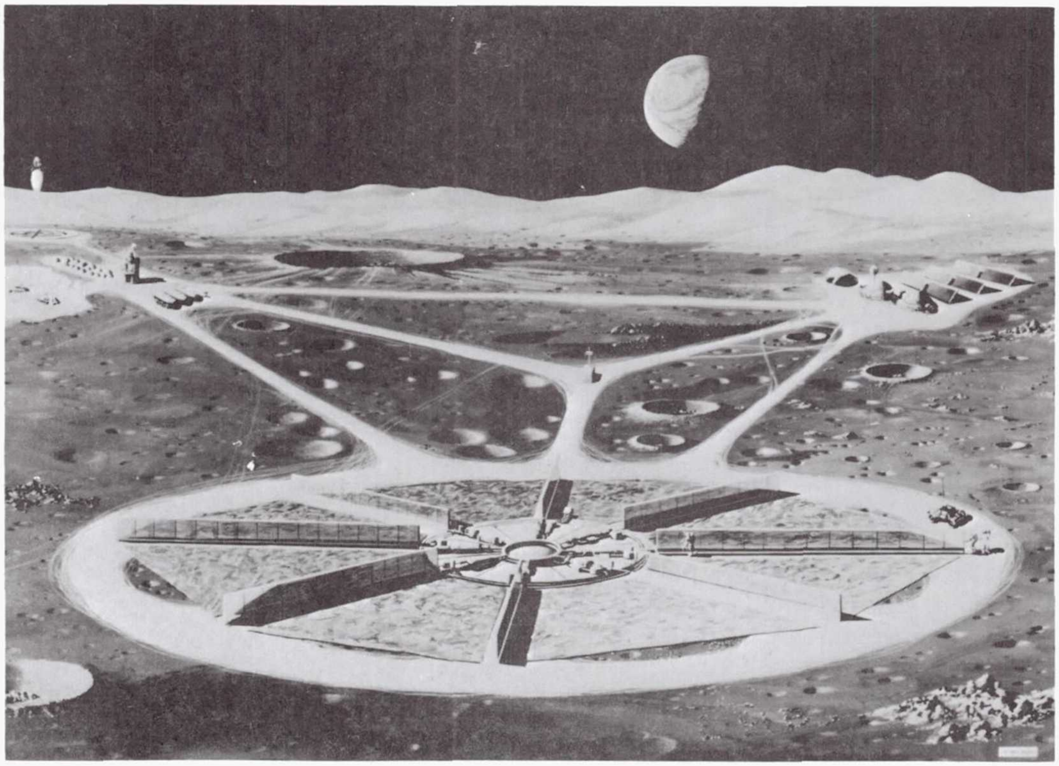


FIGURE 5. - ARTIST'S CONCEPT OF LUNAR BASE.

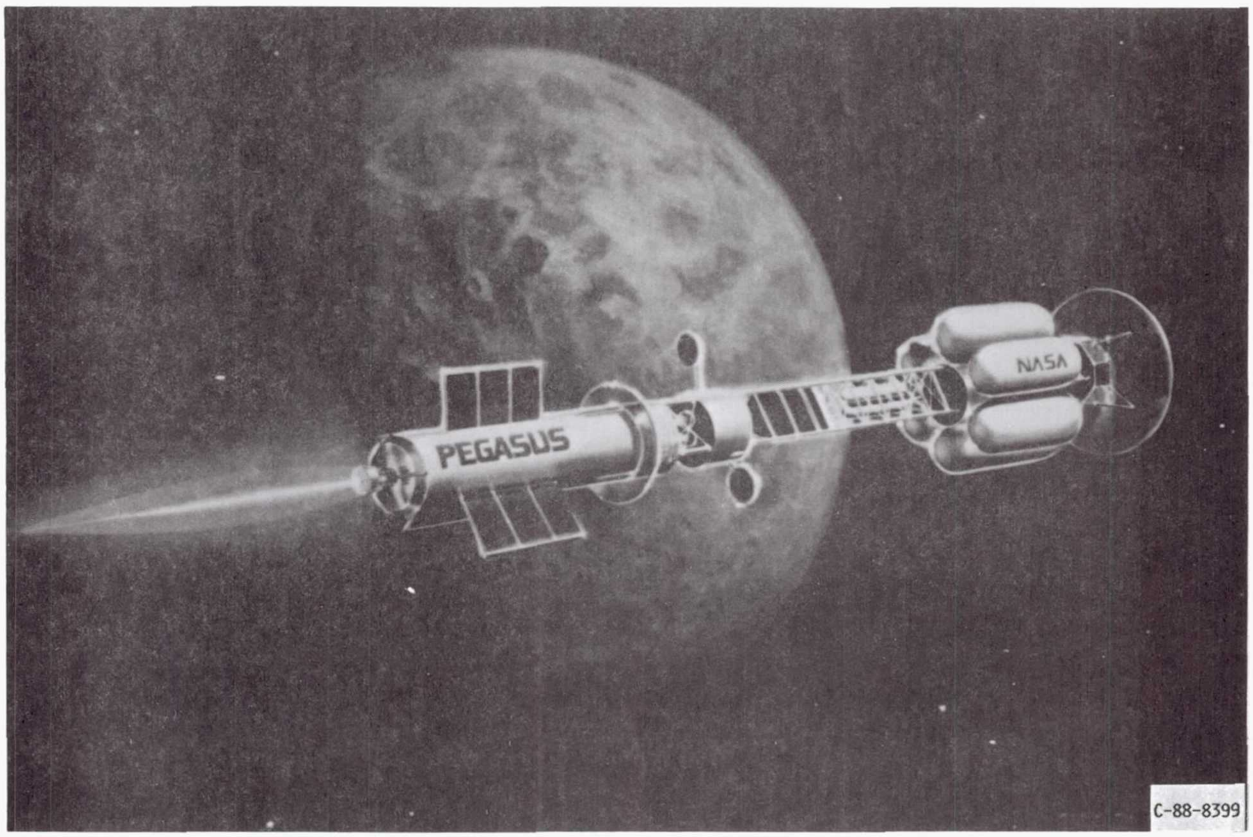


FIGURE 6. - ARTIST'S CONCEPT OF MARS MISSION.

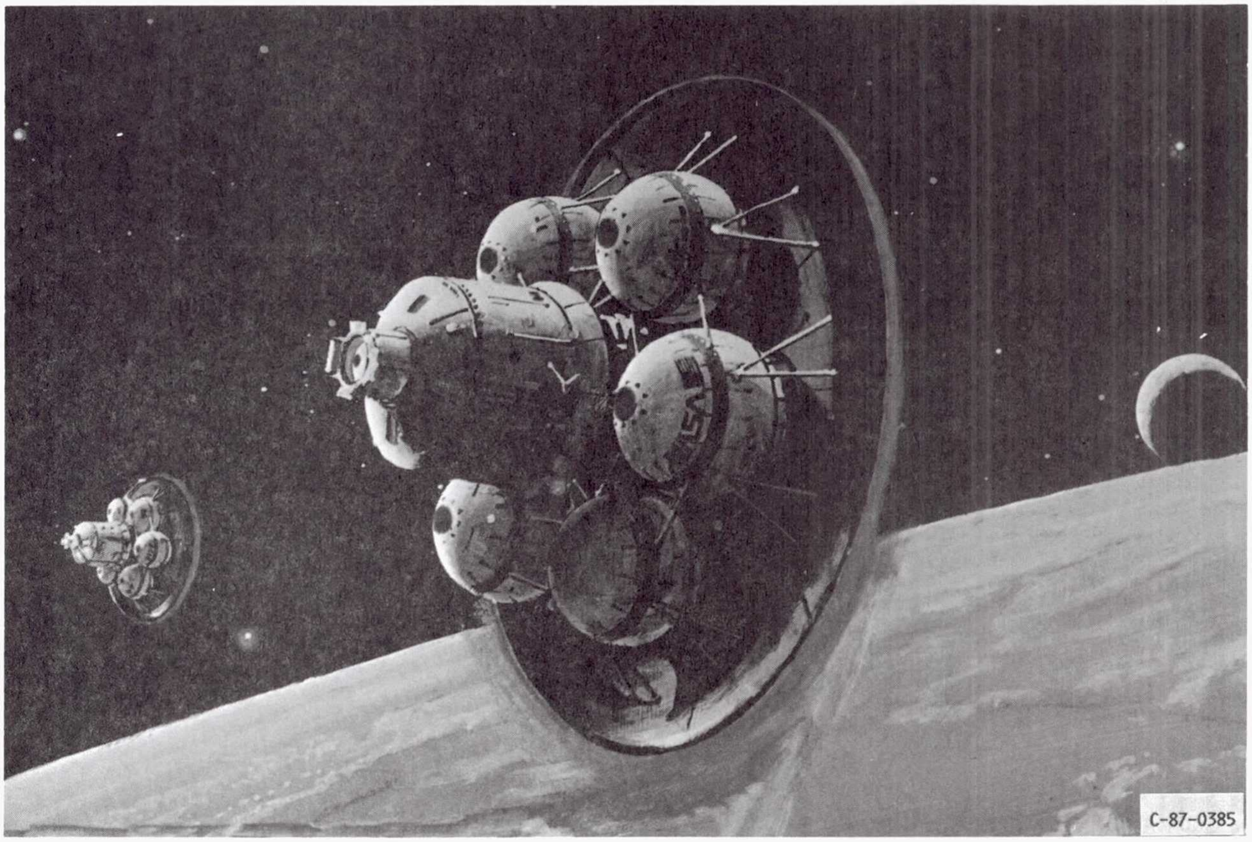


FIGURE 7. - ARTIST'S CONCEPT OF AEROBRAKING VEHICLE.

