LA-UR -84-3388

CONF-850103--2

TITLE: OPENING UP THE FUTURE IN SPACE WITH NUCLEAR POWER

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LA-UR--84-3388

DE85 002411

SUBMITTED TO

2nd Symposium on Space Nuclear Power Systems
Chemical & Nuclear Engineering Department
University of New Mexico
Albuquerque, NM 87131
January 1985

MASTER

Los Alamos

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OPENING UP THE FUTURE

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ABSTRACT

Man's extraterrestrial development is dependent on abundant power. For example, space-based manufacturing facilities are projected to have a power demand of 300 kWe by the end of this Century, and several megawatts in the early part of the next millennium. The development of the lunar resource base will result in power needs ranging from an initial 100 kWe to many megawatts. Human visits to Mars could be achieved using a multimegawatt nuclear electric propulsion system or high thrust nuclear rockets. Detailed exploration of the solar system will also be greatly enhanced by the availability of large nuclear electric propulsion systems. All of these activities will require substantial increases in space power -- hundreds of kilowatts to many megawatts. The challenge is clear! How to effectively use nuclear energy to support humanity's expansion into space.

INTRODUCTION

Man's orderly expansion into space and the development of its resource is contingent on the timely availability of abundant power supplies. One extraterrestrial development scenario is shown in Fig. 1.

DISCUSSION

The Space Station is an approved National Aeronautics and Space Administration (NASA) program expected to reach initial operational capability in 1992. It will serve as a science base, construction and assembly platform, and space processing demonstration facility. Power for the initial Space Station is planned to be 75 kWe. Stages for space station development are given in Table 1. By the year 2000, the demands for power are anticipated to reach 300 kWe in support of emerging space manufacturing activities. Just a decade into the next millennium, a fully operational manufacturing platform in space will require between 1-10 MWe power.

The initial Space Station will use solar photovoltaics or solar thermal dynamics for its 75 kWe power source. The growth station, with power levels of 300 kWe, may still be able to get by with solar thermal dynamics. However, nuclear reactor power plants must be considered. The nuclear plants will include shielding on all sides of the reactor to protect the crew and equipment from radiation and to minimize exclusion volumes. The compact size of the nuclear power plant permits shipment in a single Shuttle launch. The reactor can be placed in the center of the station, offset on a boom, tethered to the station, or on a free-flyer that is physically separated from the station (Fig. 2). Characteristics of various configurations are given in Table 2. A design trade-off study (NASA 1984) indicates that the boom configuration, including shielding for manned operations, requires the least number of Shuttle flights (Table 3). A nuclear power plant will most likely be located on a boom, though tether and free-flyer arrangements are still being considered. To meet the 1-10 MWe needs, nuclear power is the prime option.

Activities in geosynchronous Earth orbit (GEO) are expected to include large communications platforms and a construction platform to maintain and repair satellites. Power levels of 100-500 kWe are projected for the communications platform and 25 kWe for the GEO construction station.

Solar and nuclear power sources are candidates for GEO platforms. Solar systems are favored, if the power level stays below 25 kWe, because the weight is not excessive for chemical orbit transfer vehicles and any manned operations would not require shielding. Nuclear power becomes advantageous, if larger power levels are needed, or when the power plant is also used to transport large satellites to GEO. Using nuclear electric propulsion, three to five times the payload can be moved to GEO compared with a chemical Centaur transfer stage (Buden and Garrison 1984) (Fig. 3).

The next stage in extraterrestrial development would be an orderly development of lunar resource bases. Table 4 presents a scenario for stages of lunar exploration and development including projected power requirements (Angelo 1982). A polar orbiter is needed to determine if frozen volatiles at permanently frigid areas of the Moon exist and to complete the mapping of the lunar surface. This is a low power spacecraft of less then a kilowatt. Lunar rovers or explorers will require 2-5 kWe of power. These can use electrochemical power for limited duration activities and dynamic radioisotope generators for longer operation times and operation under more adverse conditions. Man's return to the Moon will probably start with "lunar day" excursions (lasting 14 Earth days) and require about 25 kWe level. These excursions will be followed by semi-permanent or permanent manned bases requiring some 100 kWe. Establishing a permanent base camp for scientific experiments and initial lunar material processing will increase power demand to the megawatt-electric level. Extensive material processing and mining could increase power demand levels to about 10 MWe. The needs for long term, continuous power and power levels above 25 kWe will probably be satisfied by nuclear power supplies.

Establishing a permanent settlement for scientific experiments and initial lunar material processing will increase power demands to the megawatt-electric level. Extensive material processing and mining could increase power demand to about 10 MWe. A fully autonomous lunar civilization will require in excess of 100 MWe power. The needs for long term, continuous power and power levels above 25 kWe will probably be statisfied by nuclear power supplies.

