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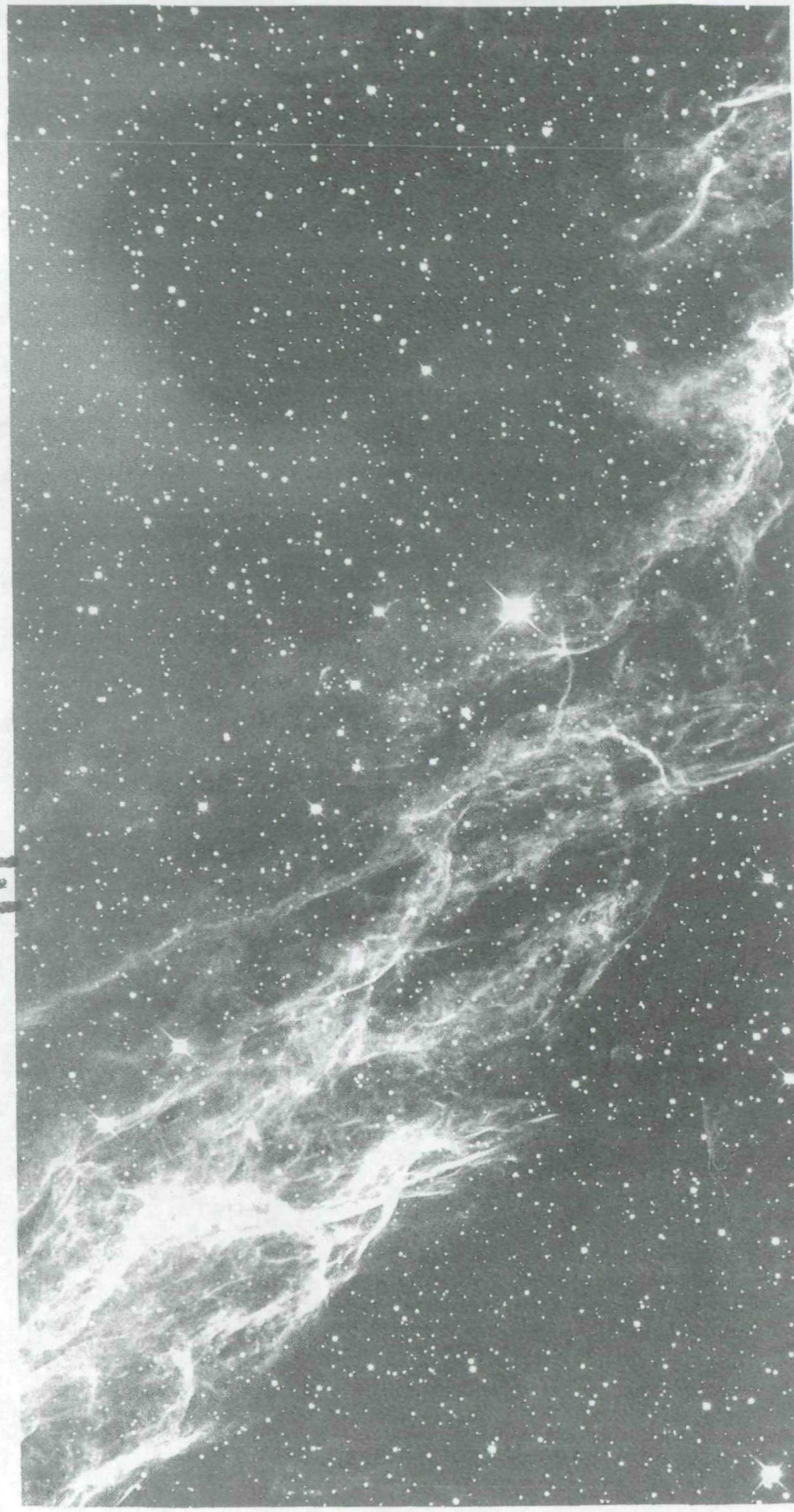

Report No. T-31

ADVANCED MISSION APPLICATIONS OF NUCLEAR ELECTRIC PROPULSION

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ADVANCED MISSION APPLICATIONS OF NUCLEAR ELECTRIC PROPULSION

by

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for

Planetary Programs
Office of Space Sciences
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FOREWORD

This technical report covers work performed on one task of NASA contract NASW-2144, Long Range Planning for Solar System Exploration. This study presents application of nuclear electric propulsion to advanced unmanned missions to the outer planets and solar system and compares its performance to advanced chemical ballistic propulsion systems.

SUMMARY

Current analysis of advanced unmanned planetary missions in the 1980's and beyond indicate the need for propulsion systems with performance capabilities beyond those of current and near state-of-art. One propulsion system concept being considered to fill this need is nuclear electric low thrust propulsion (NEP). The only on-going NEP development program is the internally-fueled thermionic reactor. The major development effort is concentrated on design proof and testing of the thermionic fuel element and overall reactor design. Technology forecasts indicate that an internally-fueled thermionic NEP system capable of 20,000 hour operating thrust time could be available for mission application by late 1983.

Two different NEP system power levels are considered for performance analysis: 100 kw and 250 kw. The 100 kw NEP system uses a Centaur(D-1T) chemical stage for injection to an interplanetary transfer and the 250 kw system uses a spiral escape maneuver. Advanced chemical systems used for ballistic performance comparison are the Centaur(GT)/Kick, Centaur(GT)/VUS and Centaur(GT)/Centaur(GT)/VUS. All systems are launched to a 270 n.mi. parking orbit via the space shuttle with a payload capability of 50000 lbs.

The set of missions selected for performance analysis includes loose elliptical orbiters and close circular orbiters of the outer planets, satellite orbiter/landers, a Saturn-Uranus-Neptune flyby, Halley rendezvous, and Ceres sample return. Performance comparison is in general made on the basis of net payload at the target as a function of flight time. NEP performance is shown for unconstrained and constrained (20,000 hours) thrusting time. Specific impulse is optimized and ranges from 4000 sec to 7000 sec.

In general, results show that both NEP systems are capable of performing all the missions considered but that the ballistic systems could perform only those missions requiring a moderate expenditure of energy at the target (loose elliptical orbiters, satellite orbiter/landers, and multi-planet flyby). For these missions, the NEP systems are found to yield as high as 30% (100 kw) to 50% (250 kw) reduction in flight time for a given payload over the chemical ballistic systems. Table S-1 shows for a selected net payload, flight time results for the various missions considered. The NEP data are for systems constrained to a maximum operating thrust time of 20000 hours. For the payload levels indicated, the 250 kw system out-performs the 100 kw system only in those missions requiring relatively high energy expenditure. For moderate energy levels, the two systems are comparable.

A detailed analysis of the Ceres sample return mission showed that the 100 kw NEP system has the capability to return as much as 120 kgs of surface sample plus a photographic coverage at 1 meter resolution of 100% of the asteroids' surface.

TABLE S-1 PROPULSION SYSTEM-FLIGHT TIME COMPARISONS

TARGET	MISSION TYPE	NET PAYLOAD (KGS)	FLIGHT TIME (DAYS)[2] NEP (100)[3]	NEP (250)[3]	CHEMICAL
JUPITER	30-DAY ORBITER	1000	450	500	545
	SYNCHRONOUS ORBITER	1000	1520	1350	-
CALLISTO	ORBITER/LANDER	1740[1]	910	870	1000
IO	ORBITER/LANDER	1830[1]	1460	1145	-
SATURN	30-DAY ORBITER	1000	940	950	1130
	RING ORBITER	1000	1640	1570	-
TITAN	ORBITER/LANDER	1890[1]	1660	1400	1660
URANUS	30-DAY ORBITER	1000	1850	1725	2440
	SYNCHRONOUS ORBITER	1000	2600	2460	-
NEPTUNE	30-DAY ORBITER	1000	2850	2630	4075
	SYNCHRONOUS ORBITER	1000	4140	-	-
S-U-N	MULTI-PLANET FLYBY	1000	< 2400	NA	2640
HALLEY	RENDEZVOUS	1000	950	950	-
CERES	SAMPLE RETURN	NA	1250	NA	-

1. MINIMUM REQUIRED PAYLOAD IN SATELLITE ORBIT RECOMMENDED BY PRICE AND SPADONI (1970).
2. - INDICATES SYSTEM NOT CAPABLE OF PERFORMING MISSION.
   NA INDICATES SYSTEM NOT APPLIED TO MISSION.
3. RESULTS SHOWN ARE FOR CONSTRAINED THRUST TIME (20000 HR MAXIMUM).

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1. INTRODUCTION

1.1 Study Purpose and Objectives

Current study efforts in advanced mission planning indicate that the energy required to perform some of these missions is beyond the capabilities of present day propulsion systems. Several programs have been initiated to develop propulsion systems which will meet the high energy requirements of future space missions. Perhaps the most outstanding of these proposed systems, from an overall performance standpoint, is the nuclear electric low thrust propulsion system (NEP).

The purpose of this study is to survey a select set of unmanned missions representative of the type currently under study by the National Aeronautics and Space Administration. Performance comparisons will be shown between nuclear electric propulsion systems and advanced chemical ballistic systems. The comparison will normally be made on the basis of net payload at the target body as a function of the flight time required for a particular propulsion system to deliver that payload. The exceptions are the two minor body missions to Halley and Ceres.

1.2 Definition of NEP Mission Classes

The types of missions for which NEP is suitable are those that have, for a ballistic system, large launch energy requirements to obtain a reasonable flight time to the target body, or missions which require large energy outputs for orbit insertion and/or maneuvering at the target body. These missions fall into the following classes: 1) missions requiring heavy payloads with medium energy requirements (e.g. sample return); 2) missions requiring medium payloads with high energy requirements (e.g. outer planet orbiters); 3) missions requiring heavy payloads with high energy requirements (e.g. outer planet satellite orbiter/landers).

For these types of missions, NEP can be used either to reduce launch energy requirements or increase payload capability, or both, over a ballistic system of comparable performance (i.e. flight time and payload). NEP can also be used at the target to perform a spiral capture; subsequent energy requirements on a chemical propulsion system can thus be significantly reduced or completely eliminated.

1.3 NEP Development Status

The basic operating principle of a nuclear electric propulsion system is to convert, in some fashion, the raw power of a nuclear fission reactor into electrical energy and deliver this energy to the low thrust engine subsystem. Several systems have been proposed for converting nuclear energy to electrical energy including in-core and out-of-core thermionic reactors, Brayton cycle reactors, and the liquid-metal magnetohydrodynamic converter. The only on-going development program to date is the internally fueled in-core thermionic reactor. Development programs in low thrust engines are mainly concentrated on the mercury ion bombardment thruster.

Figure 1[1] presents the latest experimental thermionic propulsion system design points: total propulsion system mass as a function of power input to the power conditioning unit. Design points are shown for two types of fuel, U^{235} and U^{233}. At the present time, the U^{235} system is preferred because U^{235} is less dangerous to handle and less costly to manufacture than U^{233}.

The most important is the thermionic fuel element design. Projections based on current test data indicate that 20,000 hour fuel elements will be available by late 1980. Based on this projection, a flight-rated thermionic NEP system in the 100 kw power range could be available as early as 1982. Should the operating lifetime requirement be reduced to about 10,000 hours, it may be

1. Reproduced by courtesy of Mr. J. F. Ingber, Gulf General Atomic Co.

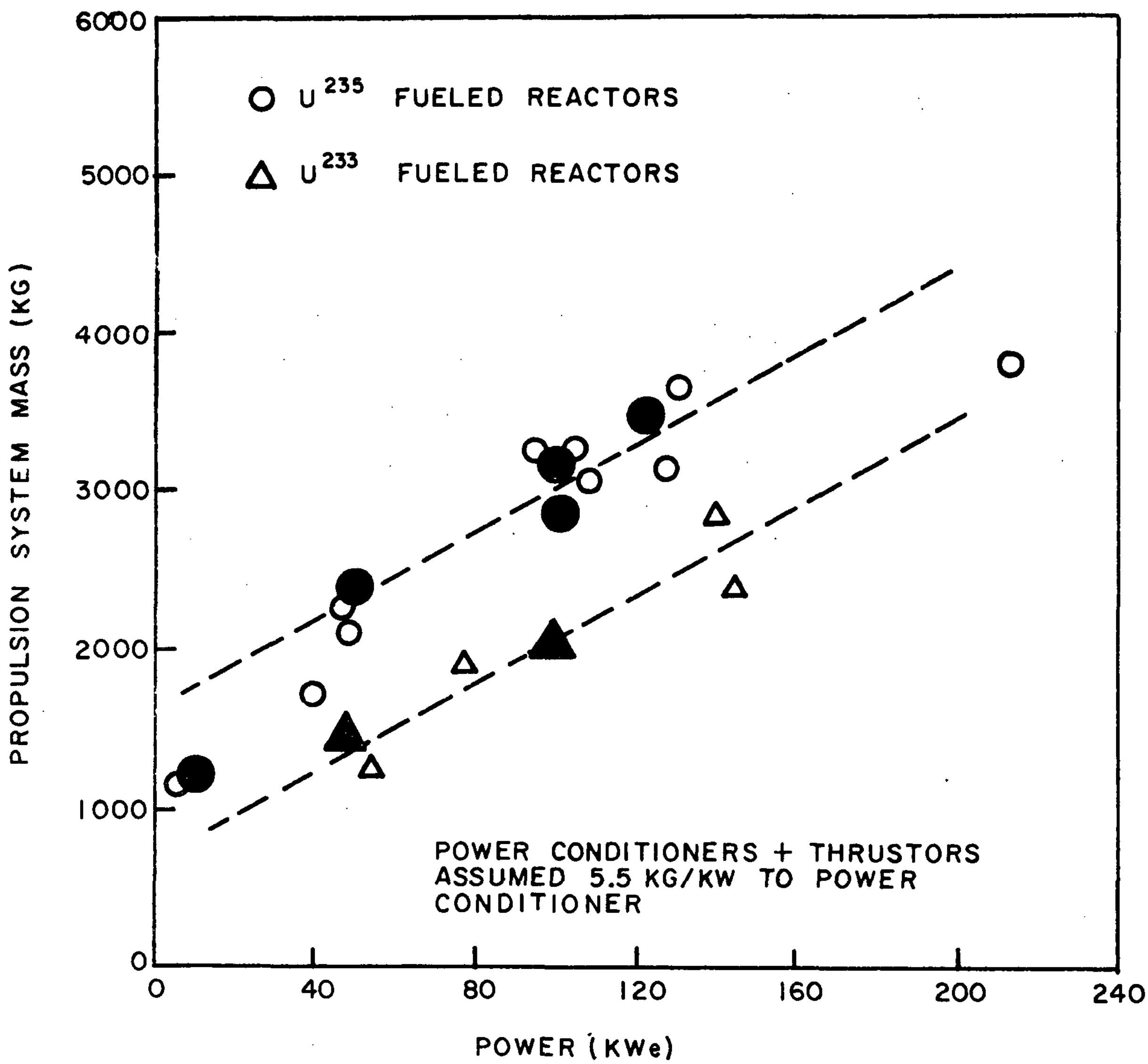

FIGURE I. THERMIONIC NUCLEAR ELECTRIC PROPULSION SYSTEM DESIGN POINTS possible to have thermionic fuel elements available by 1977, and therefore a flight-rated NEP system available for mission duty sooner than 1982.