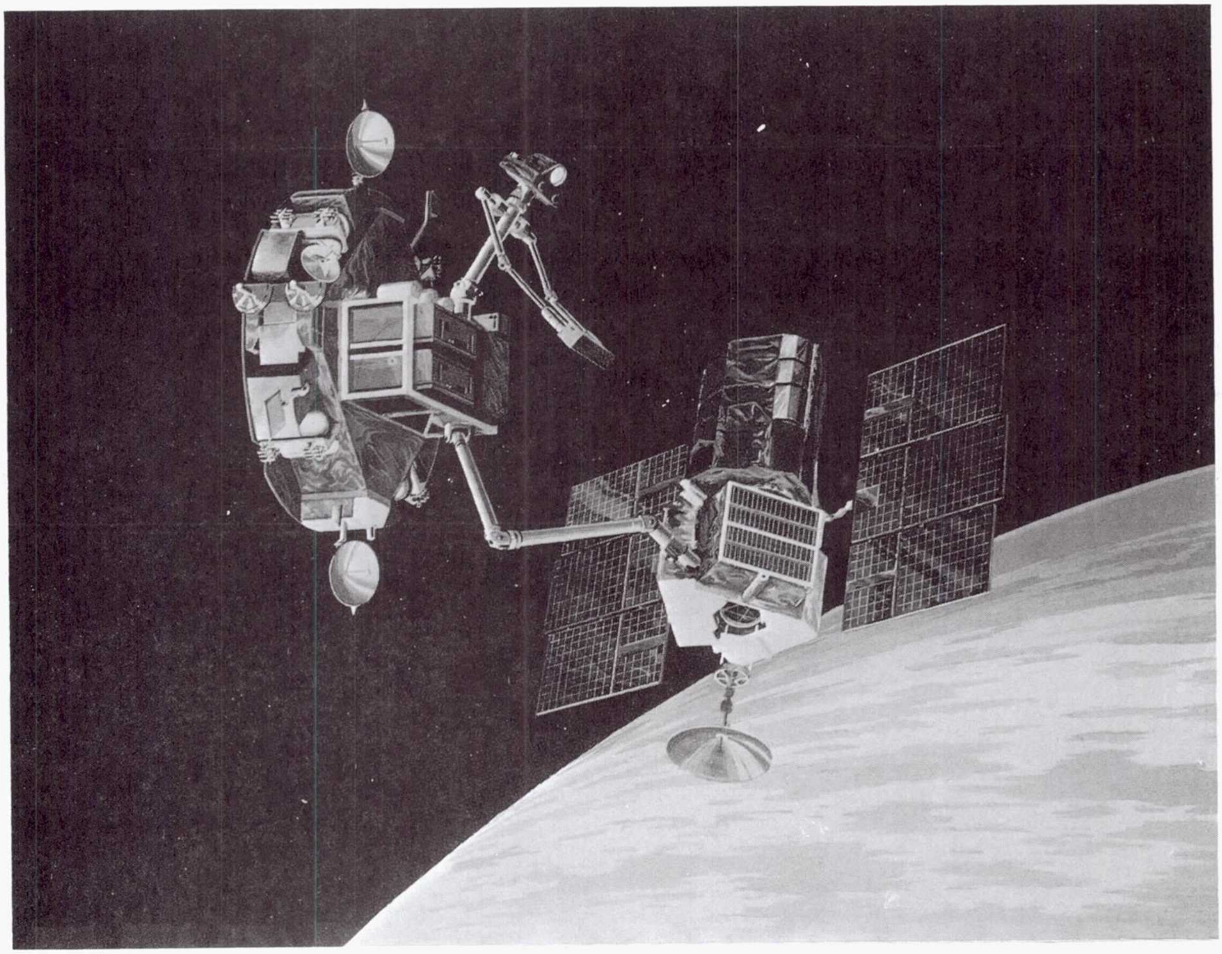


FIGURE 8. - CURRENT SPACE ROBOT CONCEPT ORBITAL MANEUVERING VEHICLE WITH MANIPULATIVE CAPABILITY.

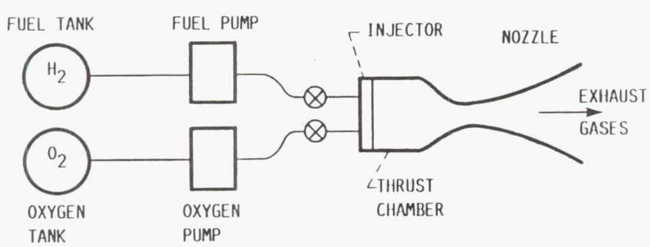


FIGURE 9. - LIQUID OXYGEN/LIQUID HYDROGEN THRUSTER.

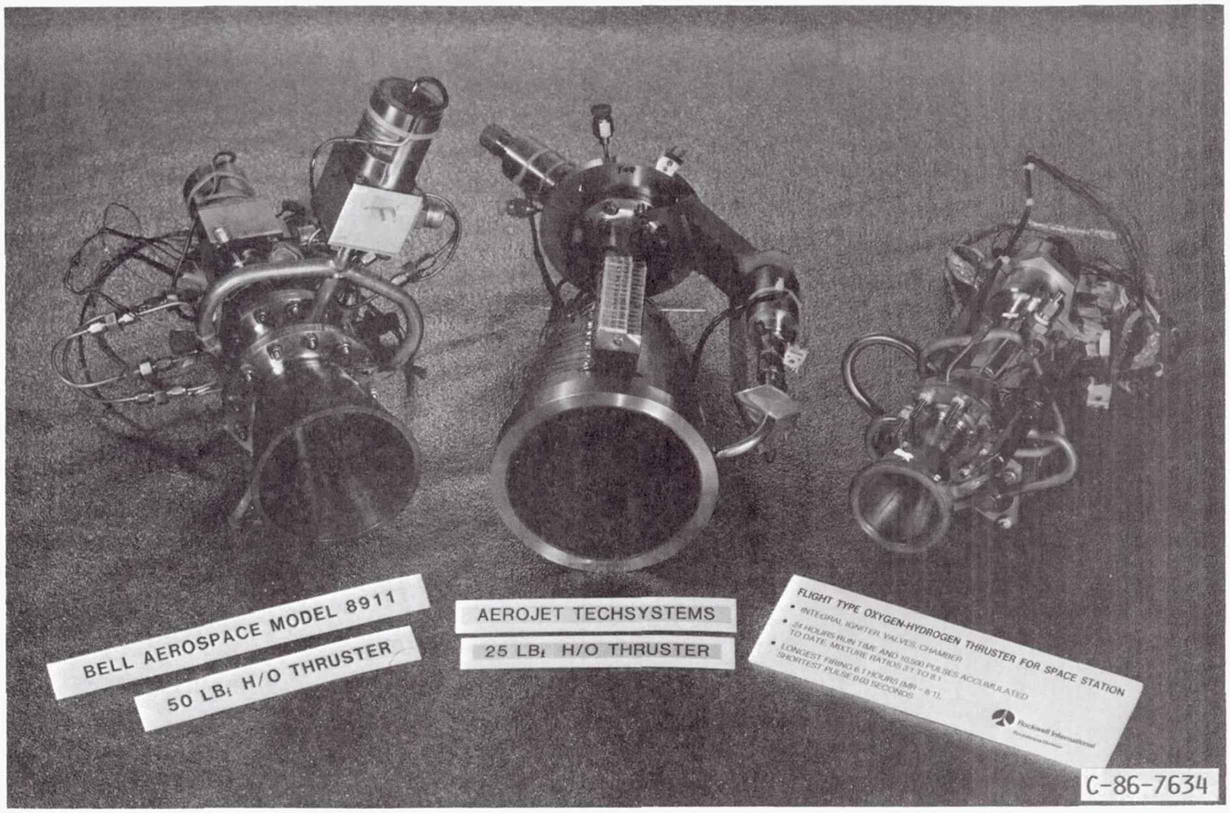


FIGURE 10. - SPACE STATION HYDROGEN/OXYGEN THRUSTERS.

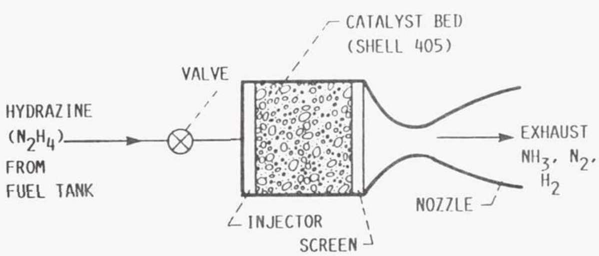


FIGURE 11. - HYDRAZINE THRUSTER.

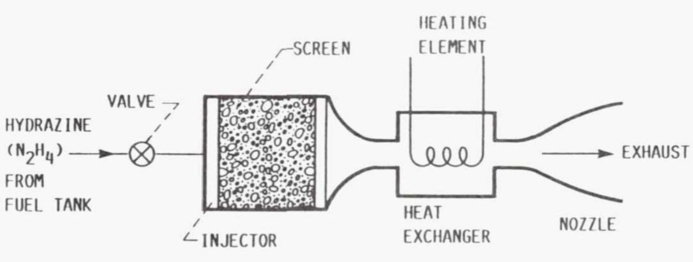


FIGURE 12. - AUGMENTED HYDRAZINE THRUSTER.

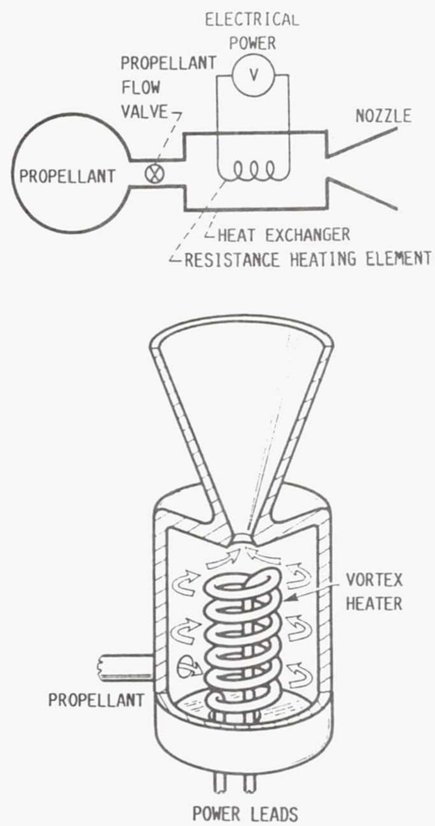


FIGURE 13. - RESISTOJET.

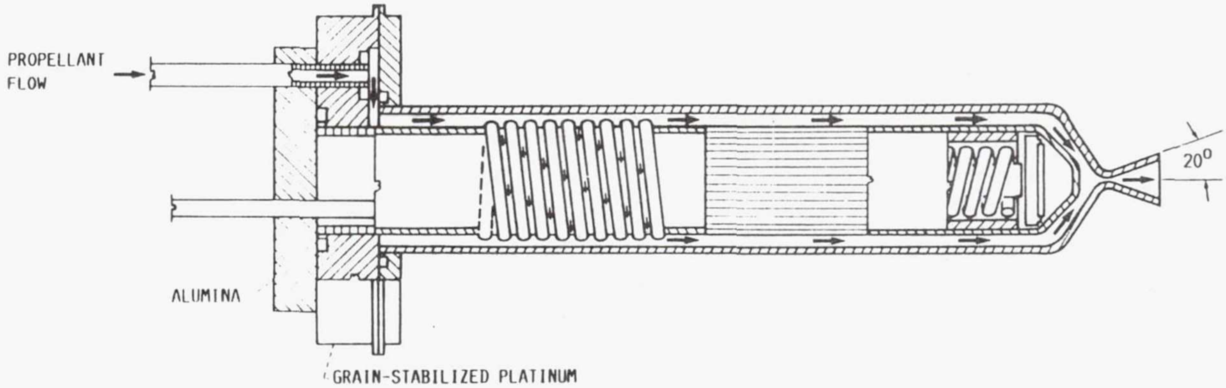


FIGURE 14. - RESISTOJET COILED-TUBE HEAT EXCHANGER.