Mars will also play a key role in Man's exploration and conquest of the Solar System. Table 5 describes one scenario for the detailed exploration of Mars and the development of its resource base (Angelo and Buden 1984a and b). Table 6 describes some of the scientific objectives for the continued expoloration of Mars. In the Martian conquest scenario described here, orbiting spacecraft and sophisticated surface rovers will be used to establish the location for the first manned expedition. This expedition might very well use electric propulsion with a multimegawatt power source (Fig. 4). The Mars space vehicle could be assembled in low Earth orbit (LEO) and then moved to GEO orbit unmanned. There, the crew can board the vehicle and depart for Mars. After several months orbiting Mars and exploring the surface, the crew would return to Earth.

The schedule shown in Fig. 1 can be accelerated by other technical commitments. If a heavy-lift launch vehicle of 100,000 kg and multimegawatt power sources are developed (Rankine 1984), then these can be used to accelerate the human expansion into space. For example, one concept of a manned mission to Mars (Atkins, et al, 1983) requires a mass in Earth orbit of 344,000 kg and a 6 MWe power supply to drive electric propulsion devices. Consequently, four launches of the heavy-lift vehicle could deliver components of a Mars vehicle to LEO.

Solar system exploration of Uranus, Neptune, and Pluto and small bodies such as comets and asteroids must still be performed. Detailed exploration will establish the physical nature of these celestrial bodies. Outer planet orbiter trip times are shown in Fig. 5 (NASA 1984). The use of nuclear electric propulsion significantly reduces the trip times to the outer planets, minimizes support facilities, reduces time until data are required, and reduces stress on spacecraft components. Multimegawatt power sources can reduce the trip times even further, as seen in Fig. 6. For instance, travel times to Neptune can be reduced to three to four years.

CONCLUSIONS

Man's movement into space will be paced by the availability of prime power, especially nuclear:

(1) Nuclear power will be needed to satisfy the power demands of manufacturing facilities in low Earth orbit. These are projected at 300 kWe by the year 2000 and megawatts in the early 21st Century.

(2) Construction platforms at geosynchronous orbit will be greatly enabled by use of nuclear energy.

(3) The successful development of lunar resource bases and exploration of Mars will also depend on nuclear power supplies.

(4) Finally, full exploration of the asteroid belts and the outer Solar System will be greatly enhanced by the availability of nuclear power supplies in the 100 kWe regime and beyond.

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ACKNOWLEDGEMENT

This work was performed under the auspices of National Aeronautics and Space Administration, Department of Energy, and the Florida Institute of Technology.

TABLE 1

SPACE STATION POWER STRATEGY

Initial Station (75 kWe)	6-12 people
Science platform	
Space processing demonstration facility	
Construction and assembly demonstration platform	
Learn to live and work in space	
Growth Space Station (300 kWe)	12-20 people
Small scale commercial manufacturing	
Construction and assembly platforms	
Satellite repair facility	
Space Base (1-10 MWe)	20-100 people
Large scale commercial manufacturing	
Space-based launch facilities for lunar and Mars activities	
Experimental food production	
Space Settlement (greater then 10 MWe)	100-500 people
Process extraterrestrial materials	
Space development center	
Manufacture own goods	
Small-scale space-based agriculture	

TABLE 2

FEATURES OF REACTOR LOCATION ON SPACE STATIONS

Near Center of Gravity Configuration (CG)

- Best Attitude Flexibility
- Allows Full EVA Operation
- Minimum Power Transmission Line Distances
- Heaviest Shield (40-50 Tonnes with 3-M Exclusion Distance)
- Separates Radiator From Reactor

Boom Configuration

- Limited Exclusion Area
- Shield 10-20 Tonnes Depending on Reactor Size and Boom Length
- Attitude Limitations but Highly Stable Gravity Gradient Mode
- Power Transmission Lines Longer than CG
- Radiator Near Heat Source

Tethered Configuration

- Less Exclusion Area and Reduced Traffic Constraints
- Lower Shield Mass
- Separates Heat Rejection Radiator from Space Station
- Introduces Gravitational Forces

Free-Flyer Reactor Configuration

- Reactor in Nuclear Safe Orbit
- Lightest Shield
- Requires Power Transmission or Tugs for Final Transport
- Uses Independent Spacecraft Systems