Figure 2 illustrates one concept for a thermionic NEP side-thrusting spacecraft. This configuration allows for separation of the high temperature power subsystem assemblies from the lower temperature thrust subsystem and payload.

2. MISSION APPLICATIONS

2.1 General

In current NEP development programs, systems in the 100 to 120 kw power range are being examined. Growth version systems in the 240 to 300 kw range are also being considered. In order to adequately describe the potentials of NEP, mission performance data for 100 kw and 250 kw systems are presented. The following NEP system parameters have been assumed in generating the data:

- Specific mass: 30 kg/kw at 100 kw
  25 kg/kw at 250 kw
- Thruster efficiency function:

$$\eta = \frac{.842}{1 + \left(\frac{16}{C}\right)^2} \quad \text{(Mascy, 1970)}$$

where C is exhaust velocity in km/sec.

The QUICKLY computer program (Mascy 1970) was used to generate NEP data for all missions to the planets and their satellites. This program assumes circular coplanar planetary orbits, a good first approximation for mission analysis to the outer planets. The CHEBYTOP (Version I) computer program

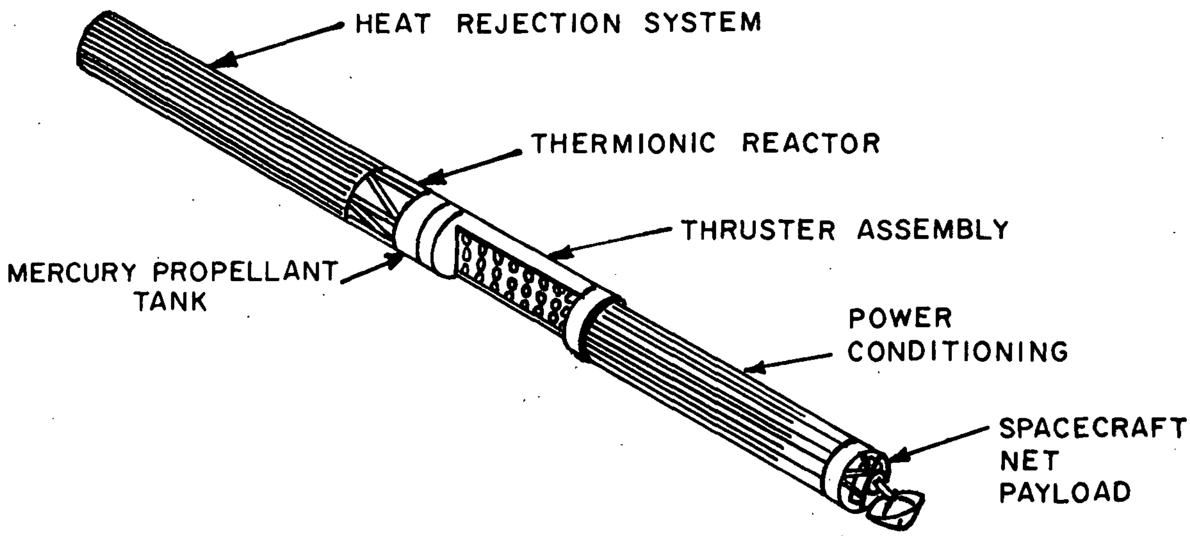

FIGURE 2. TYPICAL CONFIGURATION OF THERMIONIC NEP SIDE-THRUSTING SPACECRAFT

(Hahn, et. al. 1969) was used to allow a more detailed analysis of the multi-planet flyby and minor body missions. Ballistic trajectory data were taken from Rejzer (1967), Roth, et. al. (1968), and Waters (1971).

Performance curves are shown for unconstrained thrusting times and thrust times constrained to a maximum of 20,000 hours. A particular value of thrust time is shown on each unconstrained curve as a reference point. Unless otherwise specified, specific impulse (I_{sp}) was optimized over the flight time range for each mission. Since specific impulse can be expressed as a function of thrusting time, I_{sp} for constrained thrusting times optimized at lower values than those for unconstrained thrust time above 20,000 hours. Although it has not yet been firmly established, it is estimated that the specific impulse for NEP will fall within the range of 4000 sec. to 7000 sec.

Table 1 lists the system parameters of the advanced chemical stages used for ballistic performance comparisons with the NEP systems. The stages were combined in the following manner: Centaur(GT)/Kick, Centaur(GT)/VUS, and Centaur(GT)/Centaur(GT)/VUS. Which combination was used depended upon the launch energy requirements of the particular mission application. The Centaur(D-1T) was used solely as the injection stage for the 100 kw NEP system. Figure 3 presents the injected mass capability of each of the stage combinations. These curves are based on a shuttle launch capability of 22,675 kg (50,000 lbs)[1] to a 270 n.mi. parking orbit. Both NEP systems and the Centaur(GT)/Kick can be launched within a single shuttle. The Centaur(GT)/VUS requires a double shuttle launch with stage assembly in orbit, and the Centaur(GT)/Centaur(GT)/VUS requires three shuttle launches.

A space storable chemical propulsion system is used for orbit capture and maneuvering at the target body. For certain ballistic missions requiring such a high expenditure of energy for orbit capture that the "rubber" chemical stage would grow to unreasonable proportions, the VUS stage, in a partially expended mode, was carried to the target for orbit insertion. In this case, the VUS is

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[1] 1971 Launch Vehicle Estimating Factors handbook. This number was used to generate all data prior to the current estimate of 65,000 lbs maximum shuttle capability.

TABLE 1 CHEMICAL STAGE DATA

STAGE	THRUST (LBF)	Isp (SEC)	INERT WEIGHT (LBM)	USEFUL PROPELLANT (LBM)	PAYLOAD ADAPTER (LBM)
Solid Propellant Kick	5000	310	575	5000	100
VUS[1]	18000	460	3480	18000	150
Centaur(D-1T)[2]	-	444	5067	29369	116
Centaur(GT)[1]	29200	444	5778	45492	300
Retro[3]	-	385	Inert Fraction 0.25	-	-

1) Convair Report BNZ 72-006, Vol. I

2) 1971 Launch Vehicle Estimating Factors Handbook

3) Rubber Stage for High-Thrust Capture Applications.

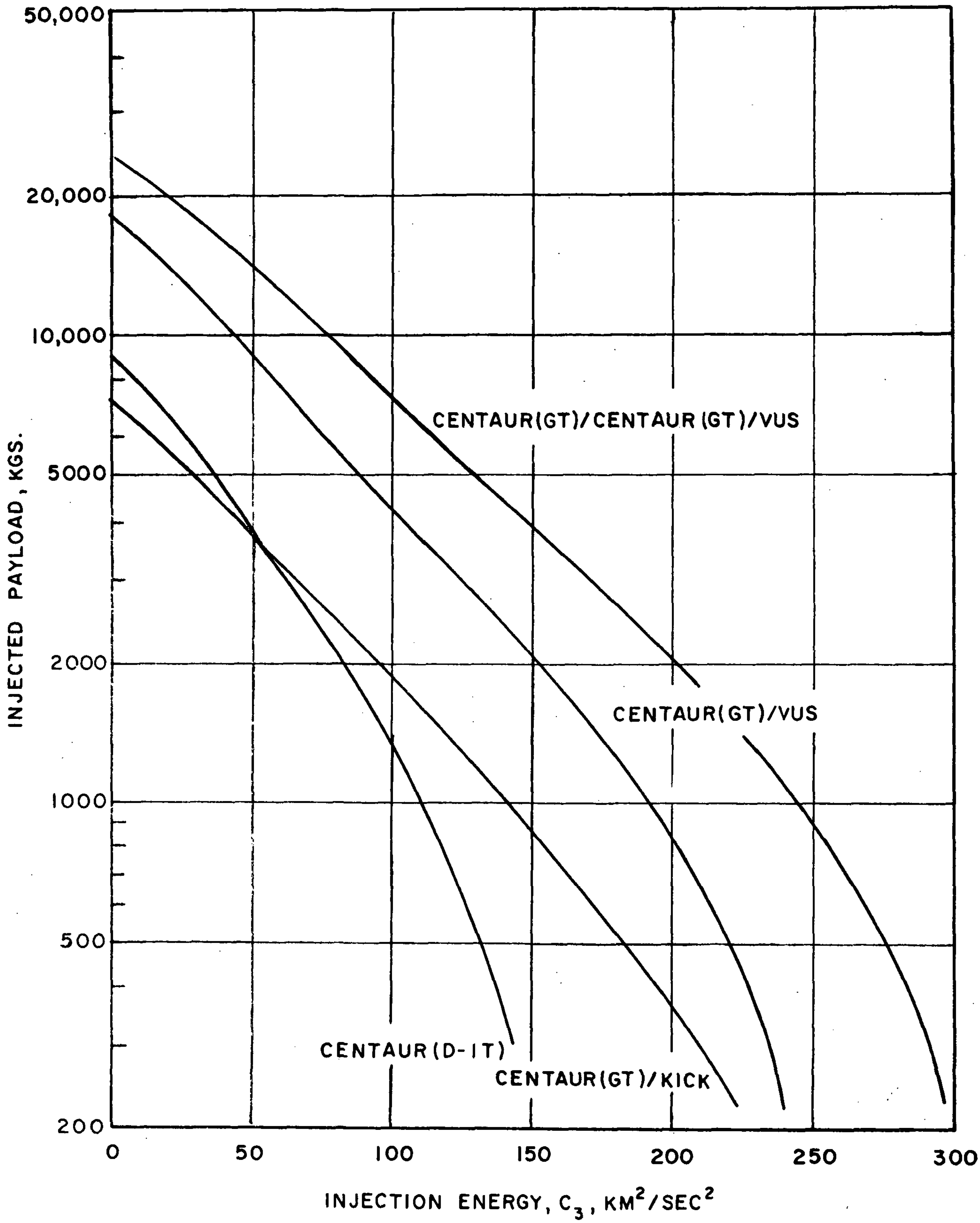

FIGURE 3. PAYLOAD PERFORMANCE OF SHUTTLE-BASED INJECTION STAGES

partially burned for injection, and the remainder saved for later use. No modifications to the VUS stage were assumed for this application. The proportion of propellant for each burn is dependent upon the required energy at the target, and the injected mass capability of the total injection system is reduced from that indicated in Figure 3.

All systems except the 250 kw NEP are injected from the 270 n.mi. parking orbit directly onto an escape trajectory. Because of its higher initial mass, it is more expedient to have the 250 kw NEP spacecraft effect a spiral escape from the parking orbit. Following the low-thrust spiral analysis as presented by Ragsac (1967), Figure 4 presents spiral time and initial acceleration requirements and final mass ratio, as functions of specific impulse, for a 250 kw NEP spacecraft to spiral from a 270 n.mi. Earth orbit to escape condition ($C_3 = 0$).

2.2 Mission Set

As previously mentioned, the types of missions for which nuclear electric propulsion is suitable are those requiring either a high launch energy at Earth or a high energy expenditure at the target, or both. Table 2 presents a set of missions representative of the kind being considered for unmanned exploration of the outer planets and solar system bodies in the 1980's. The set includes orbiters (in both "loose" and "tight" orbits) of the four giant planets, satellite orbiter/landers, a multi-planet flyby (S-U-N), comet rendezvous (Halley) and asteroid sample return (Ceres).

Also indicated in Table 2 are the types of operations for which the NEP system is utilized at the target body, mainly to effect a spiral capture. For highly elliptical planetary orbiters and satellite orbiter/landers, the NEP stage is assumed to be jettisoned prior to final orbit insertion. This leads to a higher net payload than would be obtained if the NEP stage were carried into orbit by a chemical propulsion system (excluding the use of a low thrust spiral maneuver). If the orbit insertion ΔV is relatively small, and there is sufficient payload capability, the NEP stage could be carried into orbit and used for such purposes as orbit maneuvering and payload power supply. This option was not investigated in this study.

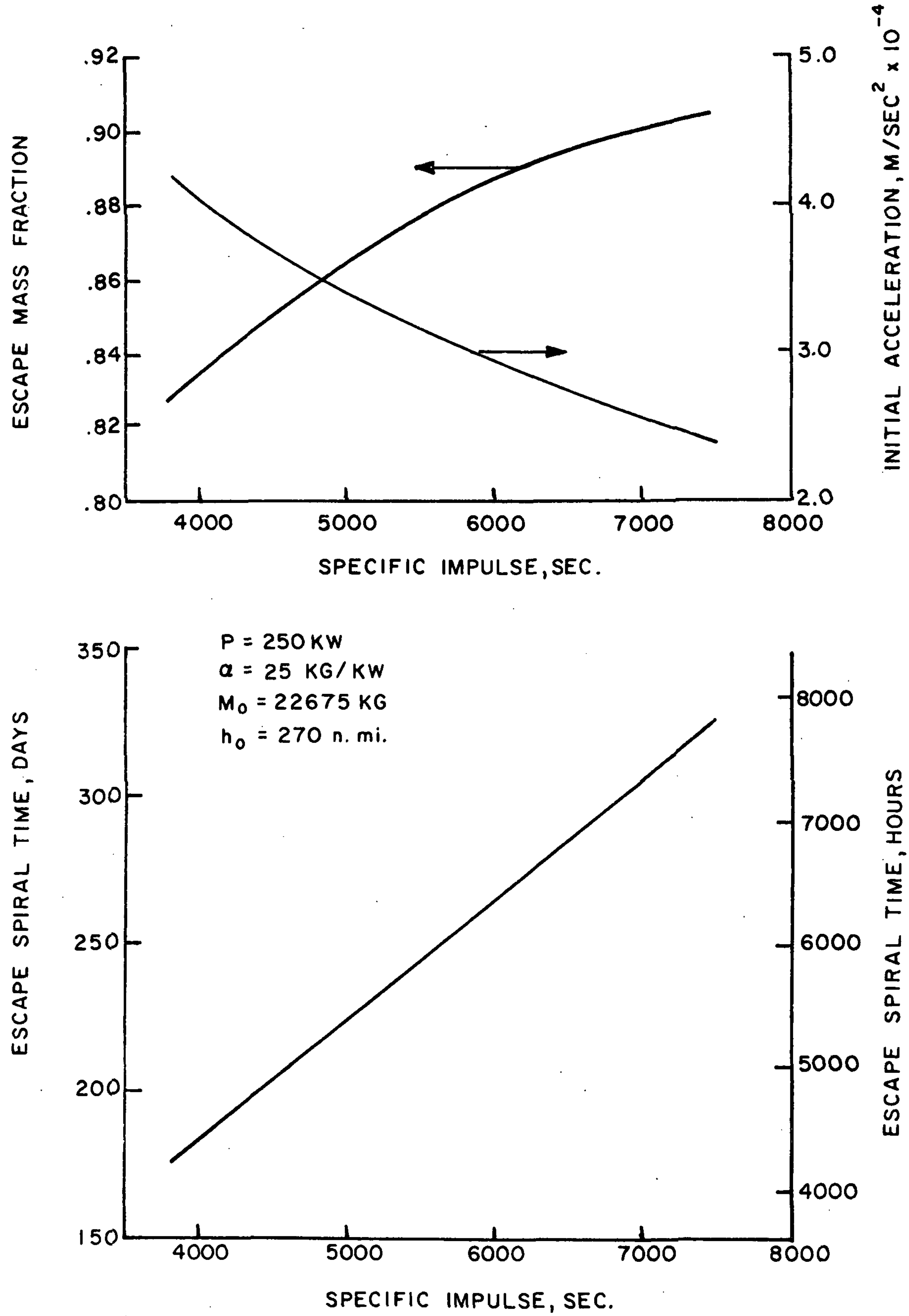

FIGURE 4. EARTH ESCAPE SPIRAL REQUIREMENTS FOR 250 KW NEP SYSTEM

TABLE 2 MISSION SET

TARGET	MISSION TYPE	ORBIT(Rp/e)[1]	NEP TARGET OPERATION
Jupiter	30-Day Orbiter	2/.973	NEP Jettisoned
Jupiter	Synchronous Orbiter	2.23/0	Spiral Capture
Io	Orbiter/Lander	1900 km/0	Spiral Capture to Orbit of Io
Callisto	Orbiter/Lander	2490 km/0	Spiral Capture to Orbit of Callisto
Saturn	30-Day Orbiter	2/.966	NEP Jettisoned
Saturn	Ring Orbiter	2.5/0	Spiral Capture and Hover Above Ring Plane
Titan	Orbiter/Lander	2540 km/0	Spiral Capture to Orbit of Titan
Uranus	30-Day Orbiter	2/.976	Net Jettisoned
Uranus	Synchronous Orbiter	2.57/0	Spiral Capture
Neptune	30-Day Orbiter	2/.978	NEP Jettisoned
Neptune	Synchronous Orbiter	3.42/0	Spiral Capture
S-U-N	Multi-Planet Flyby	-	Earth-Saturn Leg Only
Halley	Rendezvous	-	Stationkeeping
Ceres	Sample Return	495 km/0	Spiral Capture and Departure at Ceres, Spiral Capture at Earth Return

1) Rp = Planet Radii (unless otherwise specified); e = Eccentricity

In all cases except the Ceres sample return mission, performance data are presented as net payload in final position at the target. It is not within the scope of this study to determine what scientific and engineering hardware is required by each particular mission.