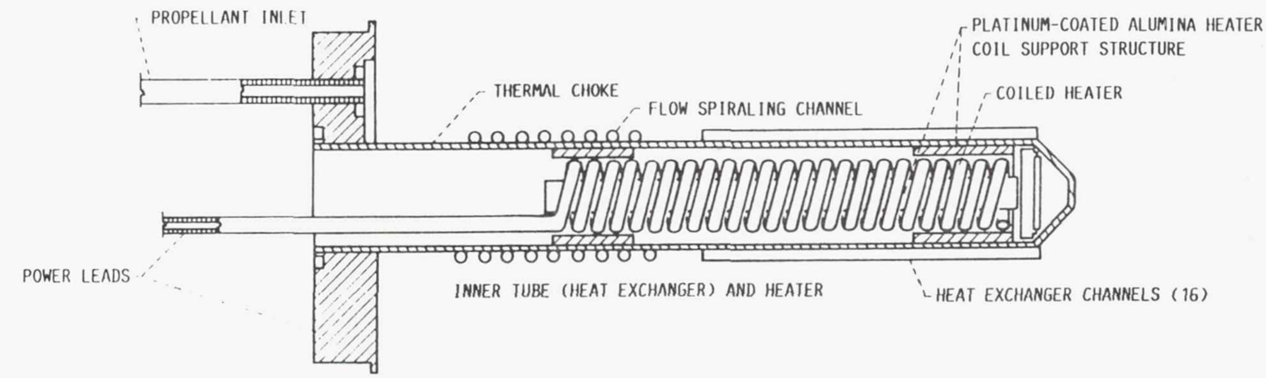


FIGURE 15. - CROSS-SECTION OF RESISTOJET MODEL. ALL DIMENSIONS IN INCHES.

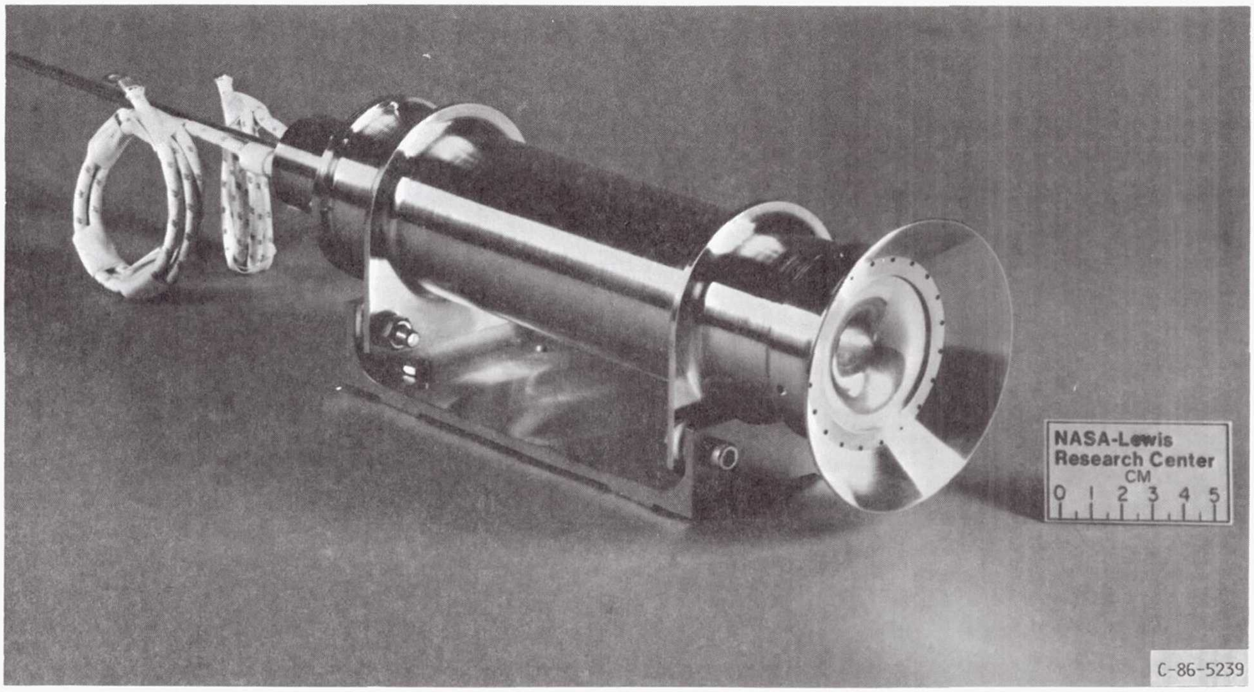


FIGURE 16. - ENGINEERING MODEL OF RESISTOJET.

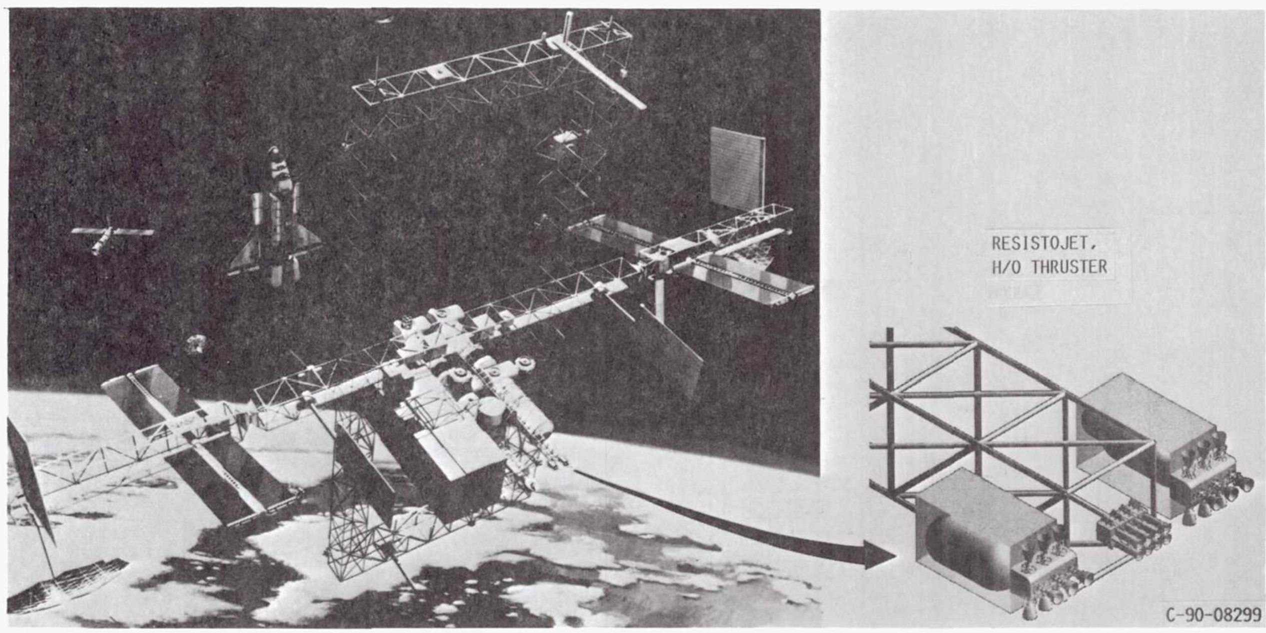


FIGURE 17. - INITIAL OPERATING CONFIGURATION OF RESISTOJET.

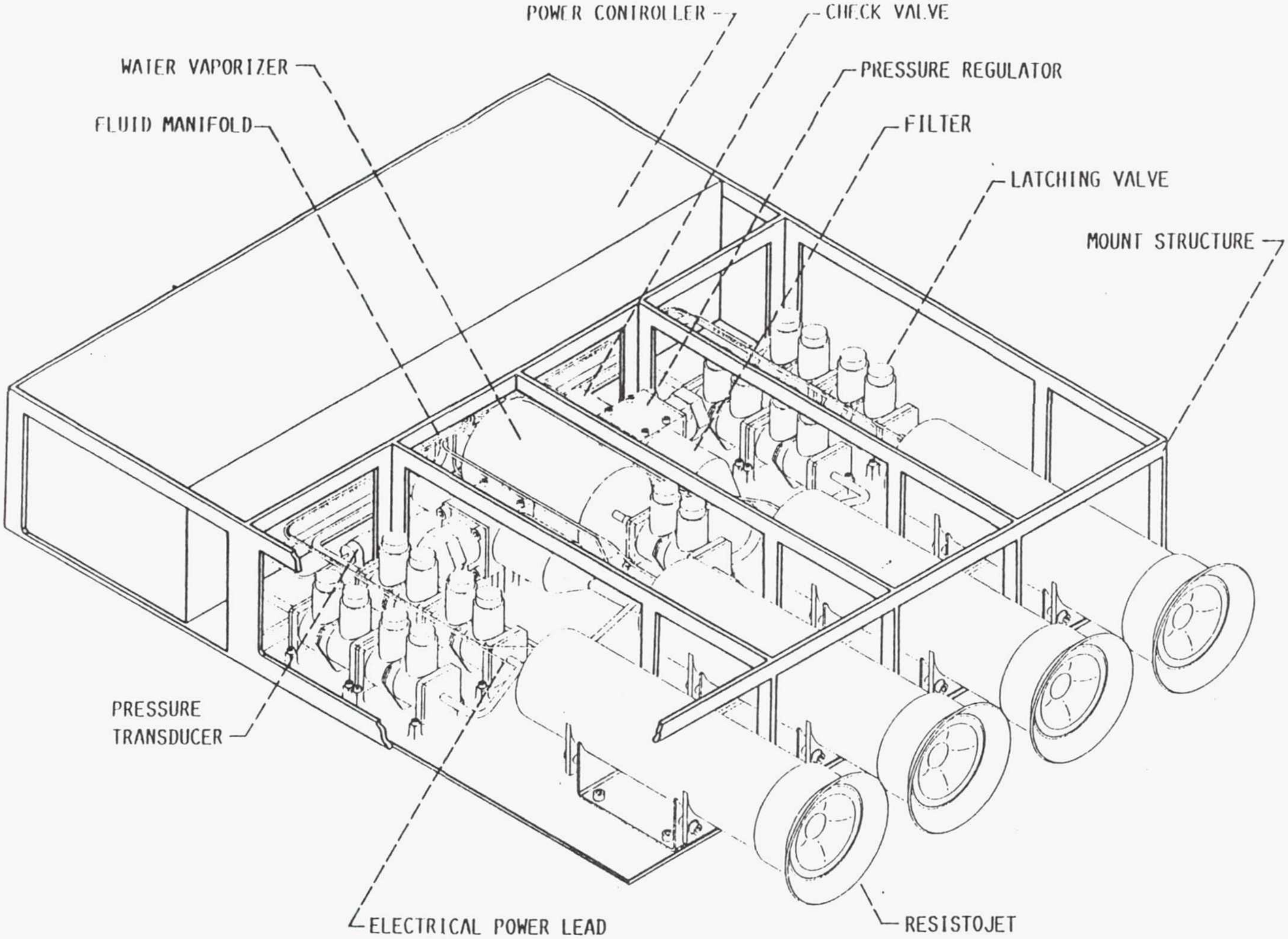


FIGURE 18. - LAYOUT OF RESISTOJET MODULE.