TABLE 3

TRADE TABLE

300 kWe at Space Station

STIRLING, η - 25Δ	ON-BOARD (MAN-RATED)	TETHER (MAN-RATED)	TETHER (INSTRUMENT RATED)	FREE-FLYER (INSTRUMENT RATED)
INITIAL MASS IN ORBIT, tons	31.1	77.6	61.1	1043
POWER LEVEL, MW_t	1.2	1.66	1.66	2.9
INTIAL VOLUME IN ORBIT, m^3	241	428	421	4640
STS LOGISTICS FOR IOC				
Number of Orbiter Flights	1.5	3.2	2.7	49.5
Number of OTV Flights	0	0	0	5
Number of OMV Flights	0	1	1	1
10-YEAR CUMULATIVE MASS, tons	31.9	94.2	77.7	2964
10-YEAR CUMULATIVE VOLUME, m^3	242	448	441	6752
CUMULATIVE STS LOGISTICS				
Number of Orbiter Flights	1.5	3.9	3.4	126
Number of OTV Flights	0	0	0	45
Number of OMV Flights	1	2	2	1

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* MW_t = Reactor Thermal Rating, Megawatts

TABLE 4

STATES OF LUNAR DEVELOPMENT AND POWER REQUIREMENTS

STAGE	ACTIVITY	POWER LEVELS	PROBABLE NUCLEAR POWER SUPPLY
1	Automated Site Preparation	few kWe	Radioisotopes (RTGs)
2	Initial Lunar Base (6-12 persons)	~ 100 kWe	Nuclear Reactor (SP-100)
3	Early Lunar Settlements (10^2-10^3 persons)	~ 1 MWe	Expanded SP-100 (Advanced Design)
4	Semi-Autonomous Lunar Settlement (10^3-10^5 persons)	~ 100 MWe	Nuclear Reactor (Advanced Design)
5	Autonomous Lunar Civilization (Self-Sufficient Lunar Economy: $> 10^5$ persons)	Hundreds of Megawatts Electric	Nuclear Reactors (Advanced Design, Complete Lunar Nuclear Fuel Cycle

TABLE 5

STAGES OF MARS EXPLORATION AND DEVELOPMENT

STAGE 1 Advanced Exploration with Sophisticated Spacecraft

- Mars Geoscience/Climatology Orbiter
- Mars Aeronomy Orbiter

STAGE 2 Robotic Surface Exploration

- Mars Network Mission (Penetrators)
- Mars Airplane
- Surface Rover(s) (MSRM)
- Mars Sample Return Mission

STAGE 3 Human Exploration of Mars

- Nuclear Electric Propulsion (NEP) Expedition

STAGE 4 Development of Martian Resources

- Site Preparation (automated)
- Initial Base (6-12 persons)
- Early Martian Settlement (10^2-10^3 persons)
  - Initiation of Planetary Engineering Projects
- Autonomous Martian Civilization (more than 10^4-10^5 persons)
  - Full-scale Planetary Engineering Projects
  - Permanent Human Presence in Heliocentric Space
  - Independent of Earth-Moon System

TABLE 6

PRIORITIZED SCIENTIFIC OBJECTIVES FOR CONTINUED EXPLORATION OF MARS

1. Intensive Study of Local Areas to:
    - Establish the chemical, mineralogical, and petrological character of Martian surface.
    - Establish the nature and chronology of the major surface forming processes.
    - Determine the distribution, abundance, sources, and sinks of volatile material.*
    - Establish the interaction of the surface material with the atmosphere and radiation environment.
2. Explore the Structure and the General Circulation of the Martian Atmosphere.
3. Explore the Nature and Dynamics of Mars' Interior.
4. Establish the Nature of the Martian Magnetic Field and the Character of the Upper Atmosphere and its Interaction with the Solar Wind.
5. Establish the Global Chemical and Physical Characteristics of the Martian Surface.

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* Includes an assessment of current and past biological potential of Martian environment.

FIGURE CAPTIONS

Figure 1	Trends in civilian power needs
Figure 2	Space station nuclear options
Figure 3	Shuttle/nuclear electric propulsion to GEO
Figure 4	Manned Mars mission
Figure 5	Outer planet orbiter mission trip times
Figure 6	Neptune orbiters