The remainder of this section presents the major results of the study. Planetary missions are grouped in subsections according to target planet, followed by the multi-planet flyby mission and finally the minor body missions. Overall conclusions to the study are made separately in Section 3.

2.2.1 Jupiter Missions

Figure 5 through Figure 8 show payload and flight time data for missions to Jupiter and two of its satellites in the 1984[1] launch opportunity.

The orbit for Figure 5 is a highly elliptical orbit with a periapse radius of 2 Jupiter radii and a period of 30 Earth days. No consideration is given here to possible environmental hazards close to Jupiter. Payload curves are shown for both the 100 kw and 250 kw NEP systems and the Centaur(GT)/Kick ballistic stage combination. NEP thrusting times are less than 20,000 hours over the flight time range shown. The 100 kw system seems to out-perform the 250 kw system at flight times below about 560 days because the Centaur(D-1T) provides better performance than the NEP escape spiral maneuver at the higher energies required by low flight time trajectories. Because of the high eccentricity of the orbit, the NEP systems are not used for spiral capture at Jupiter. The NEP systems are assumed to be jettisoned to minimize the propellant mass fraction of the orbit insertion stage.

Figure 6 shows NEP performance curves for placing a payload in a circular orbit about Jupiter having a period synchronous to the planet's observed rate of rotation. Since the final orbit is circular, the NEP systems are used for a spiral capture maneuver.

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[1] Refers only to ballistic opportunity since NEP data were generated independent of launch date.

None of the ballistic systems considered were capable of performing this mission because of the high energy required to capture into the tight circular orbit. The constrained thrust time curve levels off rapidly in relation to the unconstrained curve because of the decrease in performance of the constrained NEP system, even though the low thrust trajectory energy requirement is decreasing with increasing flight time.

Figure 7 presents performance data for an orbiter/lander mission to Callisto. The NEP systems perform a spiral maneuver to the orbit of Callisto. (At this point the spacecraft is at zero velocity relative to Callisto). The NEP system is jettisoned and a chemical propulsion system places the net payload into a 100 km altitude circular orbit about the satellite. Two types of ballistic data were examined: two-impulse Earth-Jupiter transfers and optimized three-impulse transfers. A derivative of the bielliptic transfer (Price and Spadoni, 1970) was used to place the spacecraft into orbit about Callisto. The Centaur(GT)/Centaur(GT)/VUS stage combination was used with a significant portion of the VUS utilized for the orbit capture sequence. Both NEP systems are capable of delivering the payload necessary to perform a soft-lander mission with a bus remaining in orbit (~ 1740 kgs), as recommended by Price and Spadoni. The chemical system is not capable of performing a composite orbiter/lander type mission.

Figure 8 presents payload curves for an Io orbiter/lander mission. Ballistic energy requirements are very large due to the overpowering effect of Jupiter's gravitational field in the vicinity of Io, and thus the performance of the Centaur(GT)/Centaur(GT)/VUS is quite marginal. Again, both NEP system have the capability to deliver the recommended payload (~1830 kgs) for an orbiter/lander type mission to Io.