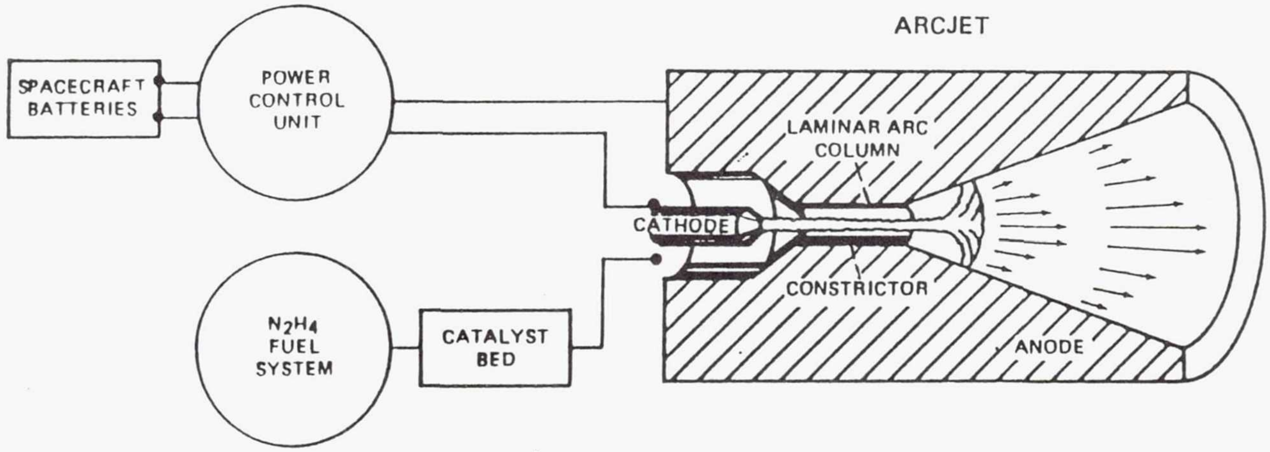


FIGURE 19. - ARCJET.

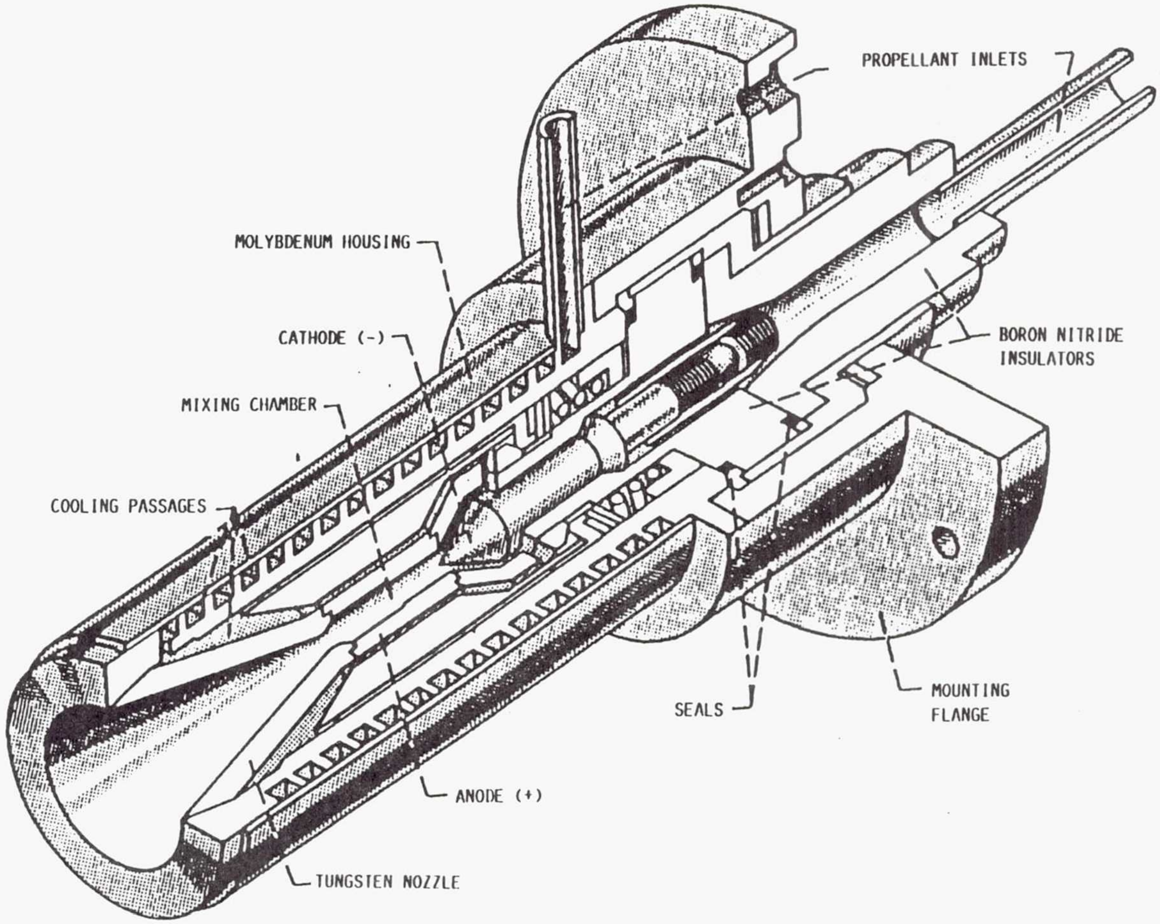


FIGURE 20. - 30-kW THERMAL ARCJET ENGINE DESIGNED BY GIANNINI SCIENTIFIC CORPORATION.

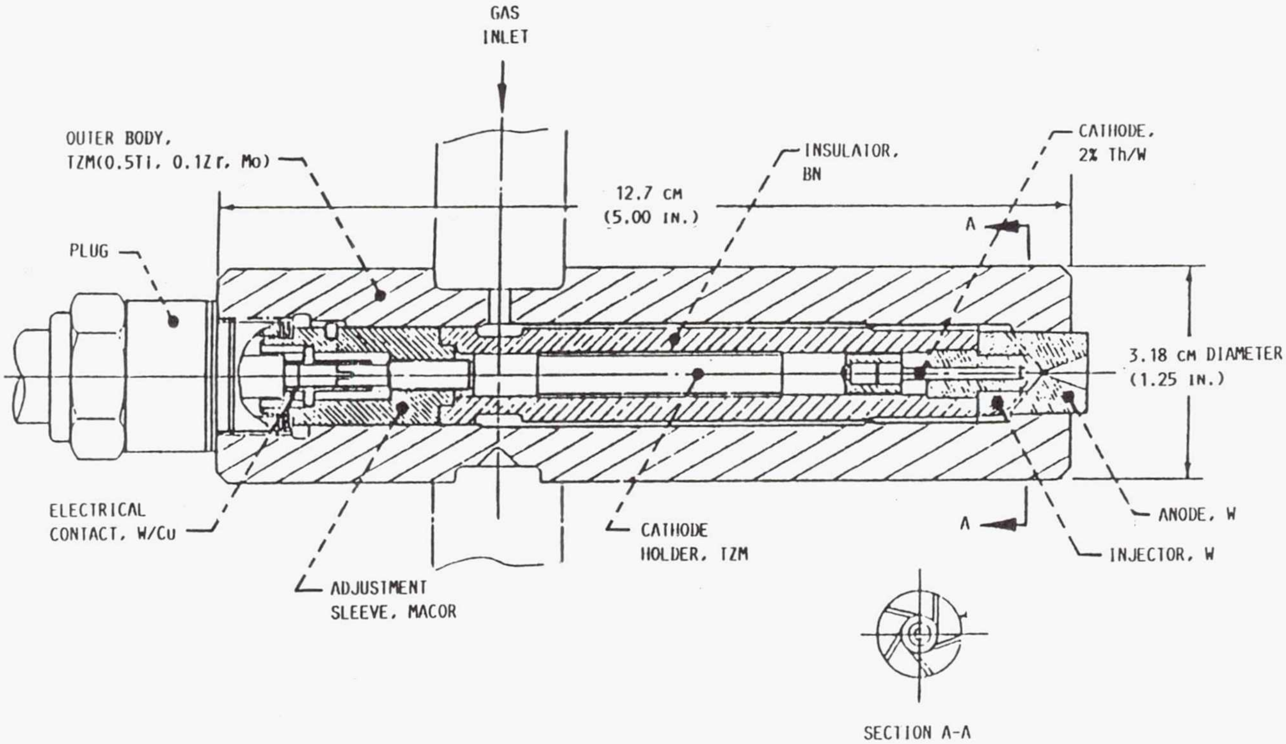


FIGURE 21. - N_2H_2 ARCJET DESIGN.

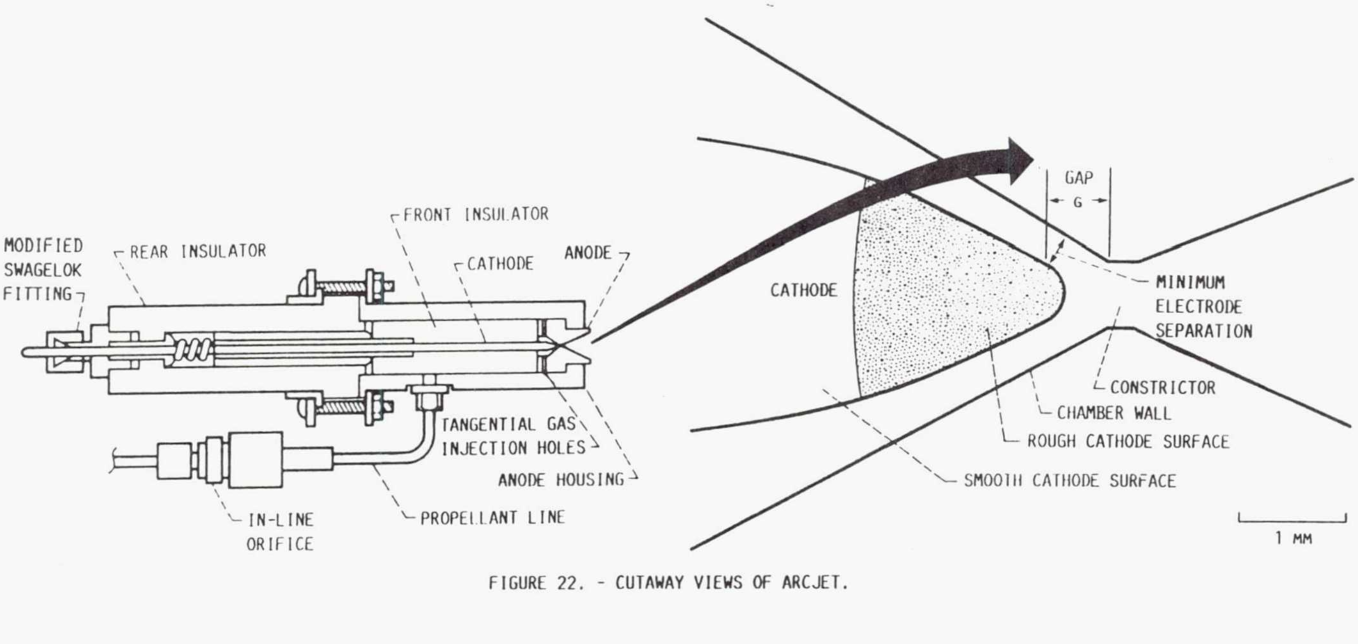


FIGURE 22. - CUTAWAY VIEWS OF ARCJET.