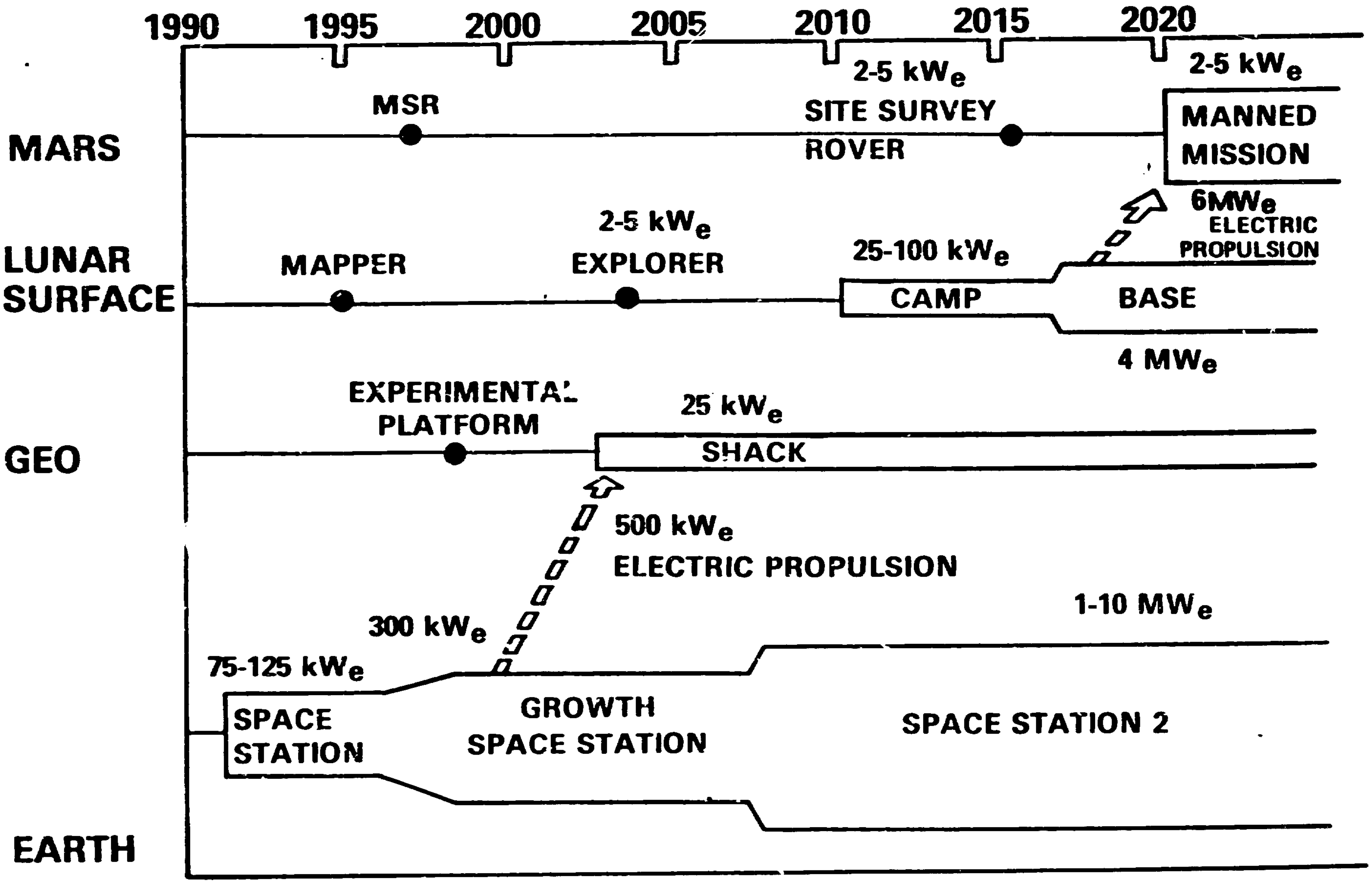