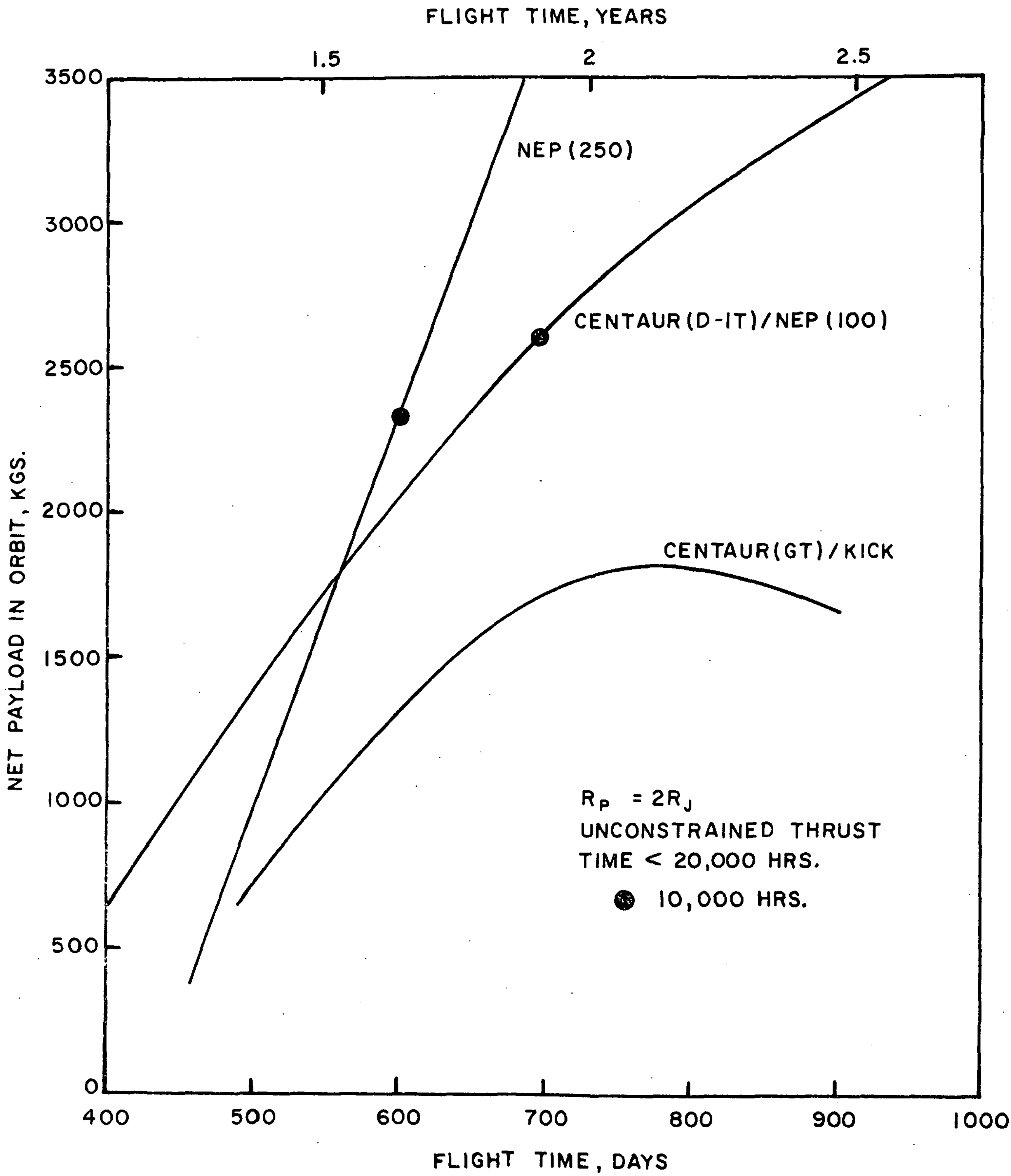

FIGURE 5. JUPITER ORBITER, 30-DAY ORBIT

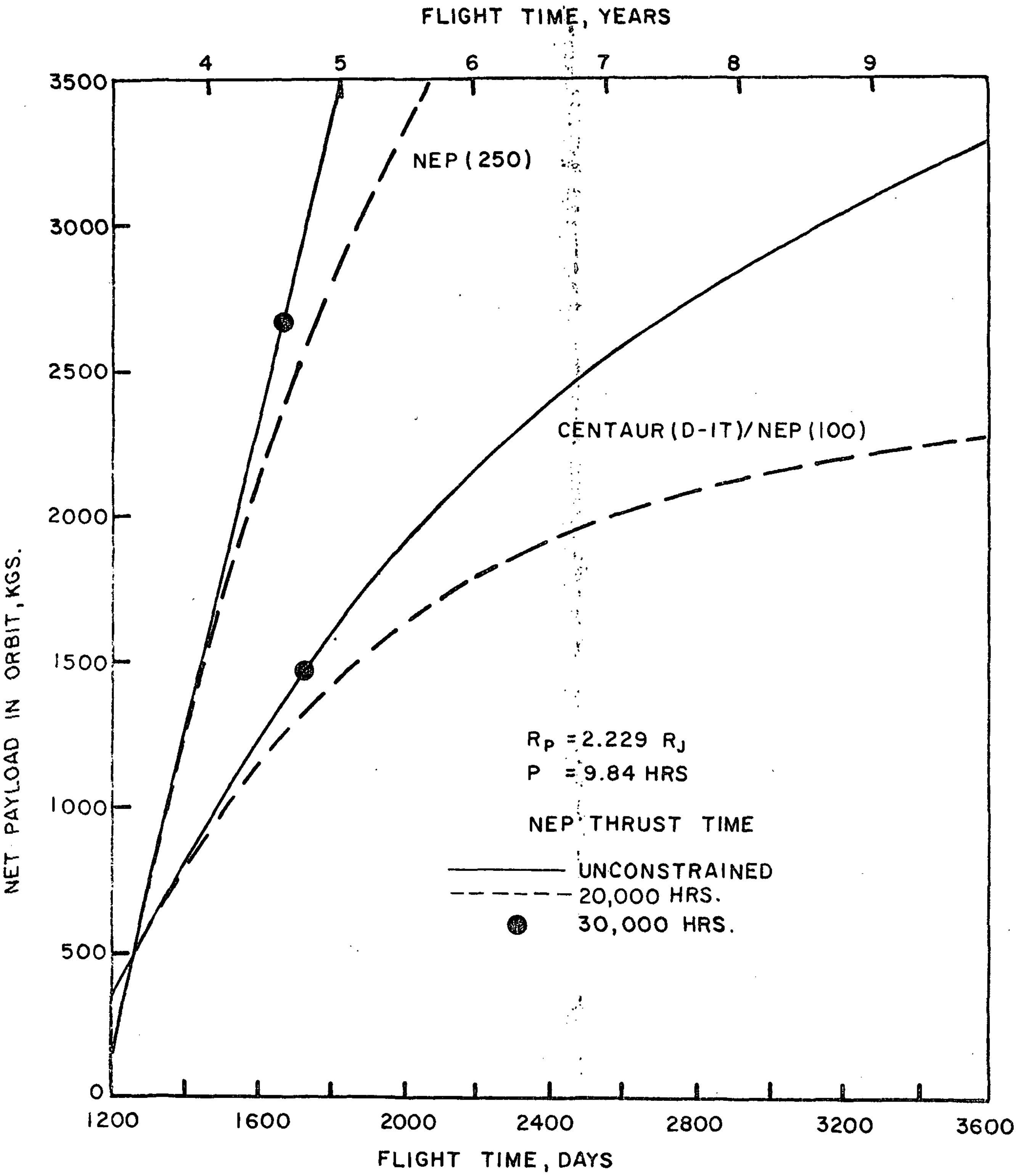

FIGURE 6. JUPITER ORBITER, SYNCHRONOUS ORBIT

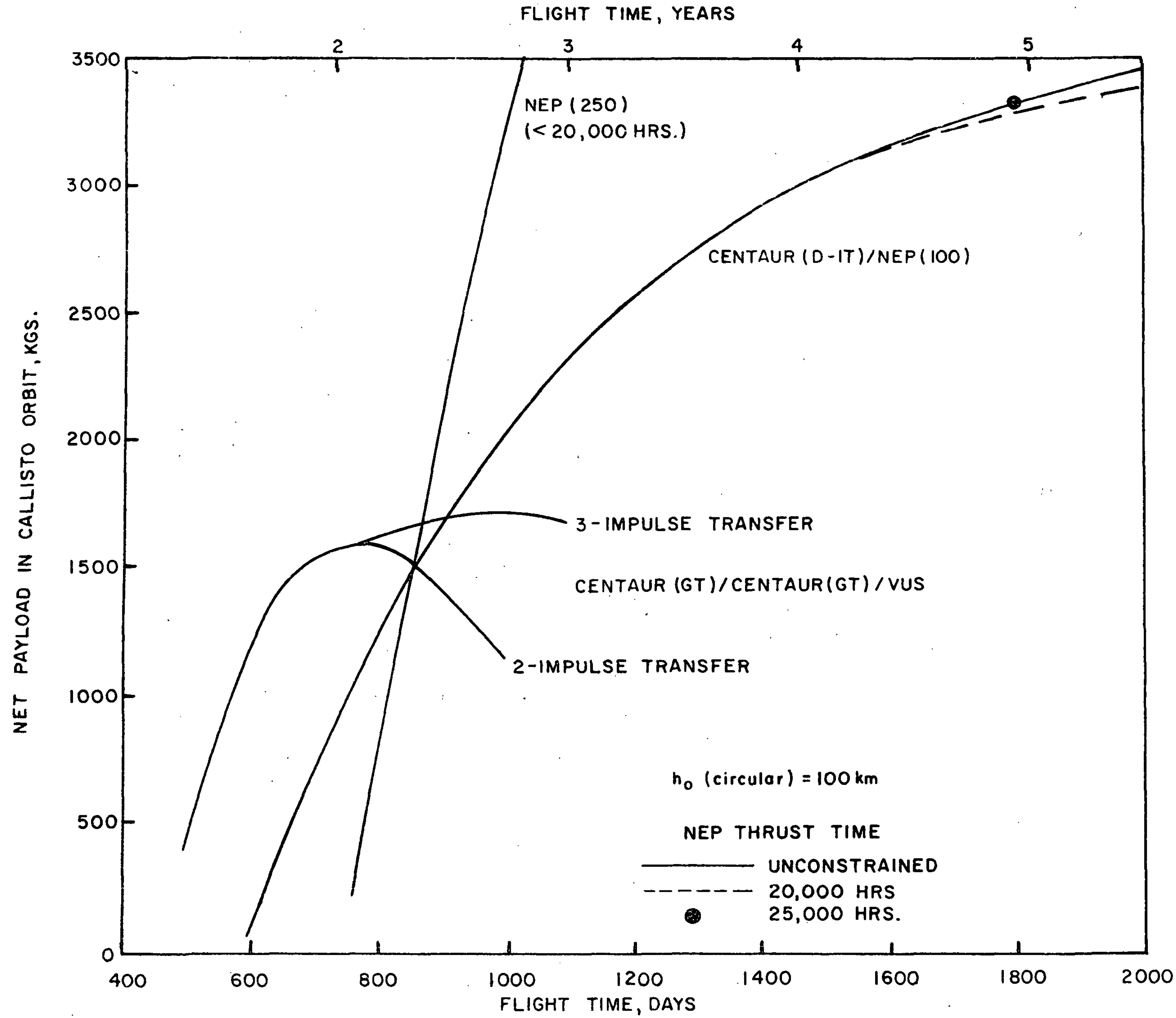

FIGURE 7. CALLISTO ORBITER/LANDER

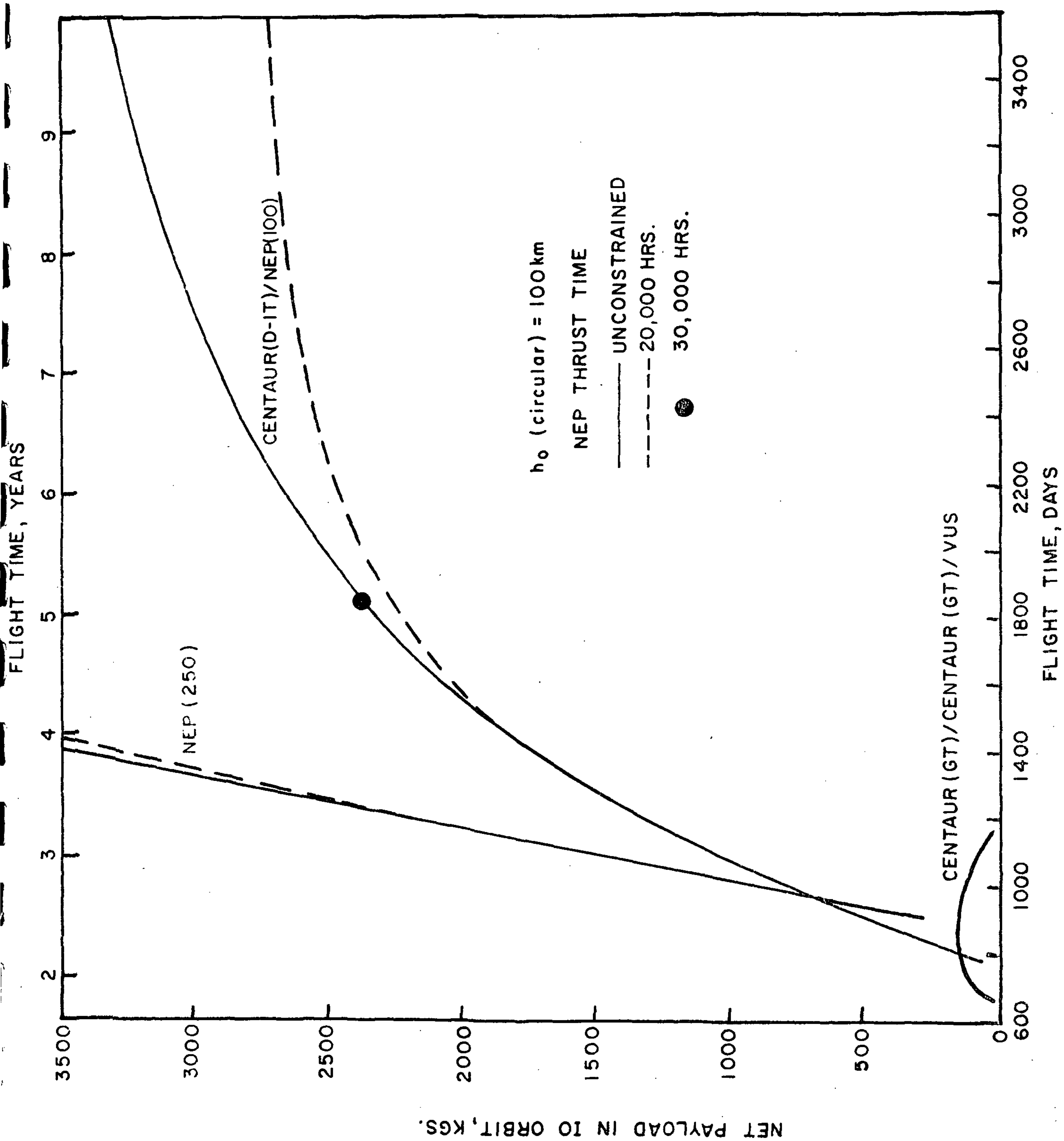

FIGURE 8. IO ORBITER/LANDER

2.2.2 Saturn Missions

Figures 9, 10 and 11 show payload and flight time performance for missions to Saturn and its major satellite, Titan, in the 1986[1] launch opportunity.

Figure 9 shows performance curves for a 30 day orbiter mission to Saturn. Thrust time for the 250 kw system is below the 20,000 hour constraint for the range of flight times considered. Because launch energies are higher for Saturn than for Jupiter, the ballistic stage was upgraded to the Centaur(GT)/VUS.

Figure 10 presents NEP performance for missions to investigate the rings of Saturn. (A synchronous orbiter at Saturn was not examined since this orbit lies within the rings). The NEP spacecraft performs a spiral maneuver to a circular orbit at 2.5 Saturn radii. If a portion of the net payload at 2.5 R_S is low-thrust propellant, the spacecraft can continue to spiral inwards in a minor circle orbit several kilometers above the rings by directing a portion of the thrust normal to the ring plane. The propellant required to maintain the minor circle orbit has been estimated by Wells and Price (1972) to be an additional 50% of the propellant required to spiral inwards in the equatorial plane. The total propellant required to perform this maneuver depends on the amount of time spent carrying it out and must be subtracted from the net payload as shown in Figure 10. The dynamic stability of the vertical thrust component is an important aspect of this maneuver and should be thoroughly investigated. None of the chemical systems considered are capable of performing this mission because of the high capture energy requirements at 2.5 R_S.

Figure 11 shows performance curves for a Titan orbiter/lander mission. As with Callisto and Io, the NEP systems spiral into the orbit of the satellite prior to a high thrust chemical insertion into final orbit. The ballistic data used for this mission are optimized two impulse Earth-Saturn transfers. Again, a portion of the VUS stage is used to perform the three-impulse capture maneuver

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1 Refers to ballistic opportunity.

at Saturn. All propulsion systems are capable of delivering the minimum payload (~ 1890 kgs) recommended by Price and Spadoni for a composite orbiter/lander mission.