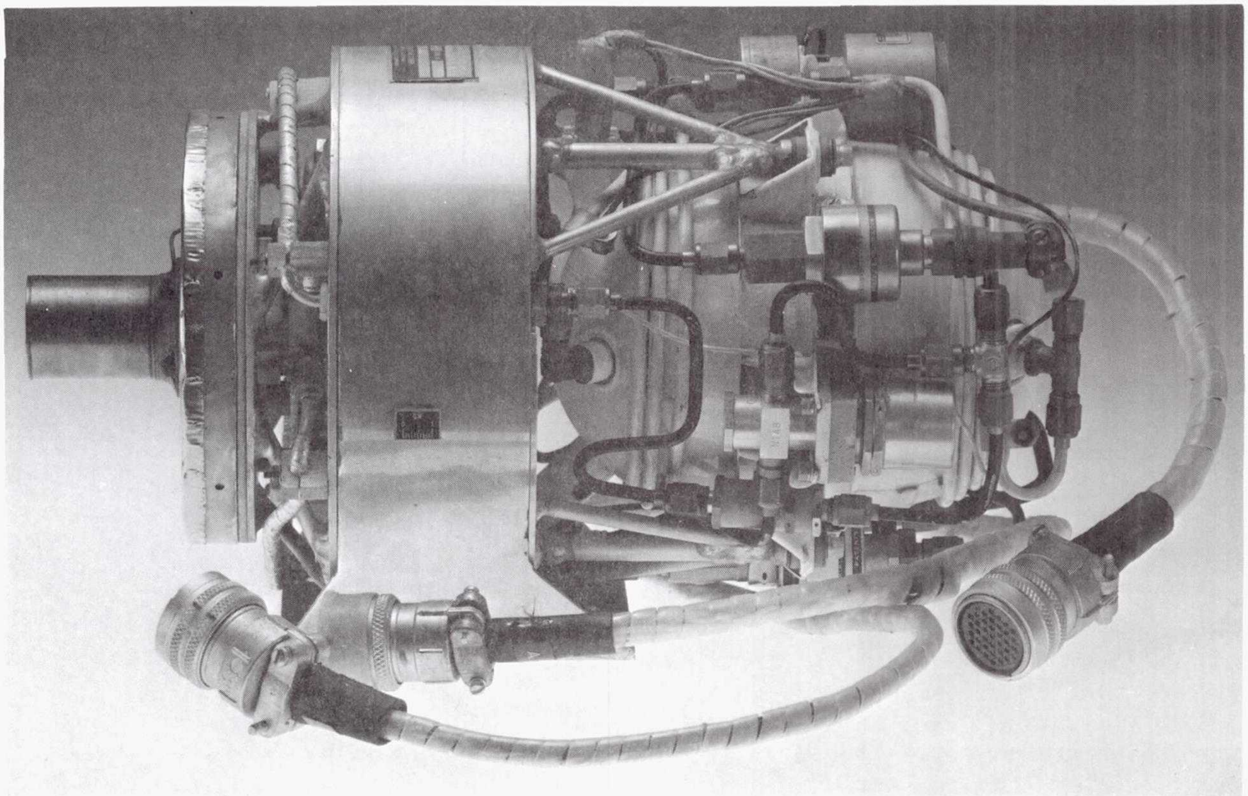


FIGURE 23. - PLASMADYNE 1-kW ARCJET THRUSTER FLIGHT SYSTEM.

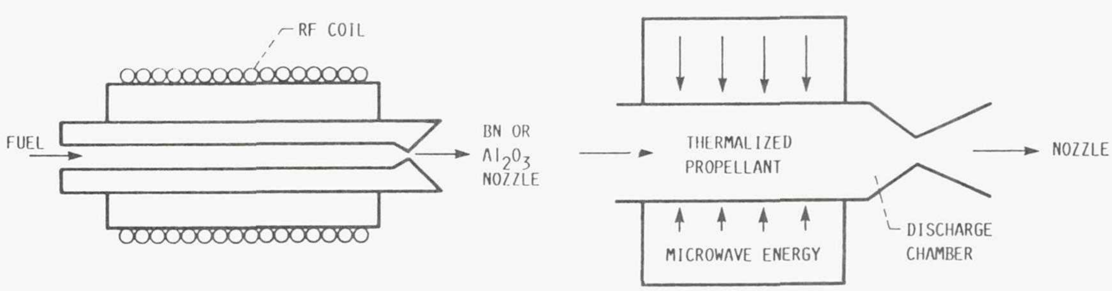


FIGURE 24. - MICROWAVE THRUSTERS.

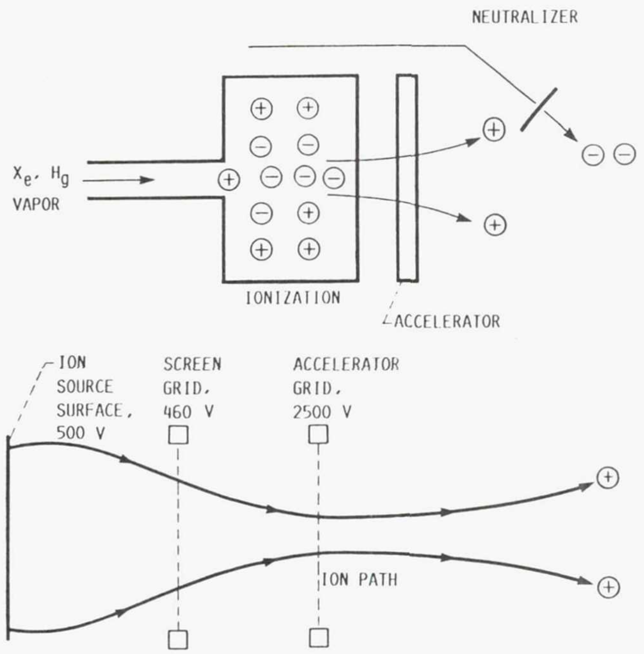


FIGURE 25. - ION THRUSTER.

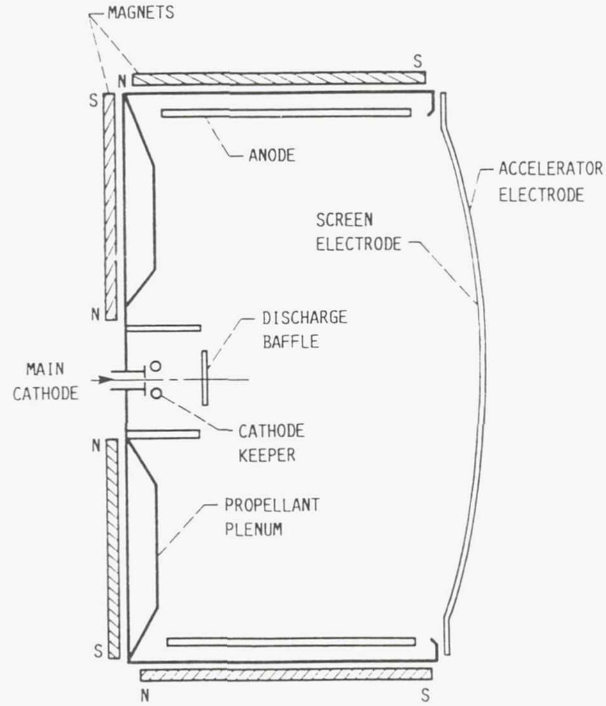


FIGURE 26. - SECTION VIEW OF DIVERGENT MAGNETIC FIELD ION THRUSTER.

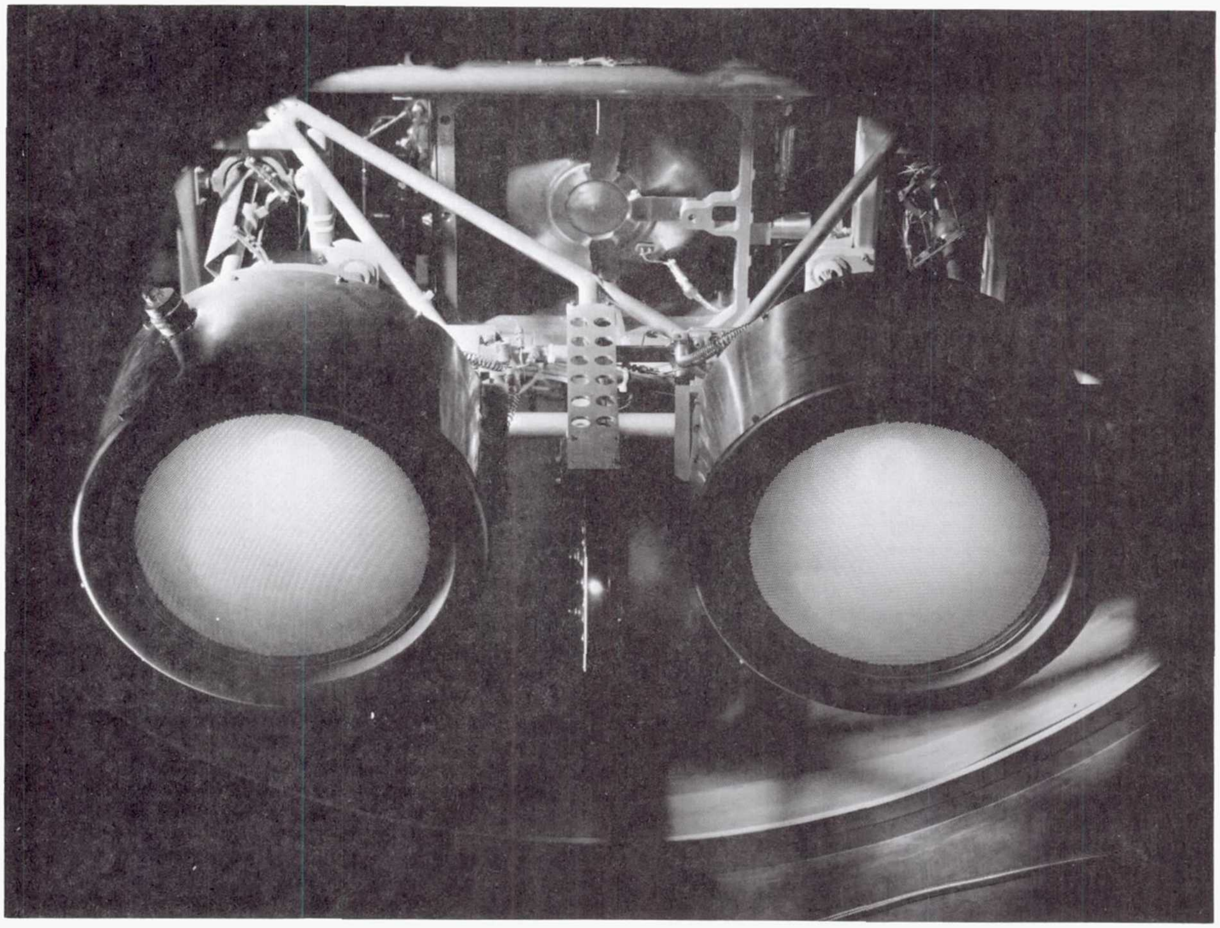


FIGURE 27. - 10-kW XENON ION PROPULSION MODULE.