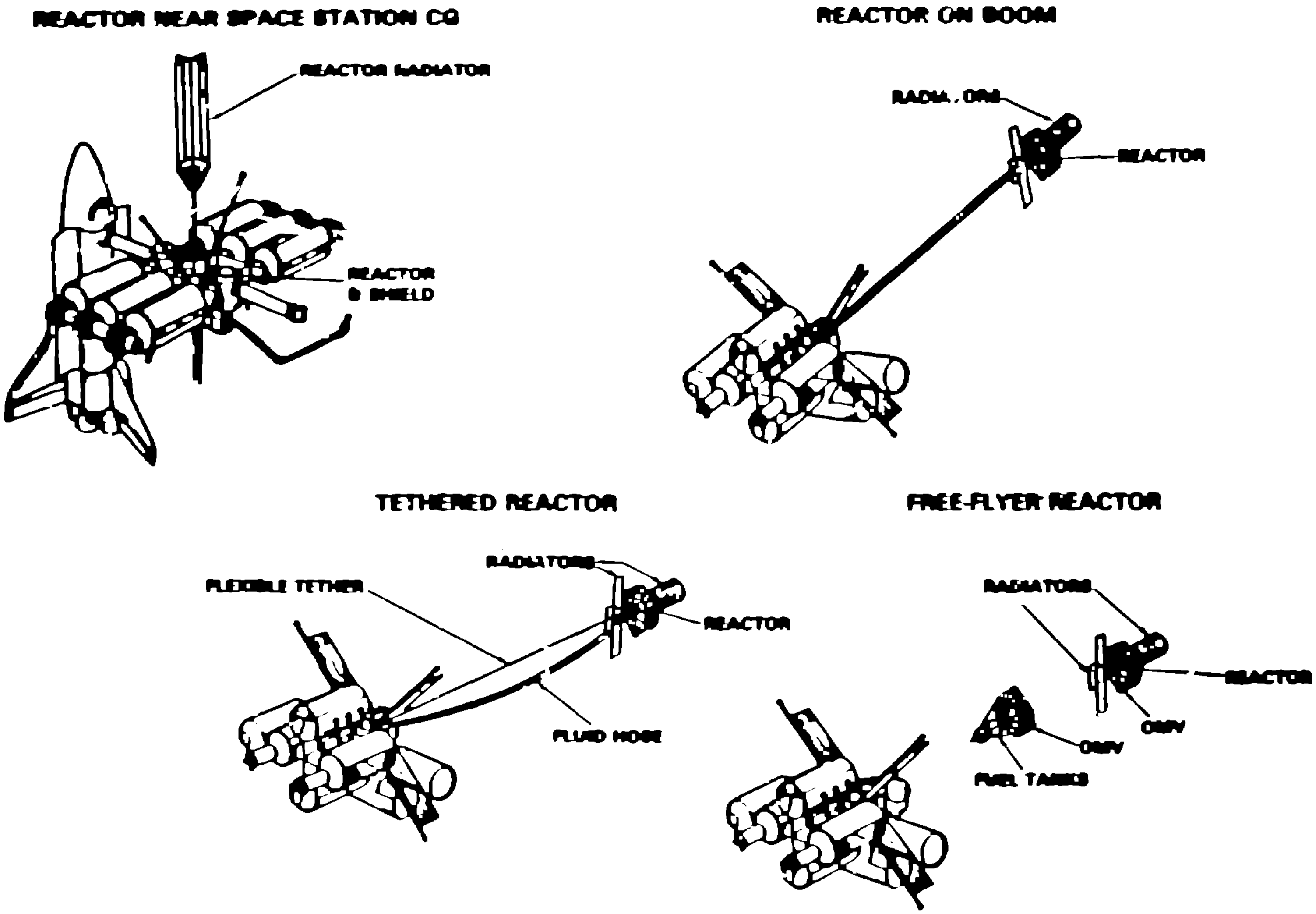