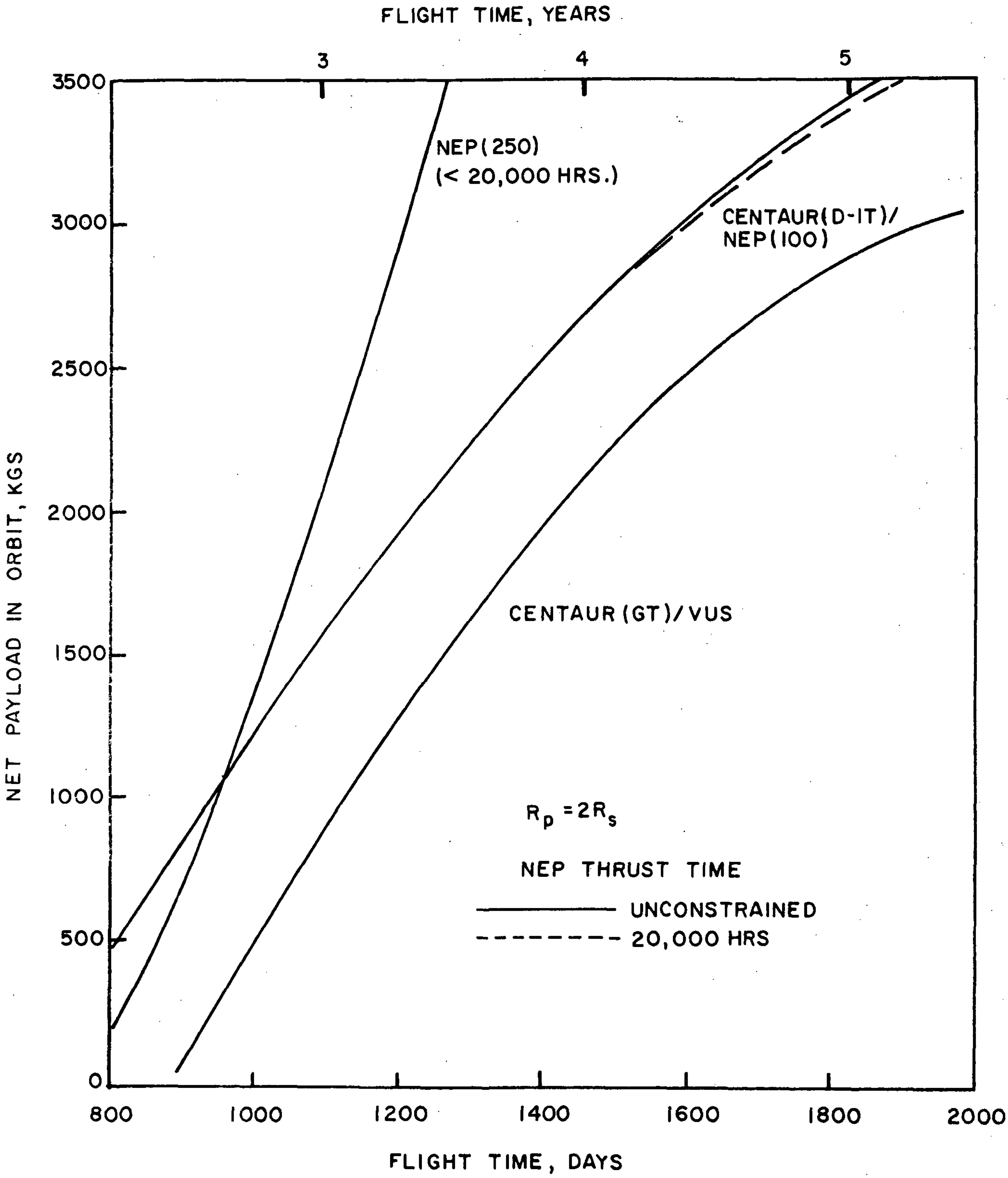

FIGURE 9. SATURN ORBITER, 30-DAY ORBIT

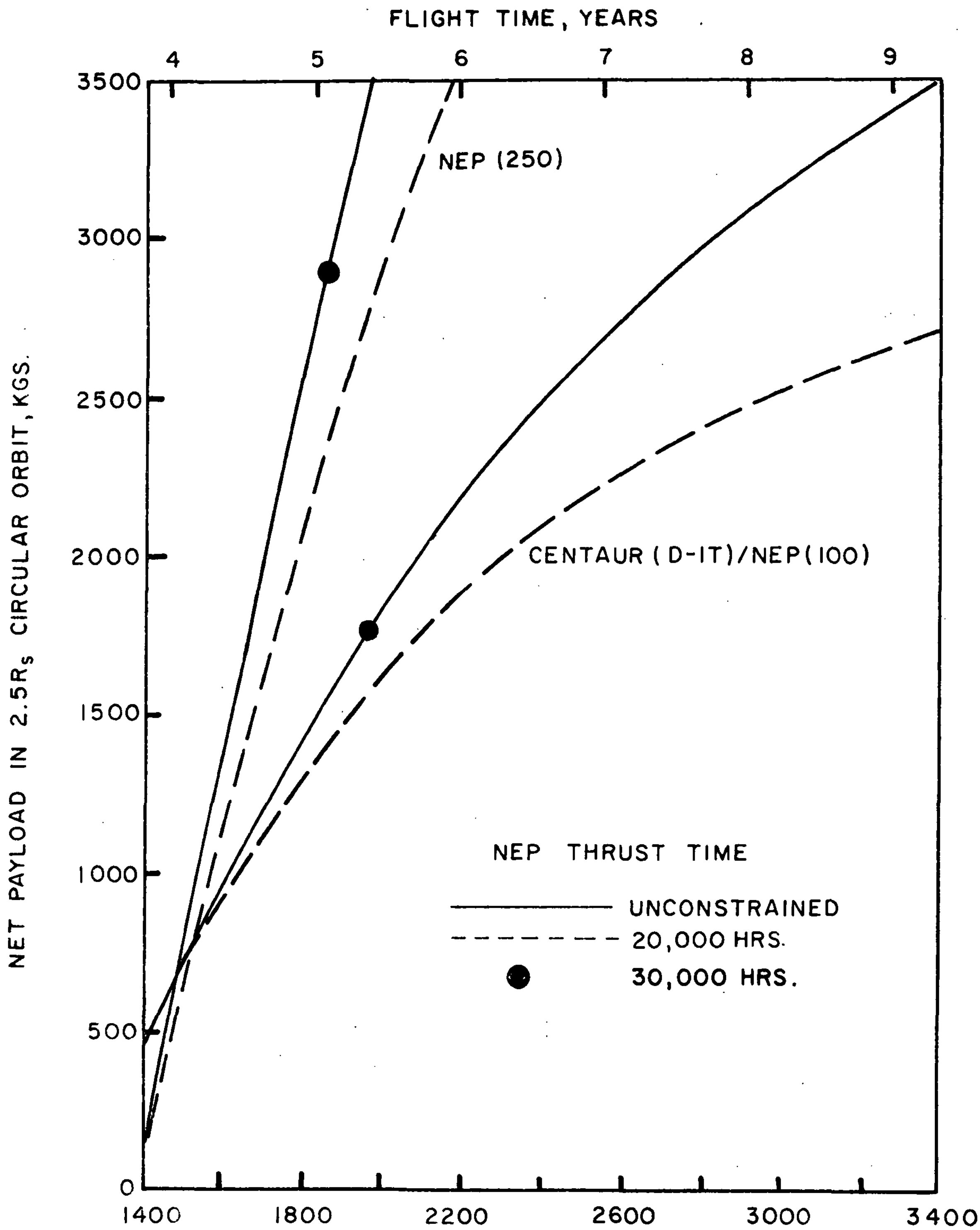

FIGURE 10. SATURN ORBITER, RING ORBIT

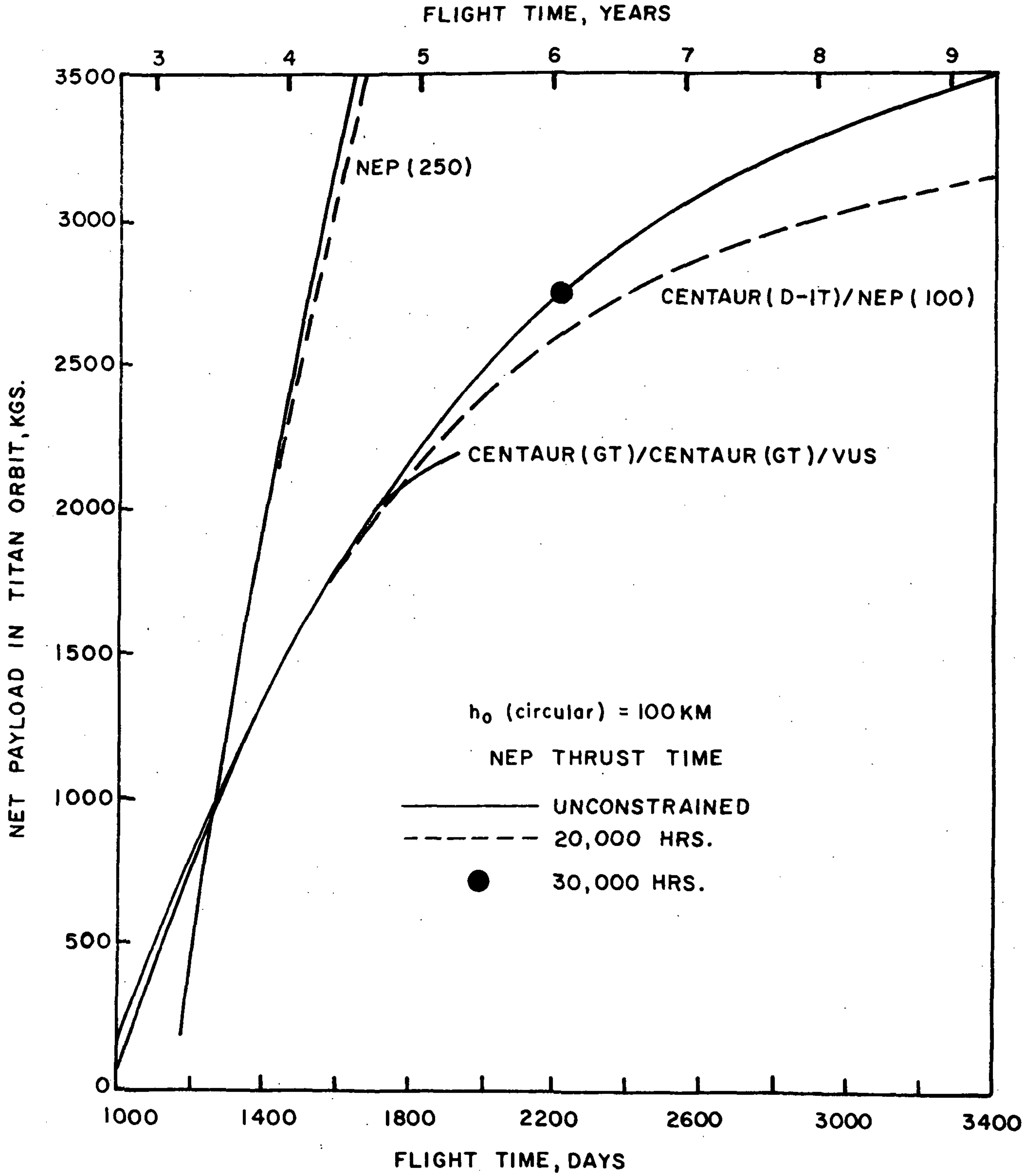

FIGURE 11. TITAN ORBITER/LANDER

2.2.3 Uranus Missions

Figure 12 and Figure 13 show performance data for orbiter missions to Uranus in the 1988[1] launch opportunity.

Payload and flight time curves are shown in Figure 12 for an orbiter in a 30-day orbit with periapse of 2 Uranus radii. The chemical injection stage for this mission is the Centaur(GT)/ Centaur(GT)/VUS combination. The chemical system shows slightly better performance at the higher flight times than the constrained thrust time 100 kw NEP system. Note that flight time is presented on a logarithmic scale in this figure.

Figure 13 presents NEP performance data for a synchronous orbiter at Uranus. None of the chemical systems considered were capable of performing this mission. A more pronounced decrease in the constrained thrust time system performance, from the unconstrained system, can be observed in this mission. This occurs because the effect of the spiral capture energy requirements is more noticeable on the relatively high energy trajectories. It is appropriate to mention here that the NEP flight times shown for this mission are probably conservative; the QUICKLY computer code tends to predict longer flight times for this type of mission than three-dimensional codes such as CHEBYTOP.

1. Refers to ballistic opportunity.

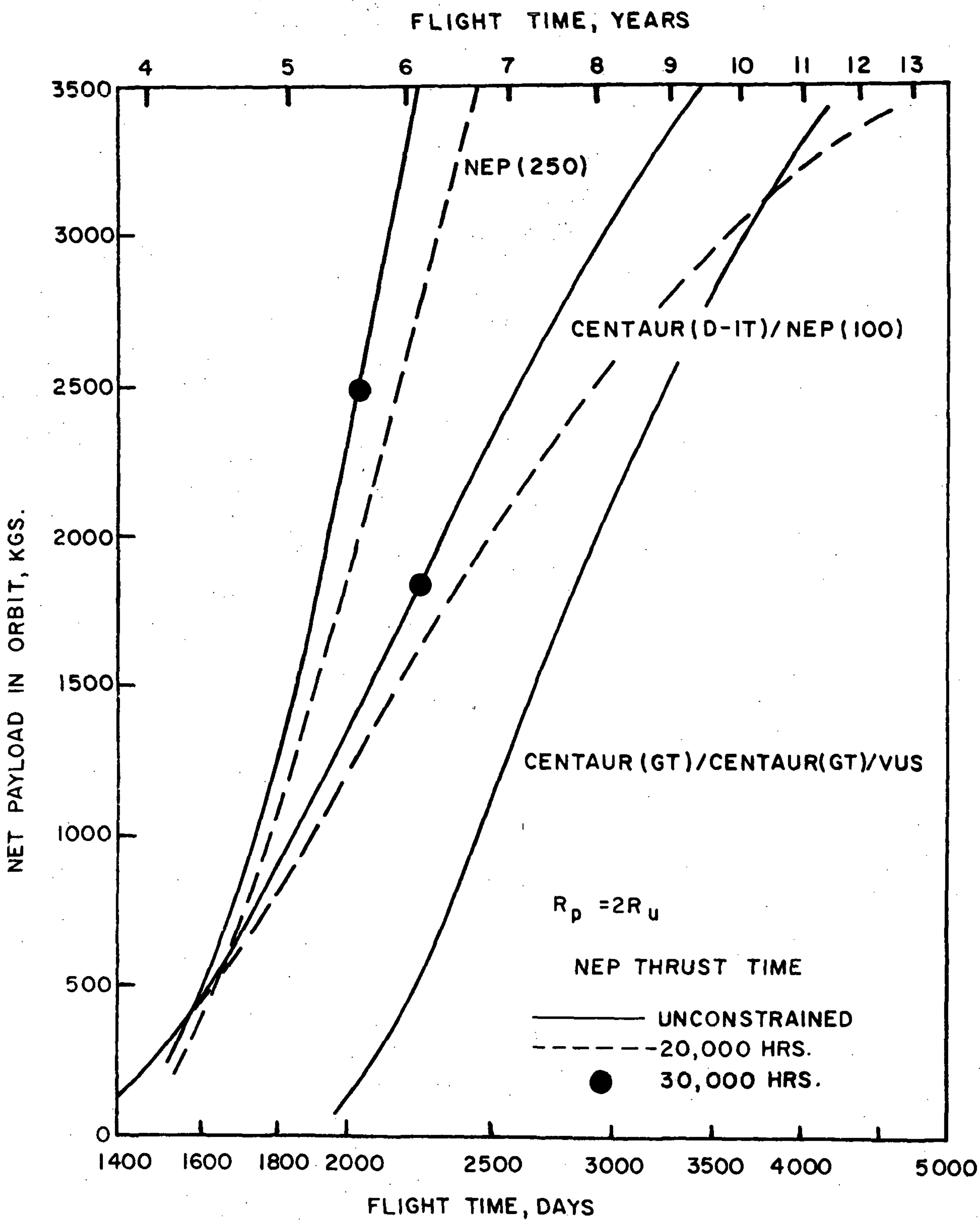

FIGURE 12. URANUS ORBITER, 30-ORBIT

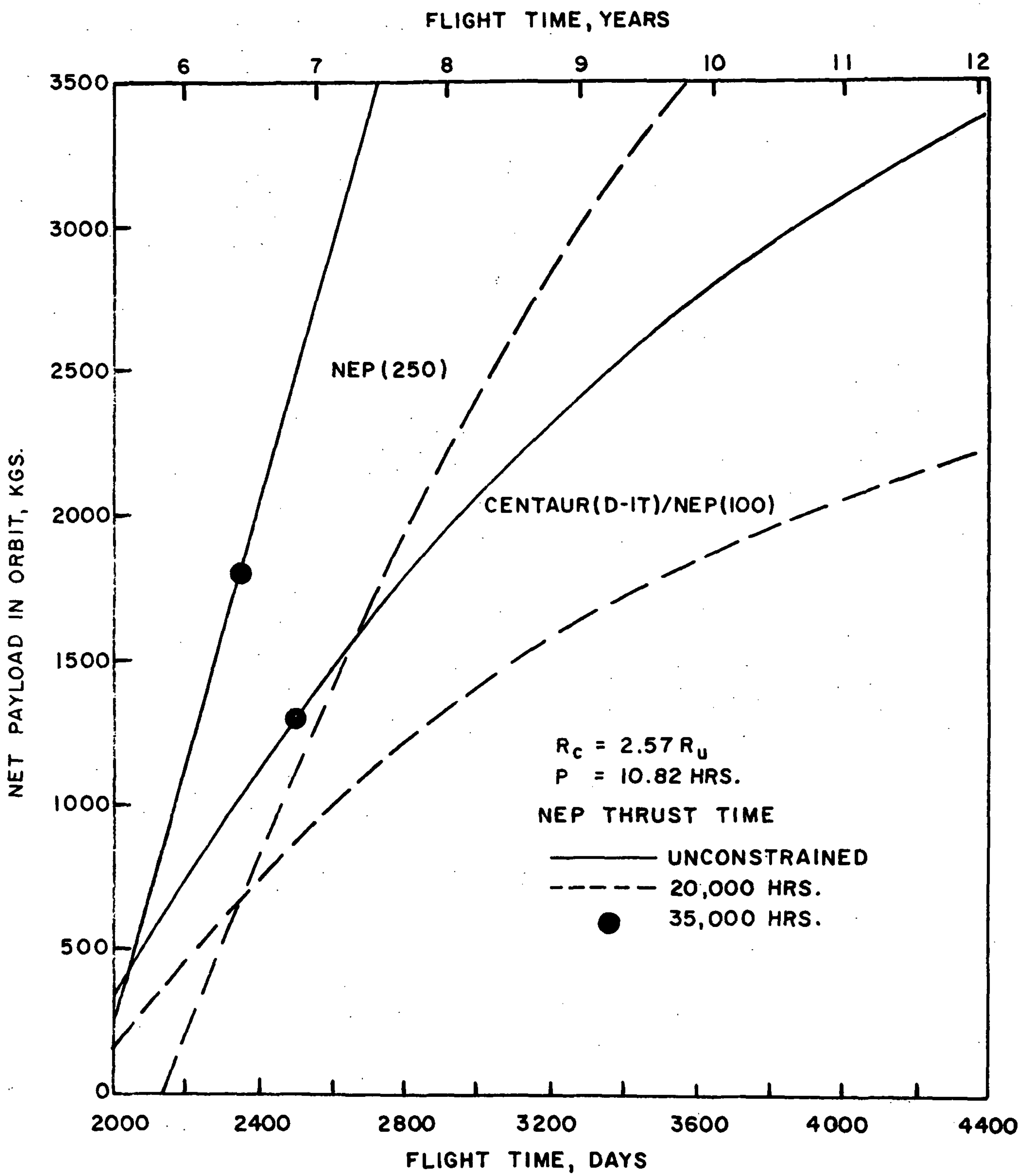

FIGURE 13. URANUS ORBITER, SYNCHRONOUS ORBIT

2.2.4 Neptune Missions

Figure 14 and Figure 15 present performance data for Neptune orbiter missions in the 1990[1] launch opportunity.

Payload versus flight time curves are shown for a 30-day orbiter mission in Figure 14. The Centaur(GT)/Centaur(GT)/VUS combination stage is used for ballistic comparison. The NEP systems are assumed jettisoned prior to orbit insertion and a space storable chemical system is used for orbit capture.

Figure 15 shows NEP performance for a synchronous orbiter mission at Neptune. Note that the 250 kw NEP system is incapable of performing this mission when the thrust time is constrained to 20,000 hours. This is because the constrained thrust-time acceleration level for this system is insufficient to perform the mission at even the longest flight times.

The NEP flight times for both Neptune orbiter missions are probably somewhat conservative due to the nature of the QUICKLY program.

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1. Refers to ballistic opportunity.