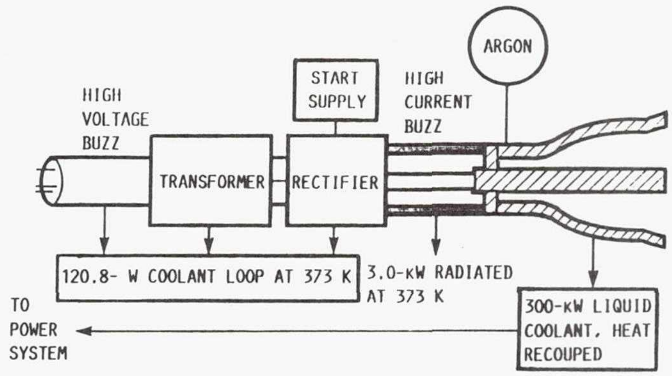


FIGURE 28. - MAGNETOPLASMADYNAMIC THRUSTER SYSTEM COMPONENTS.

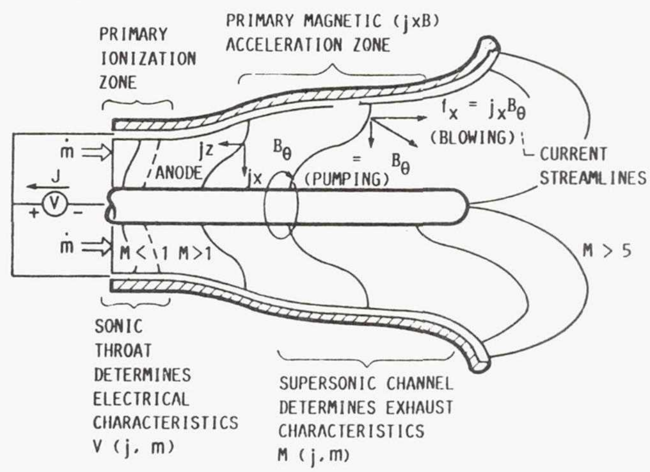


FIGURE 29. - MAGNETOPLASMADYNAMIC (MPD) THRUSTER.

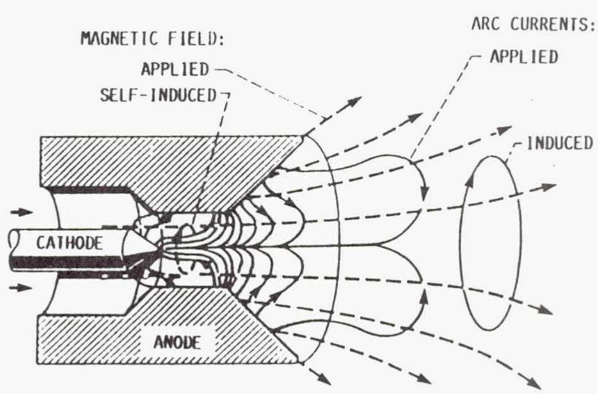


FIGURE 30. - MAGNETOPLASMADYNAMIC ARC THRUSTER CURRENTS AND FIELDS.

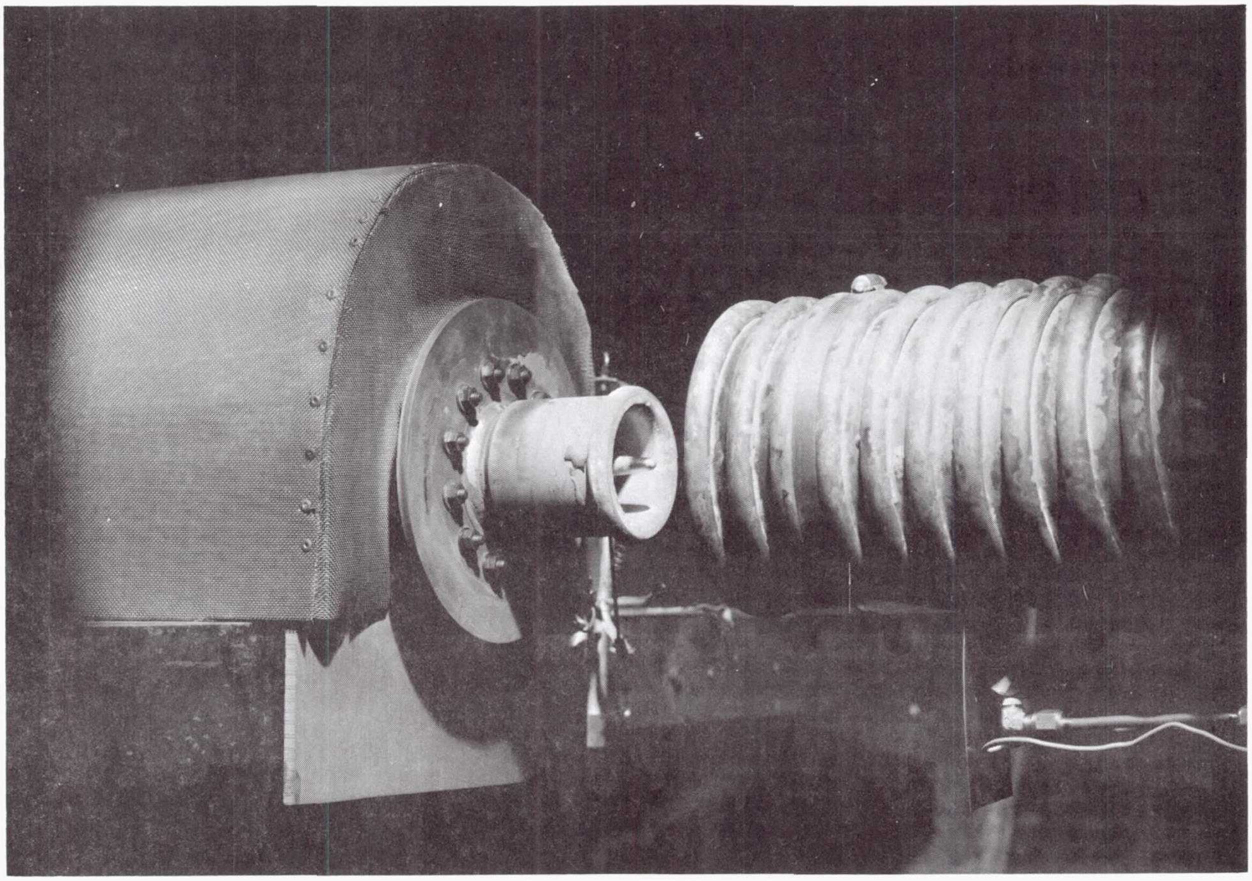


FIGURE 31. - 100-kW SUBSCALE MAGNETOPLASMADYNAMIC THRUSTER.

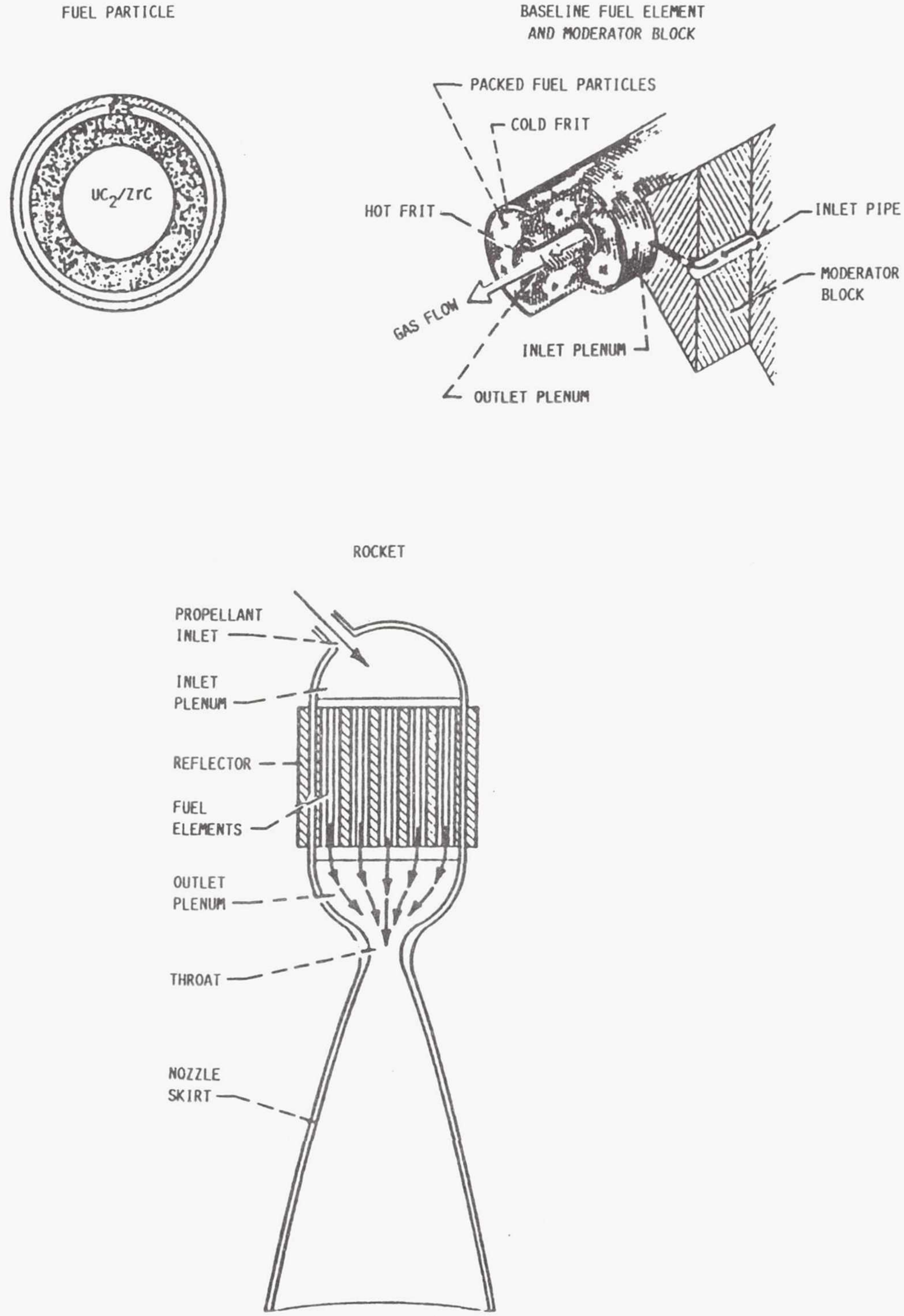


FIGURE 32. - PARTICLE BED, REACTOR-BASED ROCKET CONCEPT.