1990
1995
2000
2005
2010
2015
2020
MARS
MSR
2-5 kWe
SITE SURVEY ROVER
2-5 kWe
MANNED MISSION
6MWe ELECTRIC PROPULSION
LUNAR SURFACE
MAPPER
2-5 kWe EXPLORER
25-100 kWe
CAMP
BASE
4 MWe
GEO
EXPERIMENTAL PLATFORM
25 kWe
SHACK
500 kWe ELECTRIC PROPULSION
300 kWe
75-125 kWe
SPACE STATION
GROWTH SPACE STATION
1-10 MWe
SPACE STATION 2
EARTH

Fig. 1


REACTOR NEAR SPACE STATION CG

REACTOR ON BOOM

TETHERED REACTOR

FREE-FLYER REACTOR

Fig. 2

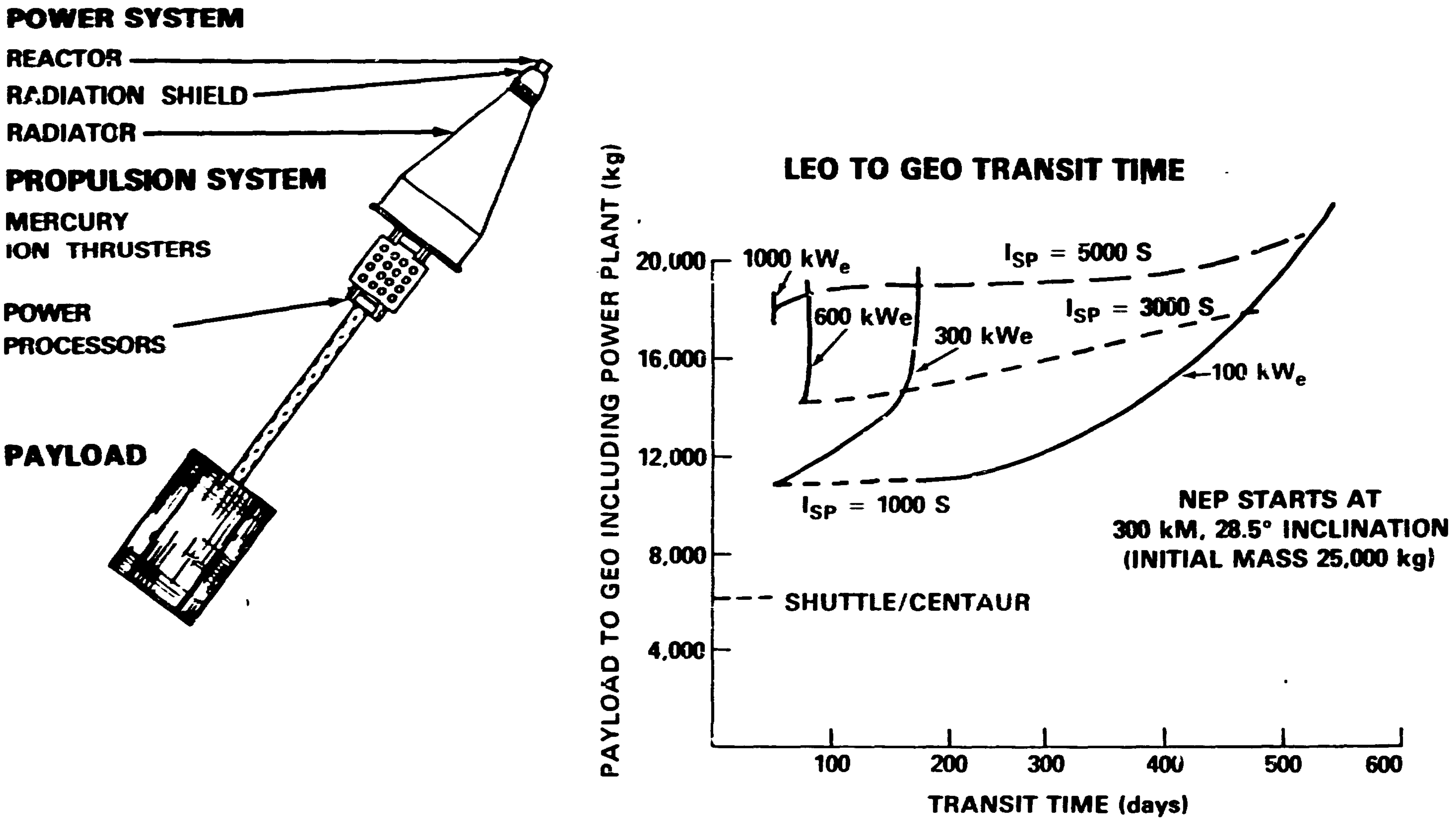

POWER SYSTEM
REACTOR
RADIATION SHIELD
RADIATOR
PROPULSION SYSTEM
MERCURY
ION THRUSTERS
POWER
PROCESSORS
PAYLOAD
LEO TO GEO TRANSIT TIME
PAYLOAD TO GEO INCLUDING POWER PLANT (kg)
20,000
16,000
12,000
8,000
4,000
1000 kWe
600 kWe
300 kWe
100 kWe
ISP = 5000 S
ISP = 3000 S
ISP = 1000 S
NEP STARTS AT
300 kM, 28.5° INCLINATION
(INITIAL MASS 25,000 kg)
SHUTTLE/CENTAUR
100
200
300
400
500
600
TRANSIT TIME (days)

Fig. 3

- **SINGLE S/C WITH LANDER**
- **NUCLEAR ELECTRIC PROPULSION (6 MW$_e$ POWER SYSTEM)**
- **MISSION DURATION 2.6 YEARS**
- **STAY TIME AT MARS 100 DAYS WITH 30 DAYS ON SURFACE**
- **TOTAL CREW OF 5 WITH 3 ON MARS**
- **MISSION PROFILE**
  - **MASS IN LEO 344 METRIC TONS**
  - **SPECIFIC IMPULSE 5000 S**
  - **PROPULSION TIME 570 DAYS**