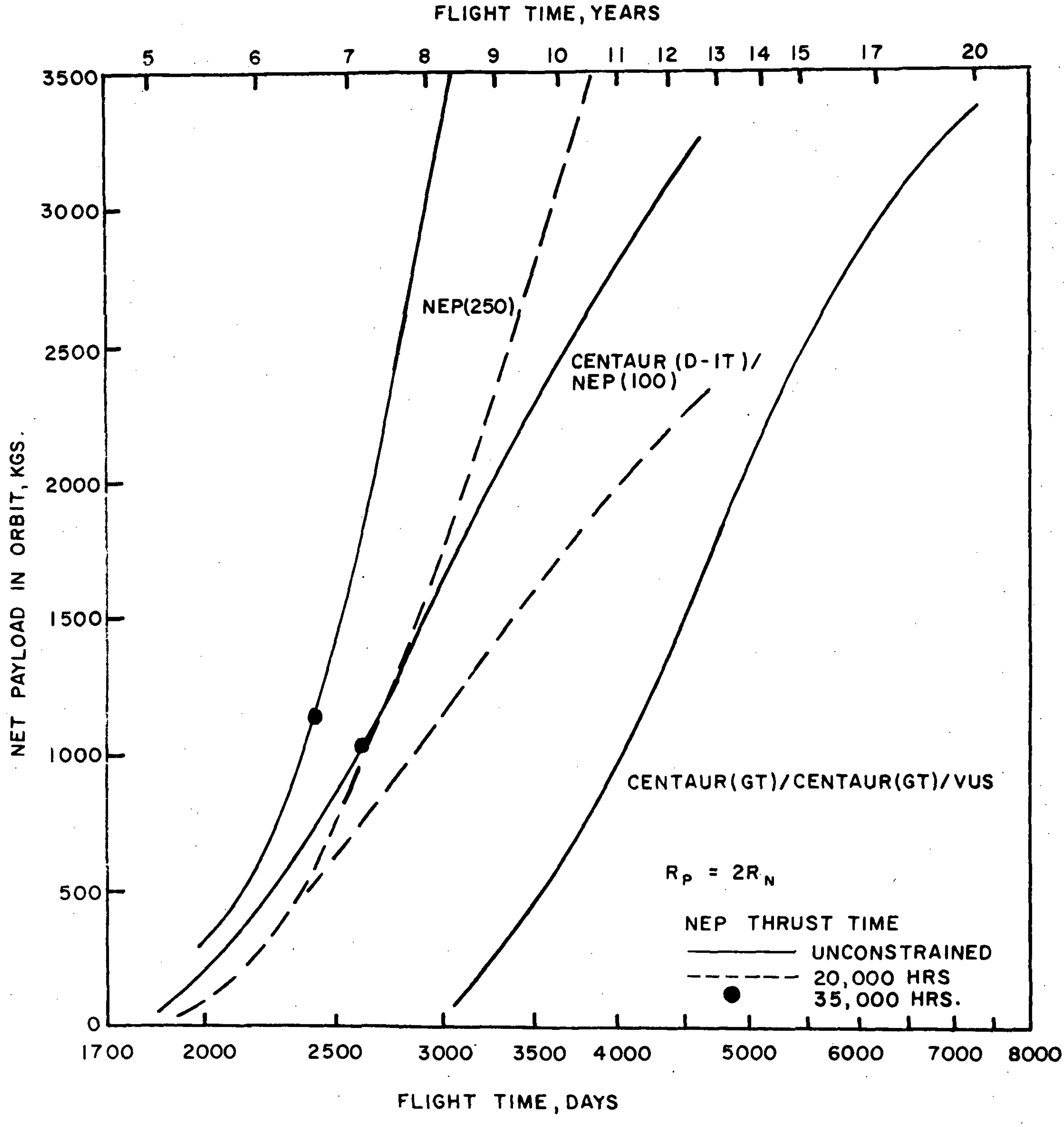


FIGURE 14. NEPTUNE ORBITER, 30-DAY ORBIT

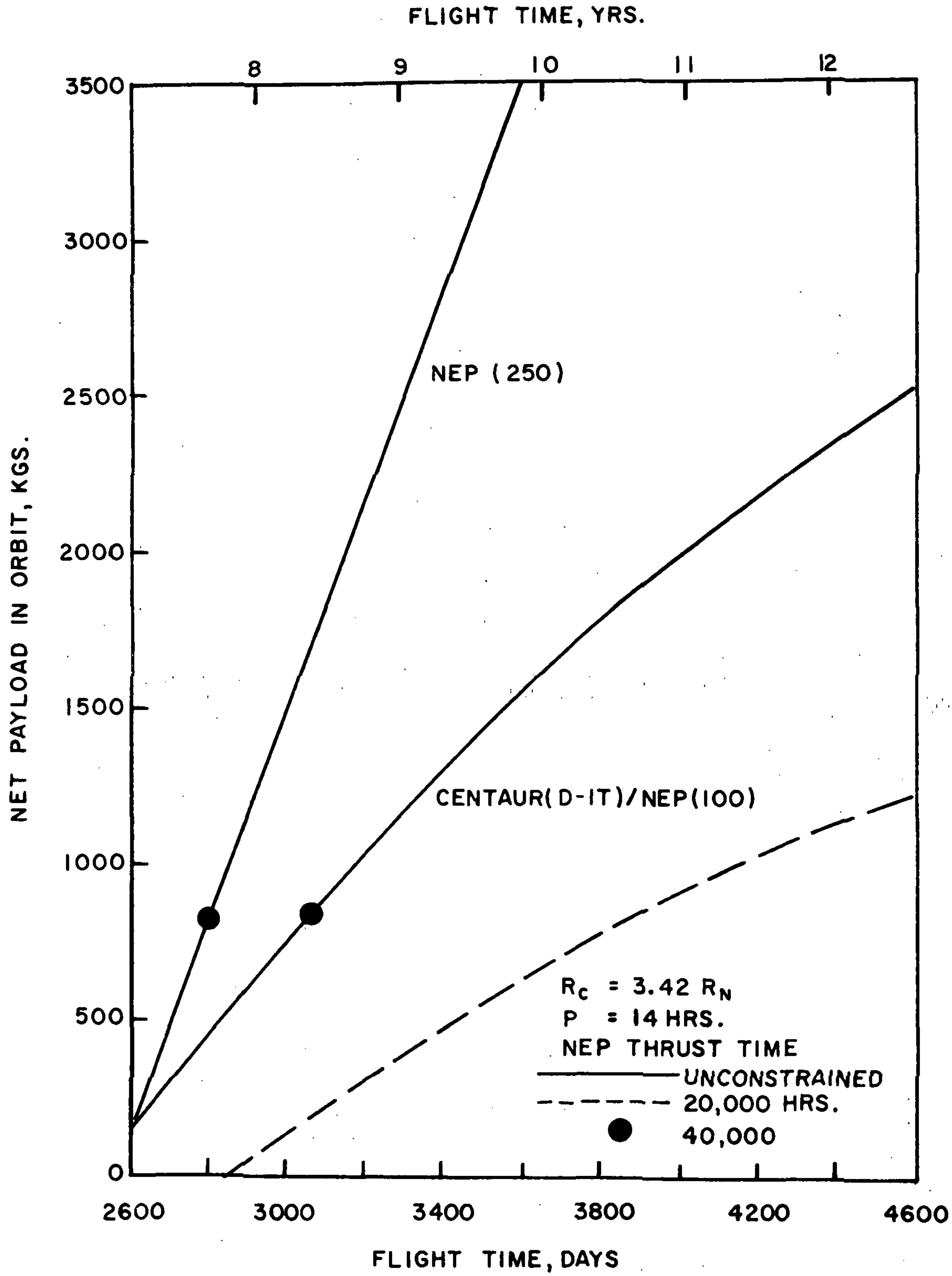


FIGURE 15. NEPTUNE ORBITER, SYNCHRONOUS ORBIT

2.2.5 S-U-N Multi-Planet Flyby

Figure 16 presents performance data for a multiple planet flyby mission, or grand tour, to Saturn, Uranus and finally Neptune in the 1984 launch opportunity. Only the 100 kw NEP system was examined for this mission, and is used only for the Earth to Saturn leg of the mission. Upon thrust cut-off at Saturn, the nuclear electric system can either be jettisoned or carried along as the net spacecraft power supply. Flight times to Saturn range from 800 days to 1500 days and the corresponding NEP thrust times range from ~ 10,000 hours to ~ 13,000 hours. Chemical ballistic system performance is shown for both the Centaur(GT)/Kick and Centaur(GT)/VUS.

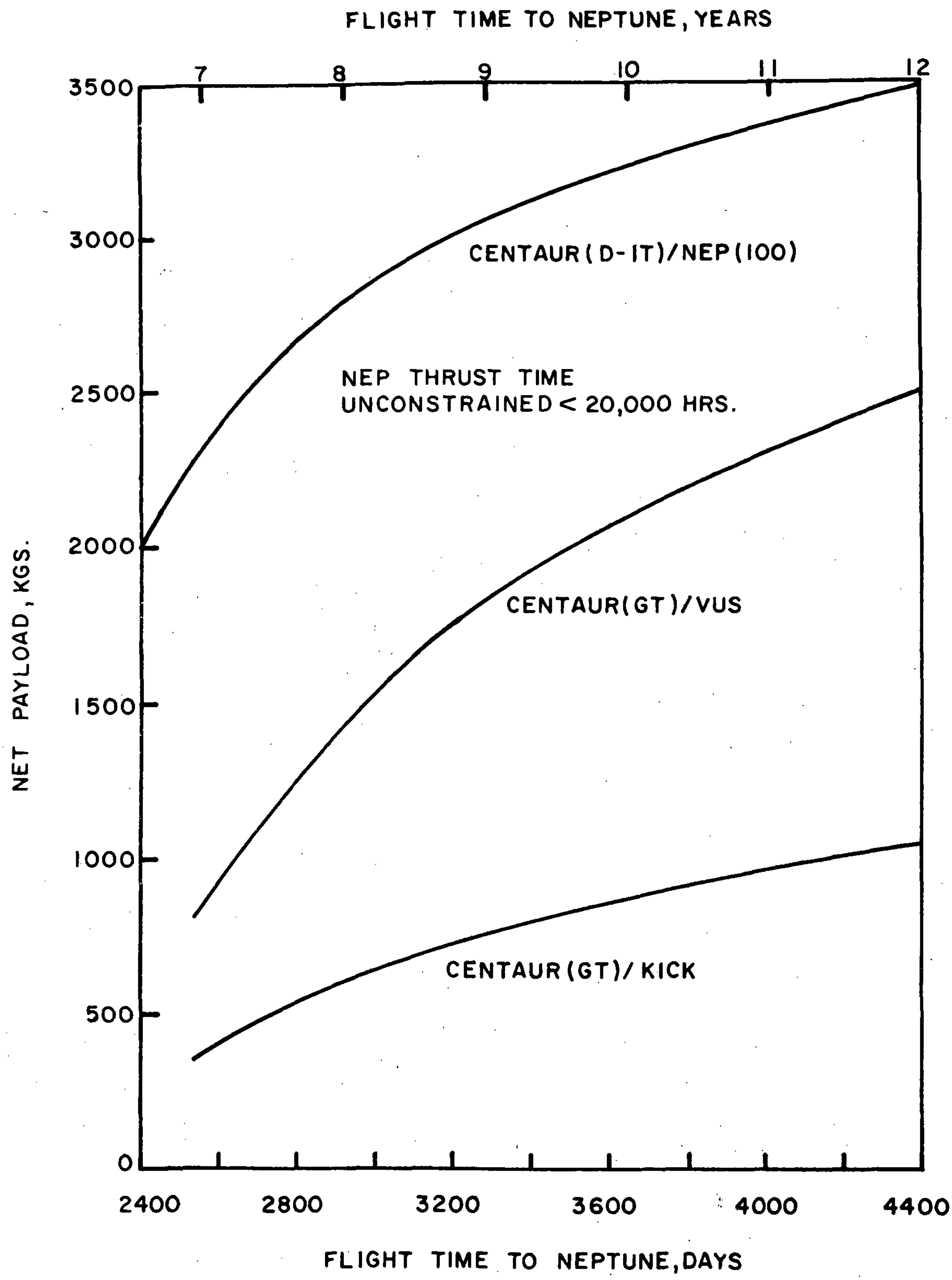


FIGURE 16. SATURN-URANUS-NEPTUNE GRAND TOUR

2.2.6 Halley Rendezvous

Figure 17 presents a nuclear electric low thrust trajectory for a rendezvous mission to Halley's Comet. The flight time for this mission is 950 days with a launch in May 1983 and rendezvous with Halley 50 days before the comet's perihelion date. Because of the comet's retrograde motion, the spacecraft, launched in a posigrade direction, must reverse its motion. As can be seen in Figure 17, the optimum location for doing this is as far out in the solar system as possible where the sun's gravitational force is lessened, while maintaining the required flight time.

Figure 18 presents NEP performance data for a 950 day Halley rendezvous mission. Note that since only one flight time is examined for this mission, net payload is shown as a function of specific impulse. NEP thrust times are indicated on the payload curves and the functional dependence between I_{sp} and thrust time can be observed. Parametric curves of launch velocity (VHL) are presented for the 100 kw NEP system, showing the trade-off which occurs between the Centaur(D-1T) and the NEP system. As the launch energy requirement increases, the injection stage must do more work, thus decreasing its injected payload capability (see Figure 3). At the same time, as VHL increases, the low thrust trajectory energy requirement is decreasing, which means, for a particular value of I_{sp}, that the low thrust propellant requirement is decreasing. But initial mass is decreasing faster than propellant mass, leading to decreasing net payload. The end points to the right of the constant VHL curves are points beyond which there is insufficient thrust acceleration to perform the mission.

Gravity assisted ballistic rendezvous trajectories to Halley using either Jupiter or Saturn swingby (Friedlander, Niehoff and Waters, 1970) were examined, but are beyond the capability of the Centaur (GT)/Centaur(GT)/VUS combination stage.