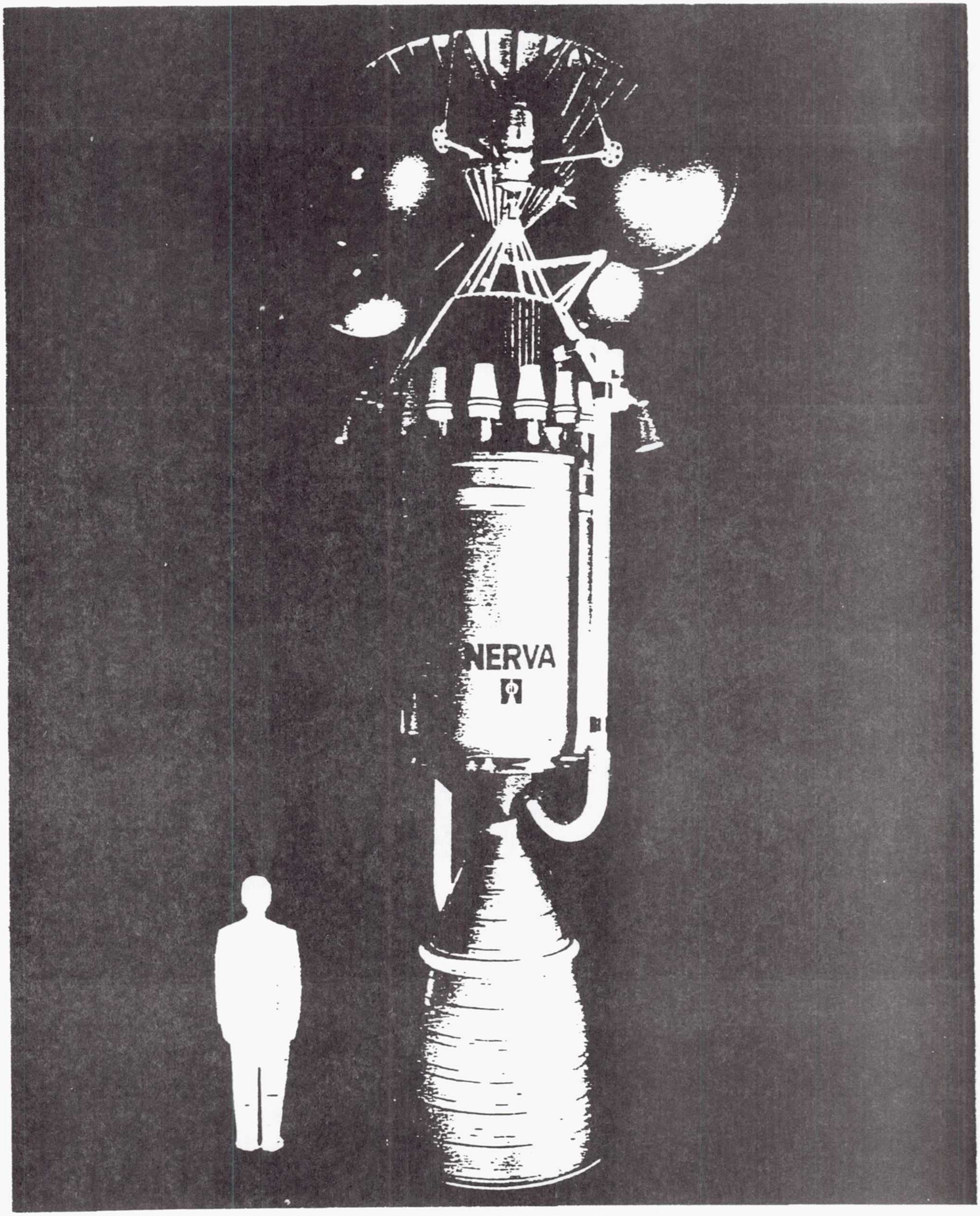
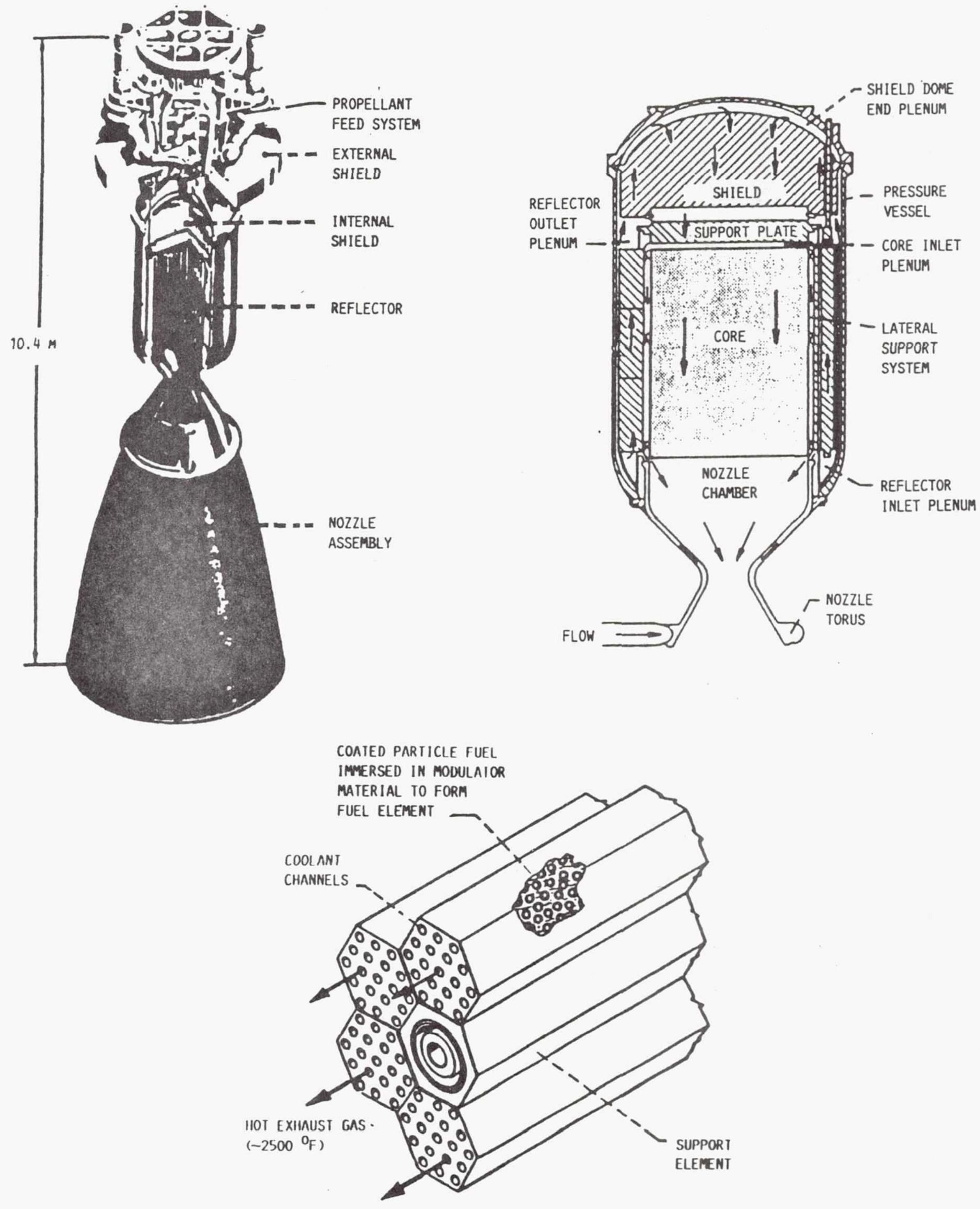


FIGURE 33. - NERVA "FLIGHT ENGINE" CONFIGURATION.



GRAPHITE MATRIX FUEL ELEMENT CLUSTER
(~1500 FUEL ELEMENTS COMPRISE CYLINDRICAL CORE)

FIGURE 34. - CUT-AWAY AND SCHEMATIC FLOW DESCRIPTION OF THE NERVA BASELINE ENGINE.

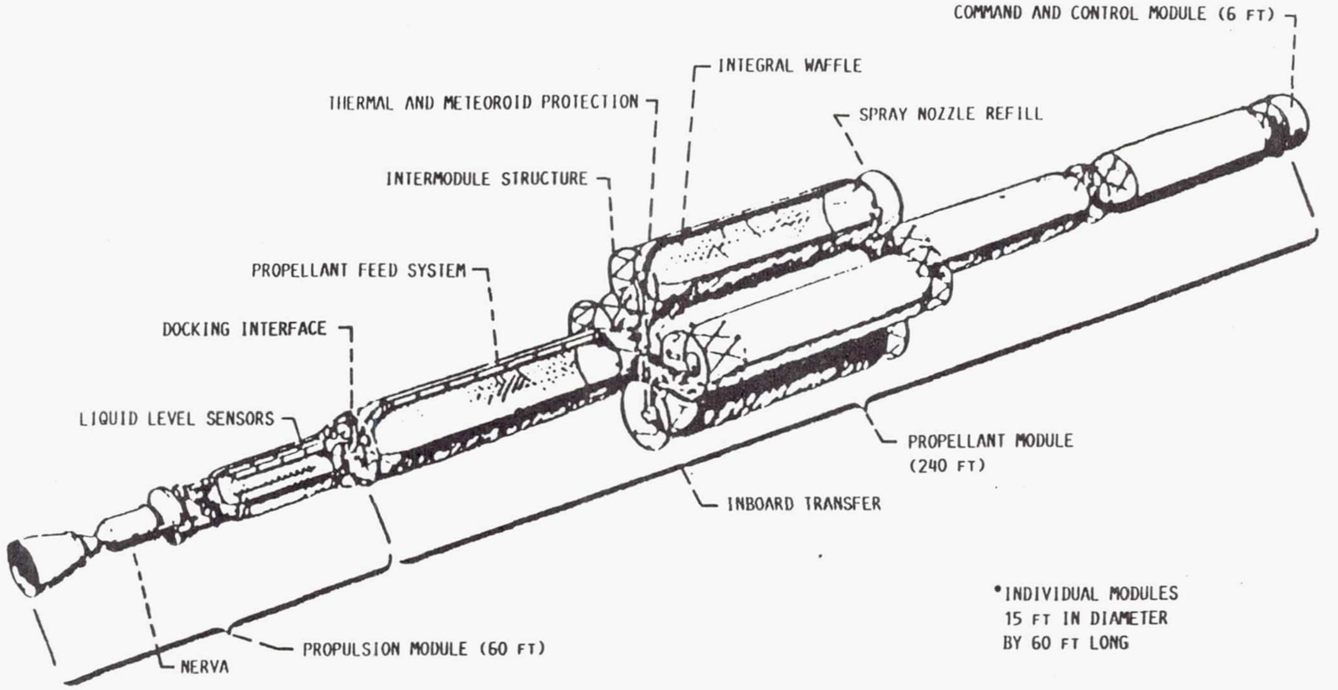


FIGURE 35. - NUCLEAR SHUTTLE. (REF. "NUCLEAR SHUTTLE SYSTEM DEFINITION STUDIES," McDONNEL DOUGLAS (1967 - 1973.)