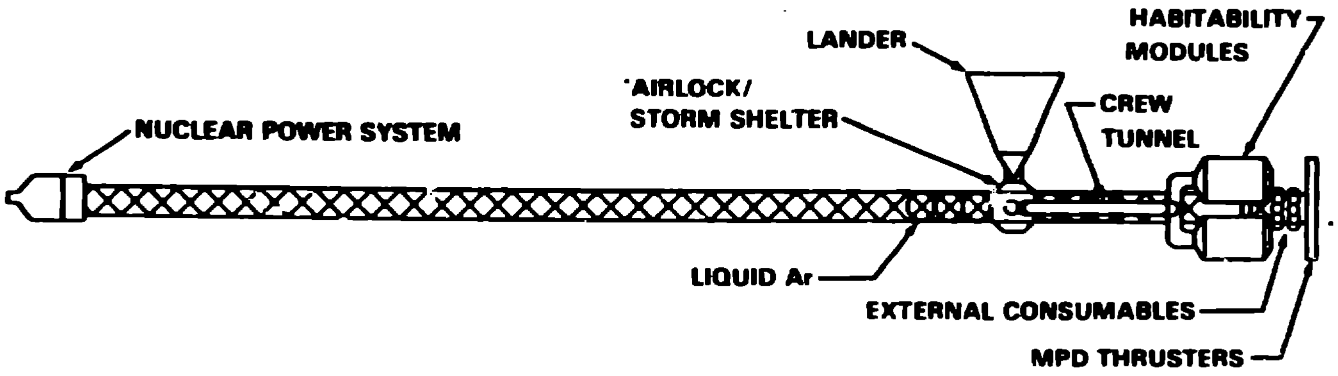


Fig. 4

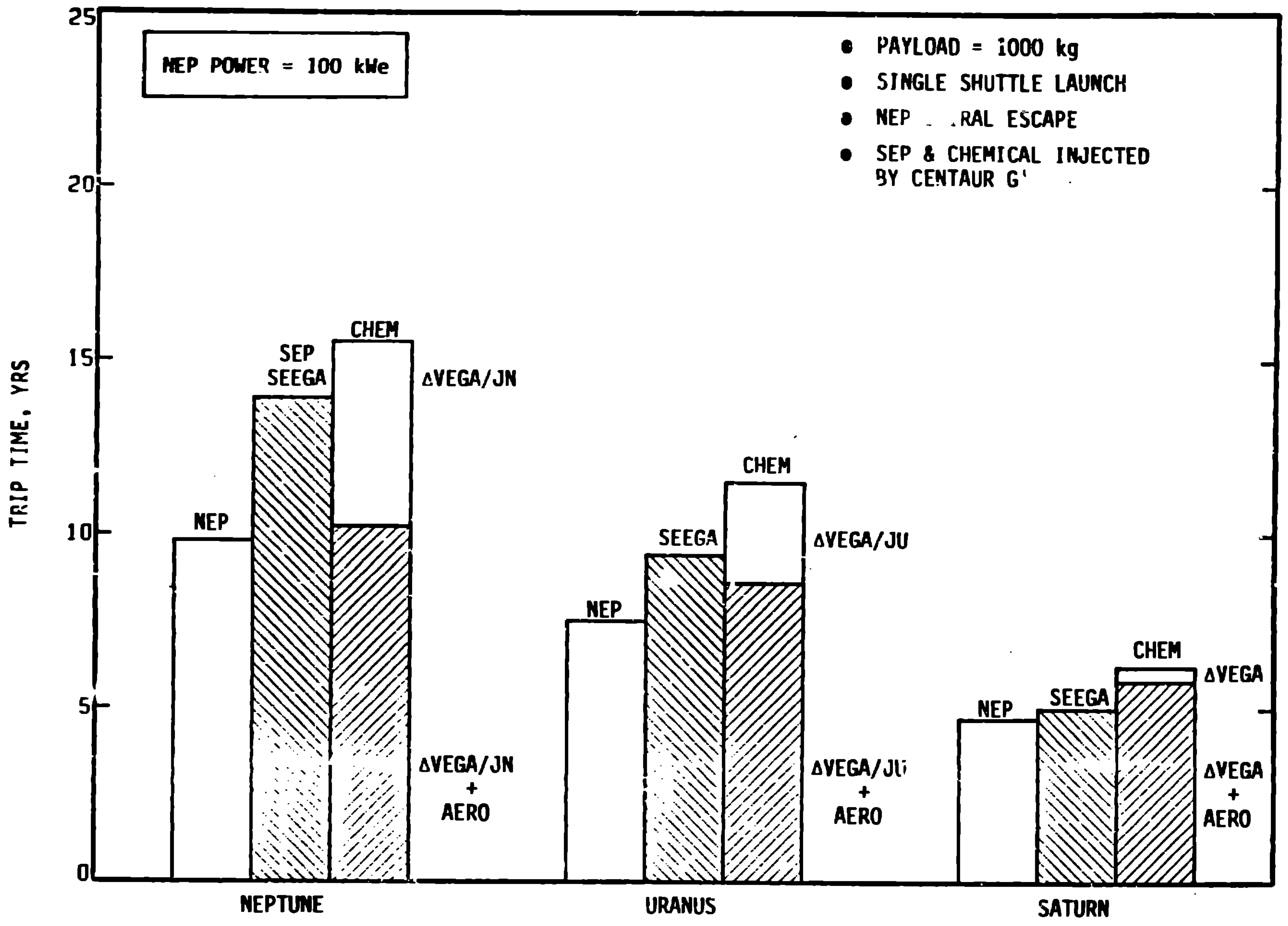

NEP POWER = 100 kWe
PAYLOAD = 1000 kg
SINGLE SHUTTLE LAUNCH
NEP .RAL ESCAPE
SEP & CHEMICAL INJECTED BY CENTAUR G'
TRIP TIME, YRS
0
5
10
15
20
25
NEP
SEP SEEGA
CHEM
ΔVEGA/JN
ΔVEGA/JN + AERO
NEP
SEEGA
CHEM
ΔVEGA/JU
ΔVEGA/JU + AERO
NEP
SEEGA
CHEM
ΔVEGA
ΔVEGA + AERO
NEPTUNE
URANUS
SATURN