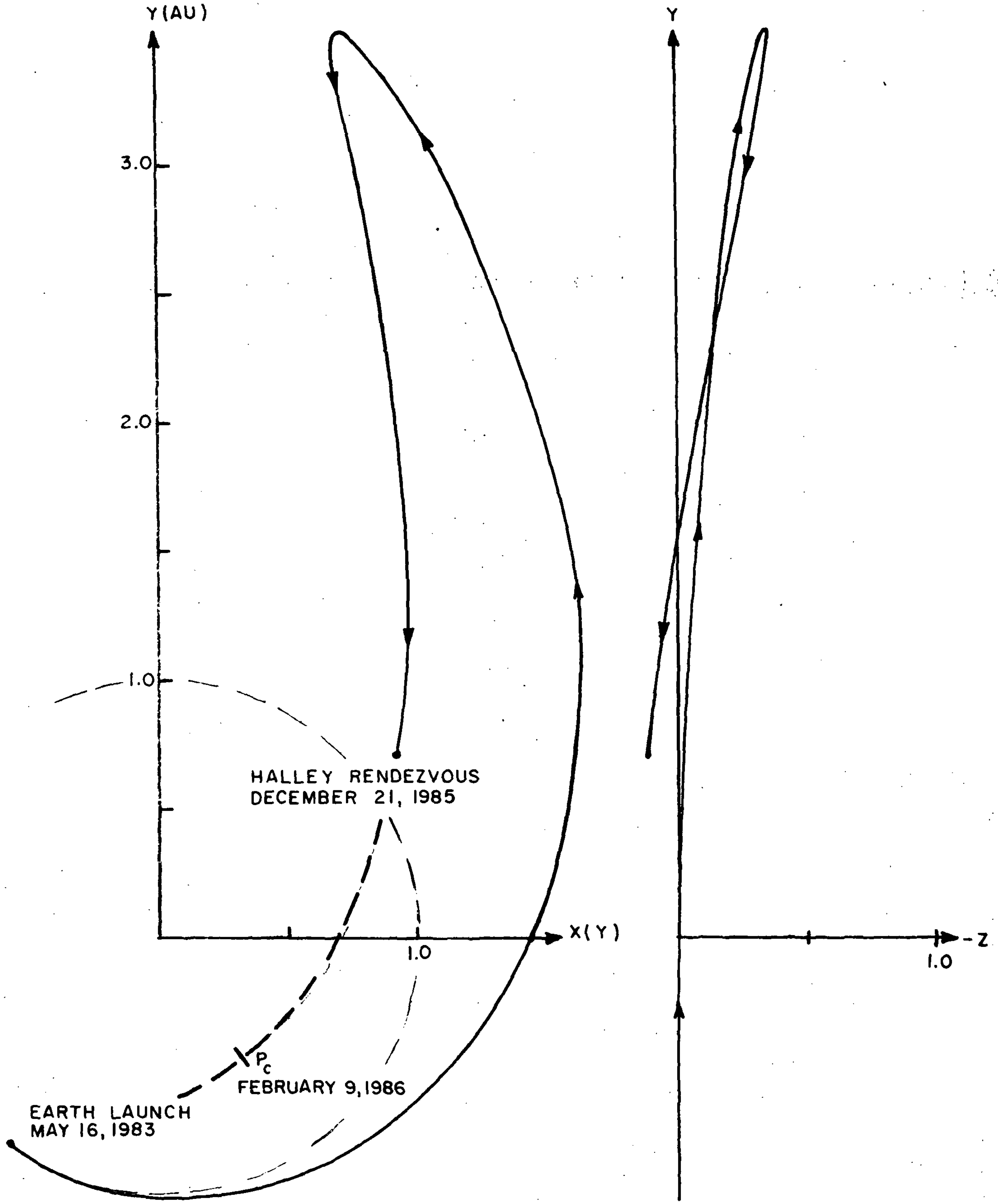


FIGURE 17. 950 DAY HALLEY RENDEZVOUS NEP LOW THRUST TRAJECTORY

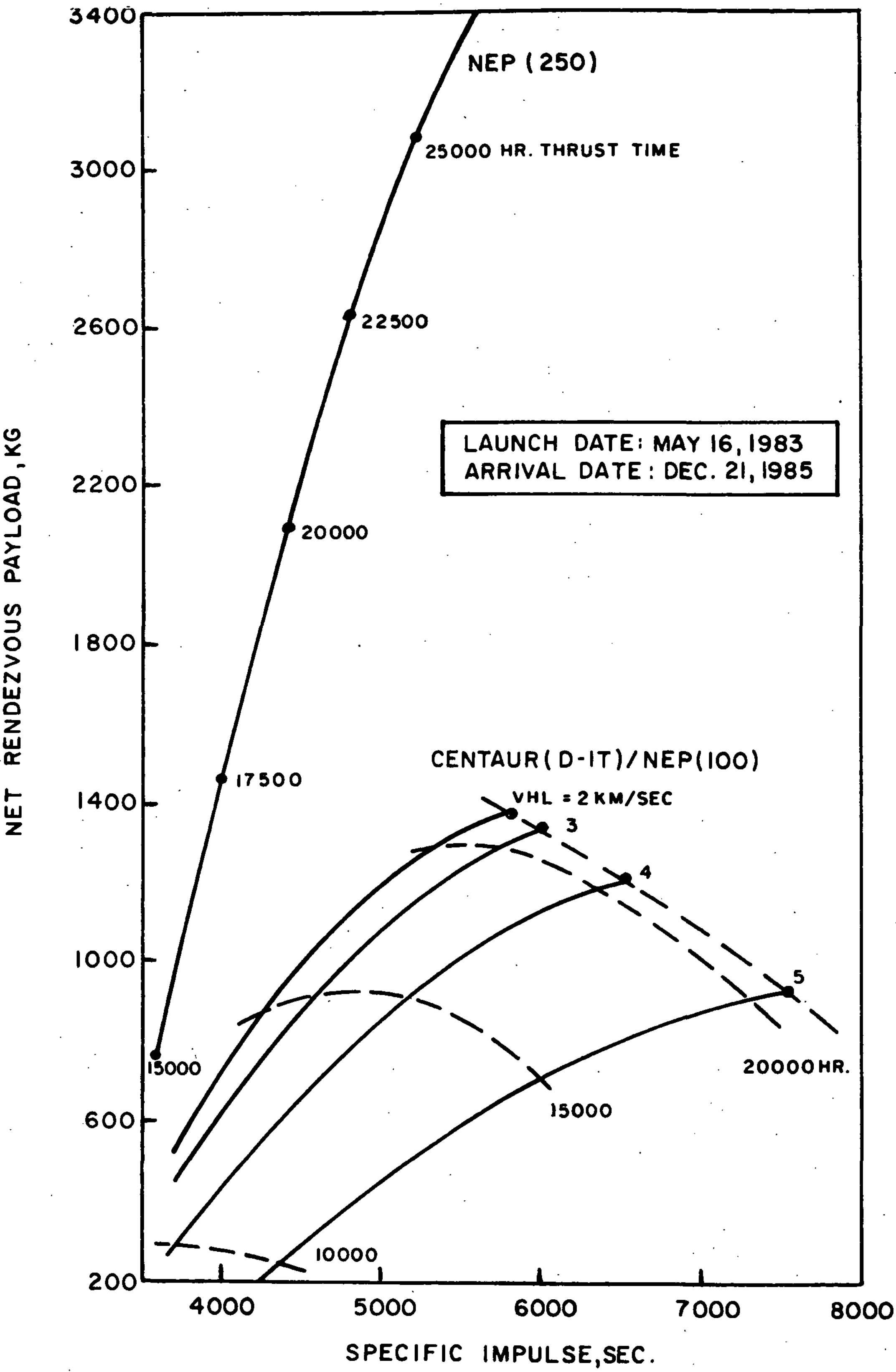


FIGURE 18. 950 DAY HALLEY RENDEZVOUS

2.2.7 Ceres Sample Return

The final mission selected for nuclear electric propulsion performance analysis is a sample return to the asteroid Ceres, launched in 1988. Results show that a 100 kw NEP system is more than adequate to perform this mission.

The method of analysis was to generate optimum Earth to Ceres and Ceres to Earth low thrust trajectories and select a representative outbound-inbound combination. Figure 19 presents a countour map of constant low thrust energy parameter, J_{VT}. The velocities indicated are nearly optimum for the Centaur(D-1T)/NEP(100) system. An example of the outbound-inbound trajectory selection procedure is shown on the figure: a 600 day Earth to Ceres trajectory, 100 day stay time, and 550 day Ceres to Earth transfer for a total mission time of 1250 days. Figure 20 presents a heliocentric plot of this trajectory combination.

The 100 kw NEP system is used for spiral capture into and spiral escape from a 100 kilometer altitude orbit at Ceres, and spiral capture into a 500 km (270 n.mi.) orbit at Earth return. The spiral operations at Ceres require on the order of 10 days each to perform, reducing the effective stay time at Ceres to about 80 days. (Spiral capture time at Earth from VHP = 3 km/sec to circular orbit requires from 120 days to 180 days, depending on the NEP acceleration level. It is not included in the 1250 day mission time but must be added to it).

Figure 21 presents sample return module and lander weights as a function of sample size following the analysis of Mars surface sample return missions by Spadoni and Friedlander (1971). The descent and ascent propulsion stages use Earth storable propellants and are sized for descent from and return to a 100 km orbit about Ceres.

A 450 kg interplanetary cruise module/orbiter bus was assumed for the parent spacecraft (excluding the NEP system). A film return system using a 5 inch aerial reconnaissance camera was sized to provide 100% mapping of the surface of Ceres at 1 meter resolution from 100 km altitude (Klopp, 1969). The total film system adds 212 kgs to the cruise module/orbiter bus.

Figure 22 presents results for a 1250 day sample and film return mission to Ceres. The specific impulse of the 100 kw NEP system was fixed at 5000 sec. for this mission. The format of the data is such that the necessary injected payload at Earth can be determined as a function of desired sample size, or amount of returned sample can be determined for a given injected payload weight within the ranges indicated. Film return is considered a baseline mission independent of sample size. The initial payload to perform a film return only is approximately 6400 kgs (off scale). Payload capability is such that either one or two lander systems can be employed. The sample mission shown requires a total of 60 kgs of sample from two landing sites (30 kgs each). Using the curves labeled "two landers", the required Earth departure weight is ~ 8300 kgs. This would require off-loading the Centaur(D-1T) stage for a launch velocity of 2 km/sec.

An optimized multi-impulse ballistic trajectory (Figure 23) was examined for a Ceres sample return. Total mission time is 1150 days with a 30 day stay time at Ceres. The Centaur(GT)/Centaur (GT)/VUS does not have the capability to perform this mission. A ballistic sample return mission to Ceres may possibly be performed by using the dual (or tandem) launch as discussed by Spadoni and Friedlander, but that mode is not examined here.

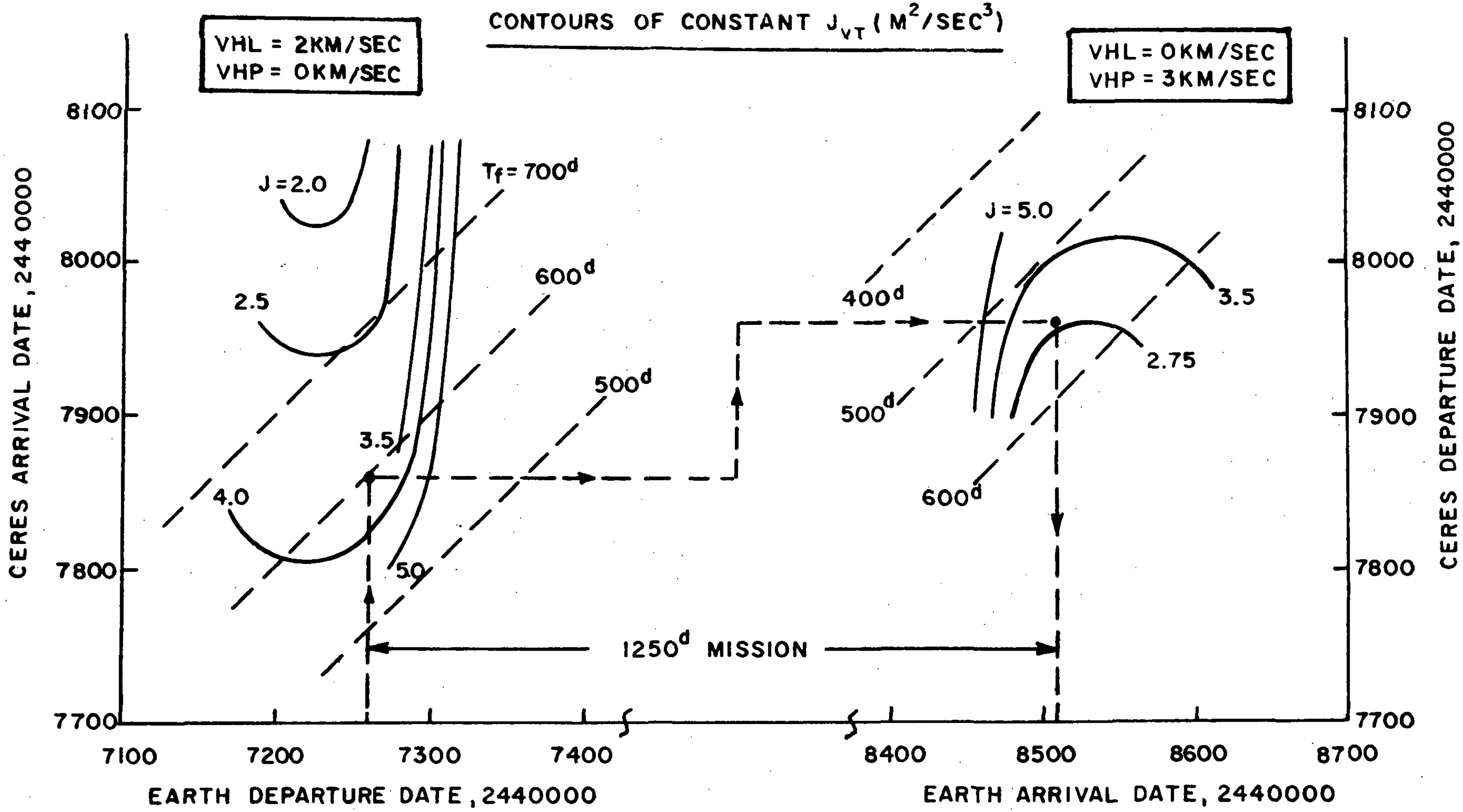
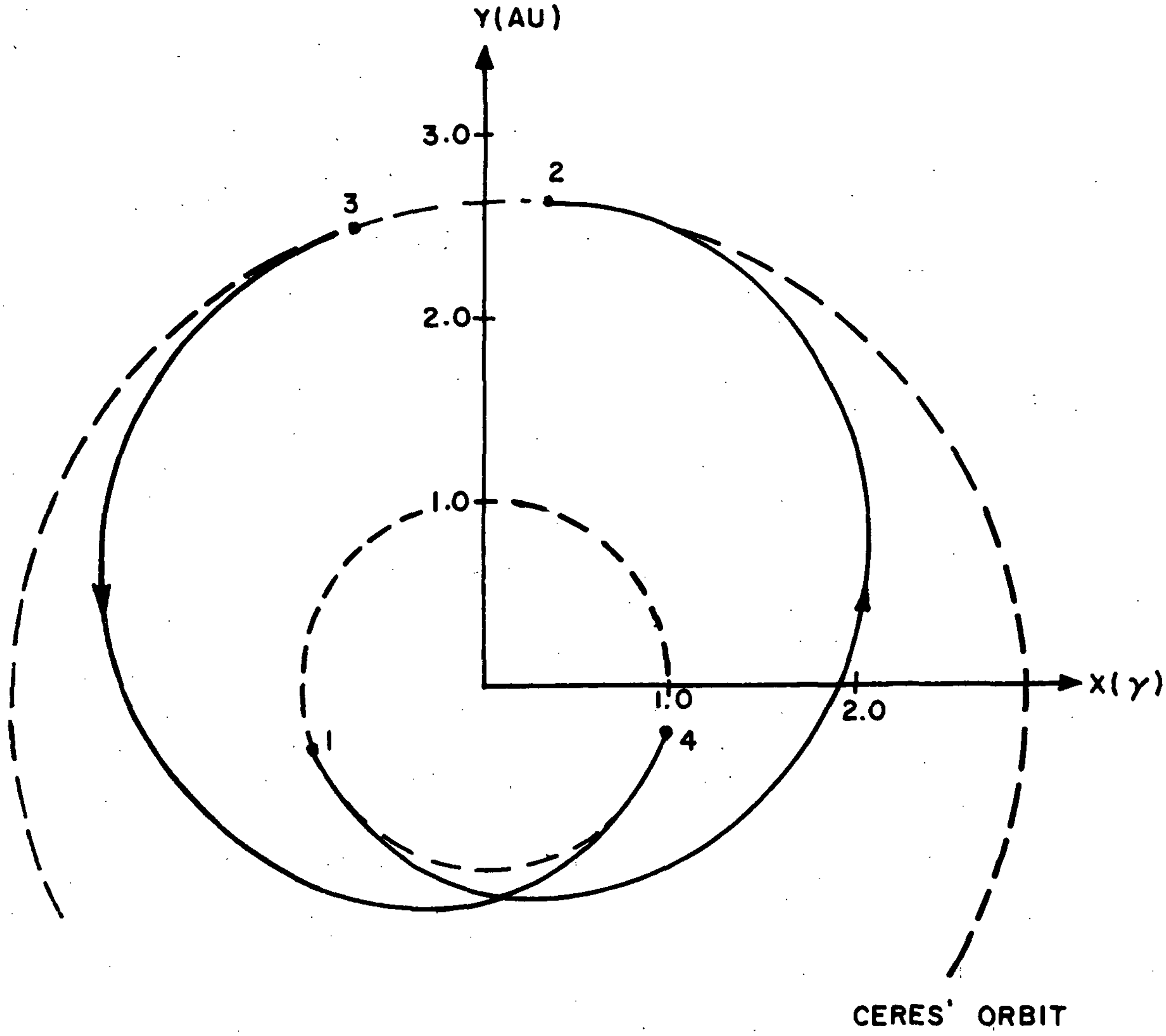


FIGURE 19. NUCLEAR ELECTRIC TRAJECTORY REQUIREMENTS FOR CERES SAMPLE RETURN MISSION, 1988 OPPORTUNITY.