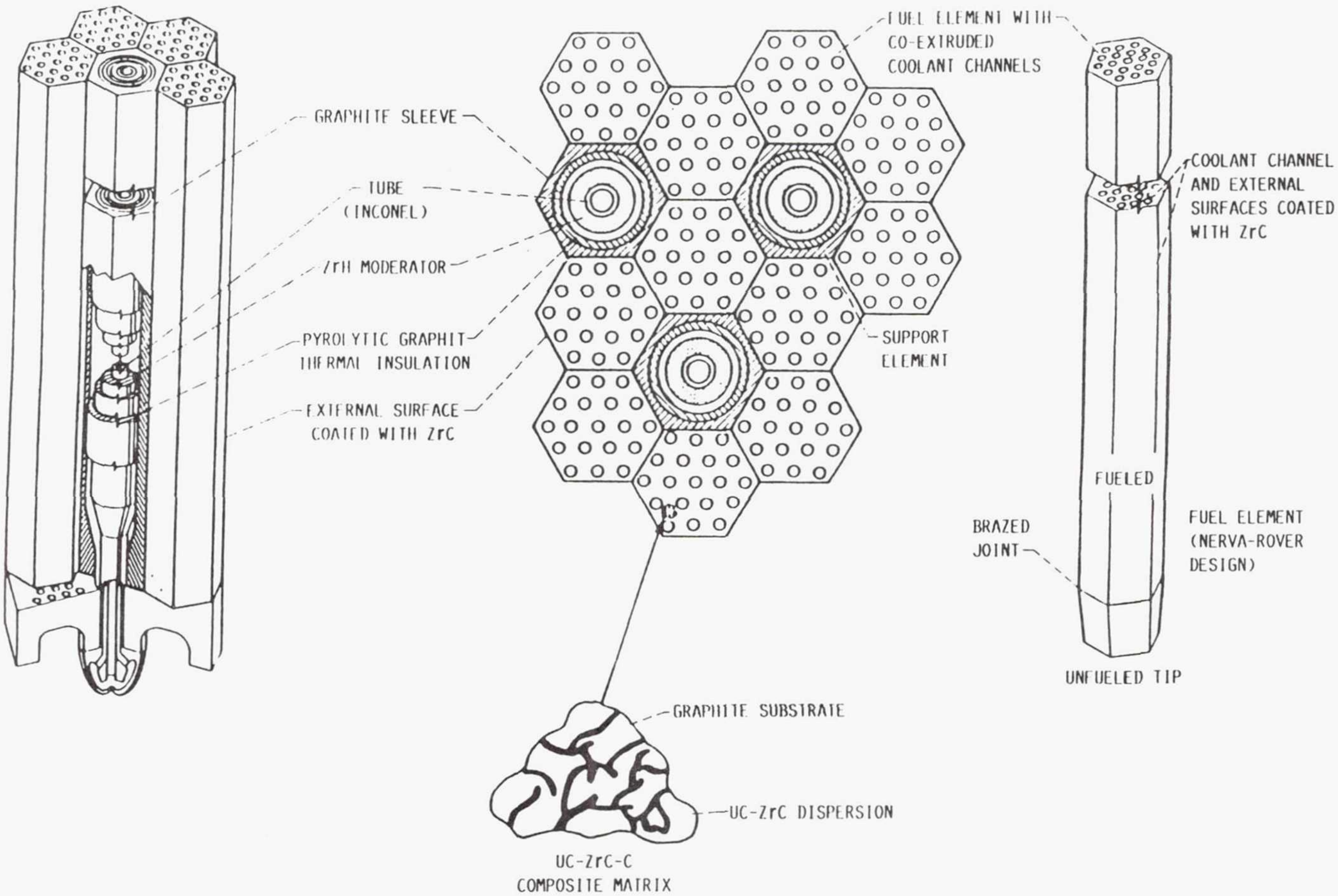


FIGURE 36. - NERVA-DERIVATIVE-ROCKET BASED ON PROVEN NERVA-ROVER REACTORS (WESTINGHOUSE).

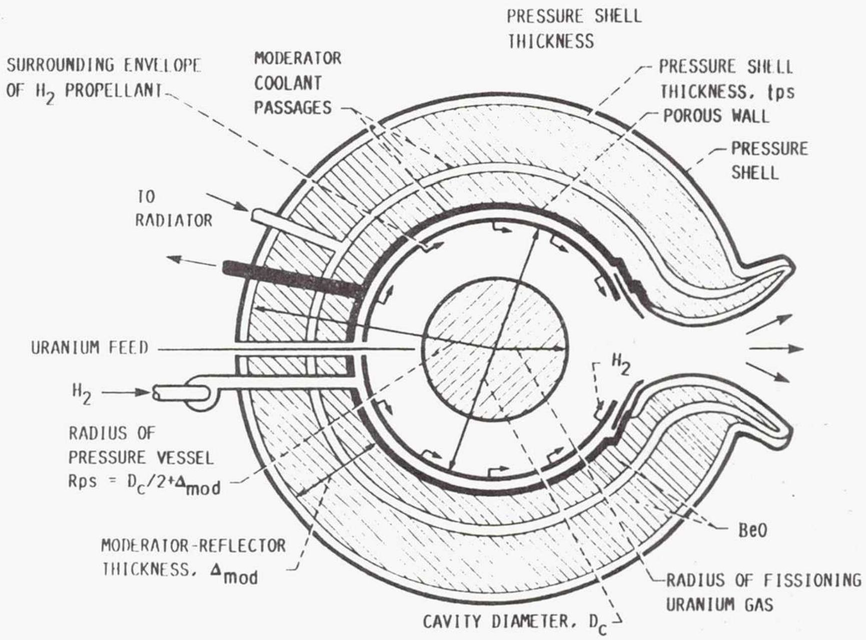


FIGURE 37. - GAS CORE NUCLEAR ROCKET.

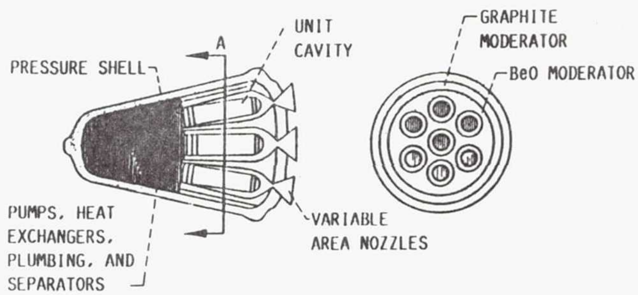


FIGURE 38. - NUCLEAR LIGHT BULB ENGINE (UNITED TECHNOLOGIES RESEARCH CENTER).

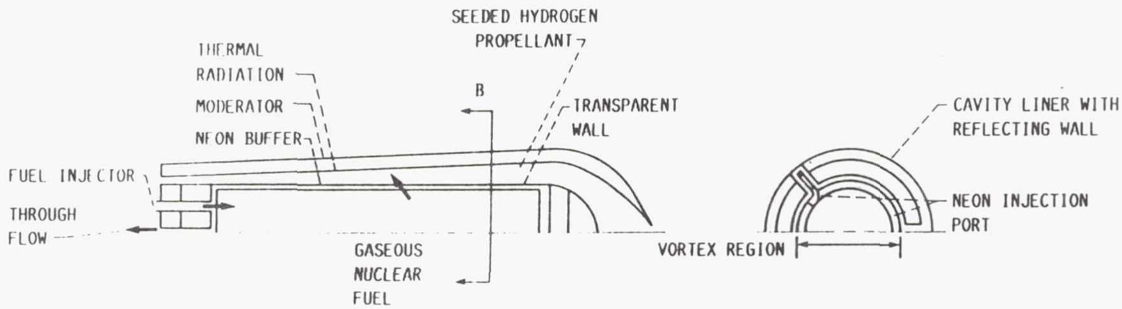


FIGURE 39. - UNIT CAVITY OF A NUCLEAR LIGHT BULB ENGINE (UNITED TECHNOLOGIES RESEARCH CENTER).

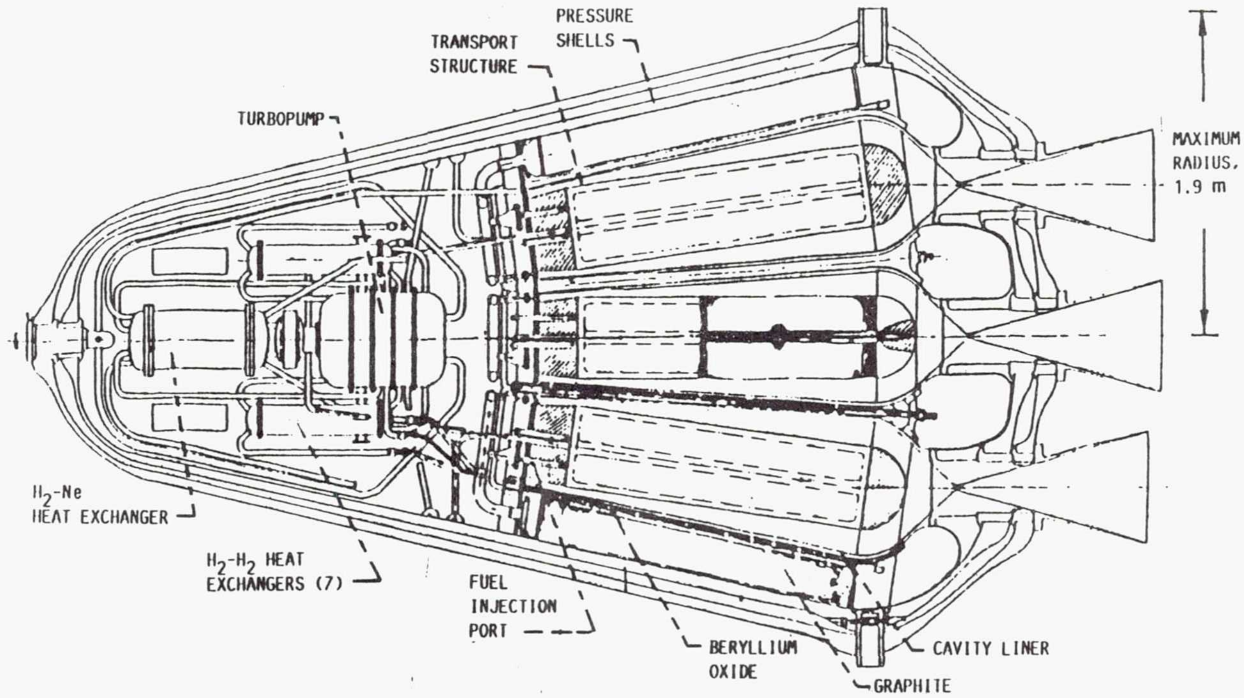


FIGURE 40. - CROSS SECTION OF NUCLEAR LIGHT BULB ENGINE (UNITED TECHNOLOGIES RESEARCH CENTER).

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15. Supplementary Notes

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16. Abstract

The next generation of space propulsion systems will be designed to incorporate advanced health monitoring and nondestructive inspection capabilities. As a guide to help the nondestructive evaluation (NDE) community impact the development of these space propulsion systems, several questions should be addressed. This report provides an overview of background and current information on space propulsion systems at both the programmatic and technical levels. It provides a framework that will assist the NDE community in addressing key questions raised during the 2-5 April 1990 meeting of the Joint Army-Navy-NASA-Air Force (JANNAF) Nondestructive Evaluation Subcommittee (NDES). The specific key questions are listed here:

(1) What types of space propulsion systems are being considered?
(2) What are the principles of operation of these systems?
(3) Who is developing and/or researching space propulsion systems?
(4) How are inspections and reliability assessments performed on the ground and in orbit?
(5) Do the space propulsion systems require health monitoring?
(6) What are the possible failure modes for these systems?
(7) Have the reliabilities of these space propulsion systems been determined?

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