Fig. 5

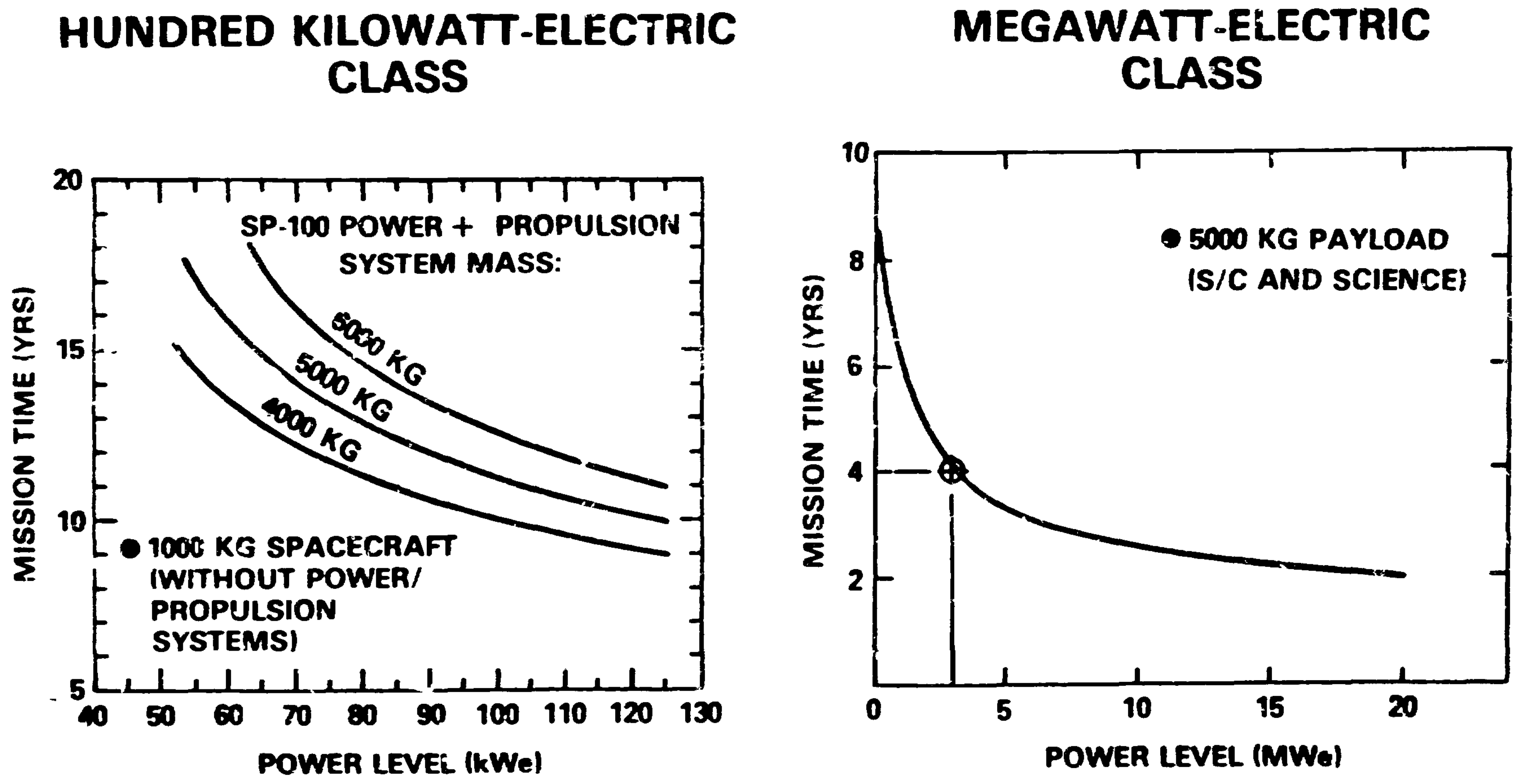

HUNDRED KILOWATT-ELECTRIC CLASS
MISSION TIME (YRS)
20
15
10
5
SP-100 POWER + PROPULSION SYSTEM MASS:
6000 KG
5000 KG
4000 KG
● 1000 KG SPACECRAFT (WITHOUT POWER/ PROPULSION SYSTEMS)
40
50
60
70
80
90
100
110
120
130
POWER LEVEL (kWe)
MEGAWATT-ELECTRIC CLASS
MISSION TIME (YRS)
10
8
6
4
2
● 5000 KG PAYLOAD (S/C AND SCIENCE)
0
5
10
15
20
POWER LEVEL (MWe)

Fig. 6