CONDITION		DATE
1	EARTH LAUNCH	APRIL 9, 1988
2	CERES ARRIVAL	NOVEMBER 30, 1989
3	CERES DEPARTURE	MARCH 10, 1990
4	EARTH ARRIVAL	SEPTEMBER 11, 1991

FIGURE 20. CERES SAMPLE RETURN NEP LOW THRUST TRAJECTORY

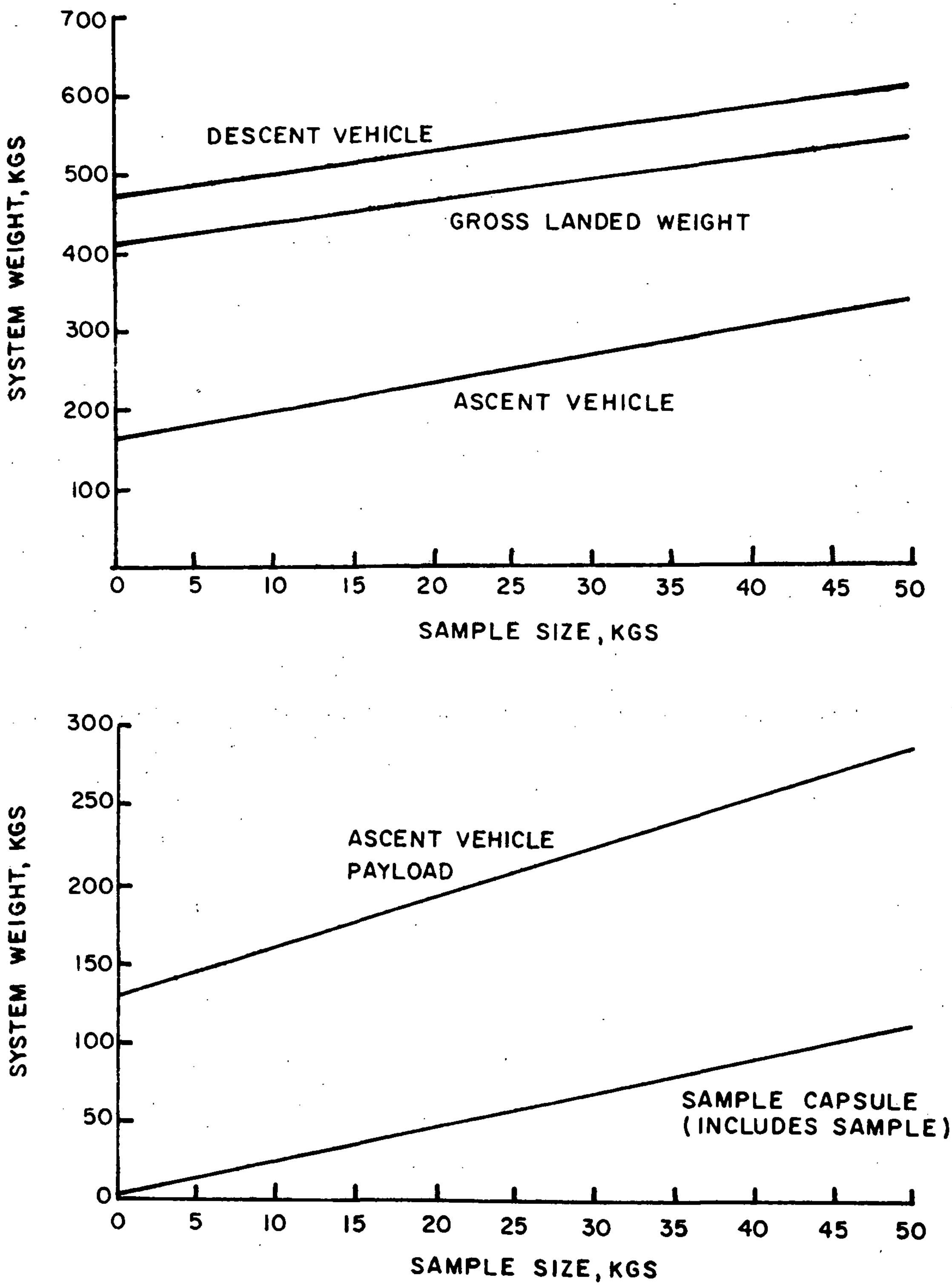


FIGURE 21. SCALING FOR CERES SAMPLE RETURN MODULE

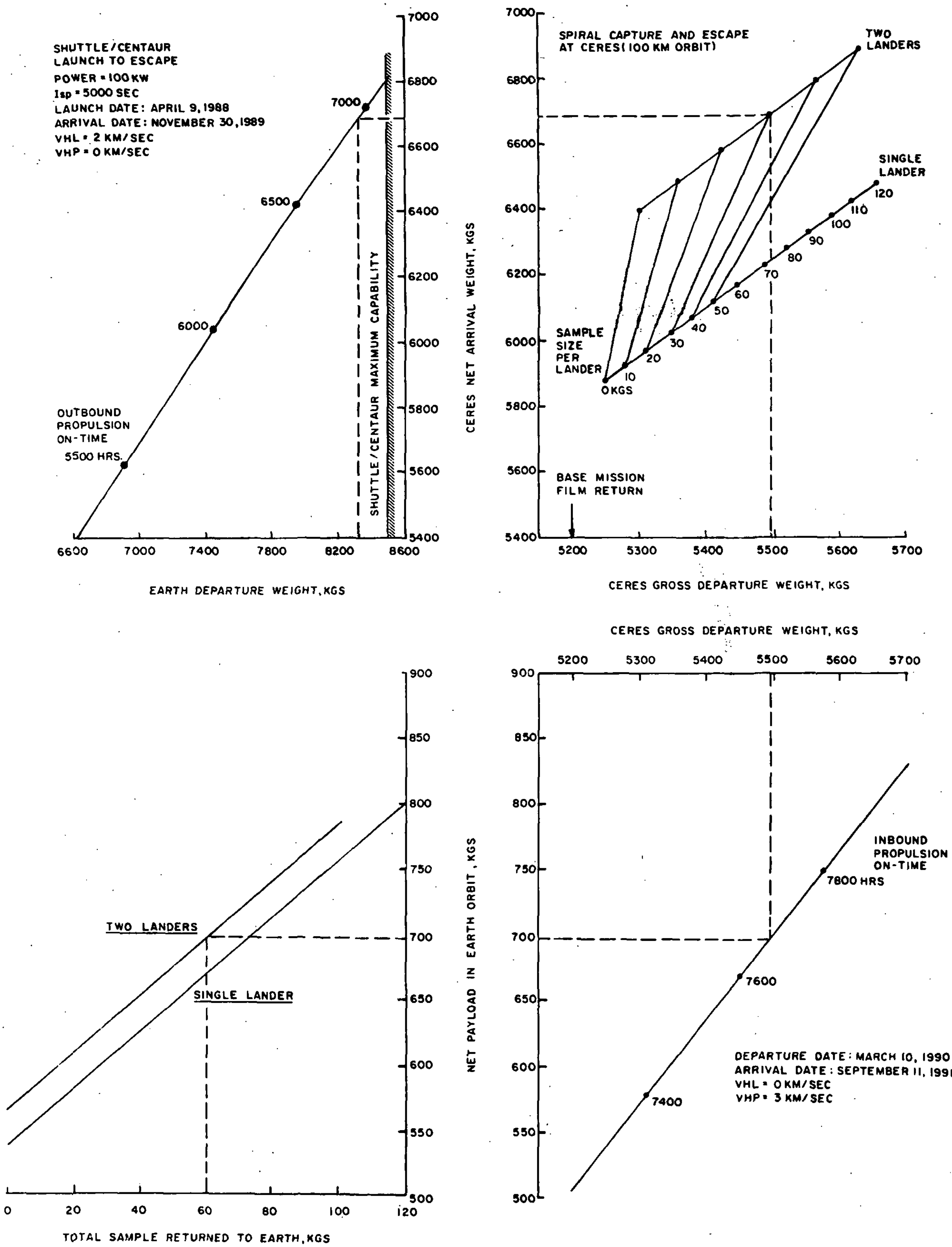
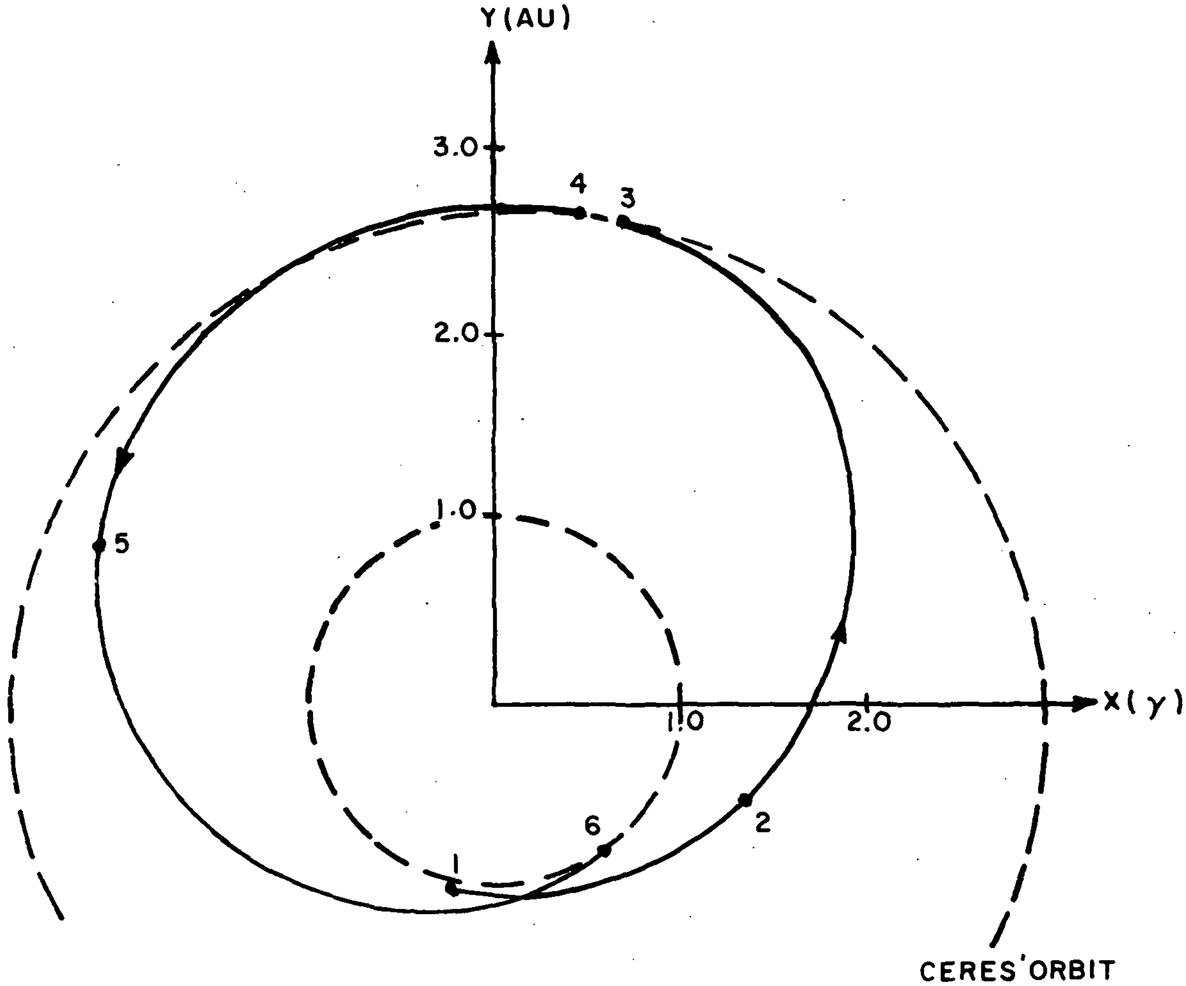


FIGURE 22. 1250-DAY CERES SAMPLE RETURN, 100 KW NEP PERFORMANCE



IMPULSE NUMBER	ΔV, KM/SEC	CONDITION	DATE
1.	5.03	EARTH LAUNCH	FEBRUARY 29, 1988
2.	0.30	OUTBOUND MIDCOURSE	SEPTEMBER 7, 1988
3.	4.89	CERES ARRIVAL	OCTOBER 8, 1989
4.	3.94	CERES DEPARTURE	NOVEMBER 7, 1989
5.	3.24	INBOUND MIDCOURSE	OCTOBER 11, 1991
6.	4.68	EARTH ARRIVAL	AUGUST 2, 1991

FIGURE 23. CERES SAMPLE RETURN MULTI-IMPULSE BALLISTIC TRAJECTORY

3. CONCLUSIONS

Nuclear electric propulsion has been shown to be a viable concept for performing advanced unmanned missions requiring high expenditures of energy. NEP can be used to effectively reduce launch system requirements at Earth and/or significantly reduce or completely eliminate chemical retro propulsion requirements at the target.

The in-core thermionic reactor, internally fueled, is the only on-going development program at the present time. Development efforts indicate that such a system, capable of 20,000 hours operating thrust time, could be available not later than late 1983 and sooner if thrust time constraints are lessened (e.g., 10,000 hours).

NEP, in the 100 kw to 250 kw power range, can perform certain missions such as planetary orbiters in close circular orbits, Halley rendezvous and Ceres sample return, which are beyond the capability of advanced Centaur/VUS class chemical injection stages. For those missions which the chemical systems are capable of performing, flight times can be reduced by as much as 30% for a 100 kw NEP and 50% for a 250 kw NEP for a given payload.

Summary results, in the form of flight times to deliver a 1000 kg net payload (except where noted) for each of the missions previously discussed, are shown in Table 3. For short flight time missions requiring only a modest propulsion expenditure at the target, the various propulsion systems can be seen to have comparable performance. The chemical systems are not capable of performing those missions which require high launch energies and/or relatively large propulsion expenditures at the target. Also, for these types of missions, the 250 kw NEP can be seen to modestly out-perform (for the payloads indicated) the 100 kw NEP.

TABLE 3 PROPULSION SYSTEM-FLIGHT TIME COMPARISONS

TARGET	MISSION TYPE	NET PAYLOAD (KGS)	FLIGHT TIME (DAYS)[2] NEP (100)[3]	NEP (250)[3]	CHEMICAL
JUPITER	30-DAY ORBITER	1000	450	500	545
	SYNCHRONOUS ORBITER	1000	1520	1350	-
CALLISTO	ORBITER/LANDER	1740[1]	910	870	1000
IO	ORBITER/LANDER	1830[1]	1460	1145	-
SATURN	30-DAY ORBITER	1000	940	950	1130
	RING ORBITER	1000	1640	1570	-
TITAN	ORBITER/LANDER	1890[1]	1660	1400	1660
URANUS	30-DAY ORBITER	1000	1850	1725	2440
	SYNCHRONOUS ORBITER	1000	2600	2460	-
NEPTUNE	30-DAY ORBITER	1000	2850	2630	4075
	SYNCHRONOUS ORBITER	1000	4140	-	-
S-U-N	MULTI-PLANET FLYBY	1000	< 2400	NA	2640
HALLEY	RENDEZVOUS	1000	950	950	-
CERES	SAMPLE RETURN	NA	1250	NA	-

1. MINIMUM REQUIRED PAYLOAD IN SATELLITE ORBIT RECOMMENDED BY PRICE AND SPADONI (1970).
2. - INDICATES SYSTEM NOT CAPABLE OF PERFORMING MISSION.
   NA INDICATES SYSTEM NOT APPLIED TO MISSION.
3. RESULTS SHOWN ARE FOR CONSTRAINED THRUST TIME (20000 HR MAXIMUM).

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