Report No. M-19

PRELIMINARY FEASIBILITY STUDY OF SOFT-LANDER MISSIONS TO THE GALILEAN SATELLITES OF JUPITER

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by

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SUMMARY

A preliminary study has been made of the scientific objectives and technical feasibility of soft-landing spacecraft of 1000 lbs. useful payload on each of the Galilean satellites of Jupiter.

The major scientific objectives of such missions would be:

1. To develop a much-needed link between studies of the Inner and Outer planetary groups by comparing the physical properties of the satellites with those of the smaller planets.
2. To obtain data essential for studies of;
   (a) the mode of formation of the smaller planetary bodies in the solar system.
   (b) the origin of satellite systems.
   (c) the origin of the solar system itself.

A further objective would be to use the satellites as bases for the remote observation of the Jovian cloud layer. Advantages of such bases would be:

1. The stability of the observation platform.
2. The proximity to the planet.
3. The expected long lifetime of the electronic components of the remote sensing instruments, because all the satellites revolve well-outside the most intense regions of the Jovian radiation belts.

Consideration of the use of the satellites as bases for the measurement of the physical properties of the Jovian magnetosphere produced a negative conclusion.

For trajectory and payload analysis, the mission was separated into four distinct phases, and various propulsion/propellant system combinations were studied. The breakdown was:

1. Launch and Earth-escape, using chemical, chemical-

nuclear, or chemical-nuclear-electric propulsion.

2. Interplanetary trajectory, using either ballistic or low thrust (solar-electric or nuclear-electric) propulsion.
3. Satellite capture maneuver using chemical, cryogenic, or nuclear rocket propulsion.
4. Terminal descent maneuver using variable thrust chemical propulsion.

Results indicate that missions to Callisto are possible using as the launch vehicle either the SIC/SIVB/Centaur or the Titan 3F/Solar-Electric systems, together with a space-storable chemical retro-maneuver for satellite capture. Ganymede and Europa are also accessible if the Saturn V and Saturn V/Centaur launch vehicles are used, respectively. If a cryogenic or nuclear propulsion system is available for the retro-maneuver then Io becomes accessible also. All four satellites become accessible with a Titan 3F-Nuclear-Electric launch vehicle and a solid chemical retro-maneuver.

Callisto, Europa and Ganymede are accessible using a solar-electric low thrust flight mode for interplanetary transfer and the SIC/SIVB/Centaur as a launch vehicle. Io is not accessible, however.

With each of these flight mode/propulsion system combinations questions of feasibility do remain, however, concerning such items as large two-stage retro-maneuvers, direct satellite approach, long periods of hibernation of propellants in space, and the development of the more advanced propulsion systems.

If flight times of 2½ to 3½ years can be tolerated the ideal flight mode/propulsion system for these missions would appear to be low-thrust/nuclear-electric. Missions to all four of the satellites then become possible, the direct approach to the satellite can be replaced by a simpler spiral interception of the satellite orbit together with a single stage retro-maneuver, and the smaller Titan 3F rocket can be used to launch the required nuclear-electric spacecraft.

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1. INTRODUCTION

The objectives of this study were:

1. To determine the scientific objectives of soft landing unmanned spacecraft on the four Galilean satellites of Jupiter.
2. To determine the technical feasibility of such missions assuming the existence of a variety of advanced propulsion systems for the interplanetary spacecraft. The systems considered were space-storable chemical, cryogenic, nuclear, solar-electric, and nuclear-electric. Presently available interplanetary launch vehicles (Titan 3F, Intermediate Saturn, and Saturn V) were considered for the missions.

It was assumed throughout this study that a thorough reconnaissance of the surfaces of the satellites will have been completed by fly-by spacecraft or satellite orbiters before soft-landing missions are attempted.

For soft-lander missions to be scientifically rewarding it would be highly desirable for substantial useful payloads to be deposited on the surface of the satellites. For the purpose of this preliminary study minimum useful payloads of 1000 lbs. were assumed. Useful payload in this context means the weight available for scientific instrumentation, telemetry equipment, and power supplies. With 1000 lbs. available a broad range of experiments could be performed by each spacecraft, broader in fact than that performed by Surveyor on the Moon.

The scientific objectives associated with these missions are reviewed in Section 2, while their technical feasibility is discussed in Section 3. The conclusions of the study are contained in Section 4.

2. SCIENTIFIC OBJECTIVES

The scientific objectives associated with the soft-landing of spacecraft on the four Galilean satellites of Jupiter may be grouped in three broad areas of investigation:

1. The study of the physical properties of each satellite, treating it as an individual, and distinct, planetary body.
2. The use of each satellite as a base for remote observation of Jupiter.
3. The use of each satellite as a base for measurement of the physical properties of the Jovian magnetosphere.

2.1 The Galilean Satellites as Individual Planetary Bodies

The basic physical parameters of the satellites are listed in Table I. The masses are taken from a review by Brouwer and Clemence (1961). The radii, taken from Price (1970), were obtained from a thorough review of all observed values. The tabulated mean densities have been calculated using these data.

The physical parameters of the satellites may be compared with those of the Moon and the two smallest Inner planets, Mercury and Mars, listed in Table II. These data are taken from Allen (1963).

A review of the data presented in Tables I and II leads to the following conclusions:

1. Each of the four satellites is of sufficient size and mass that it may be considered as a distinct planetary body in its own right.
2. Europa, the smallest satellite, is smaller and less massive than the Moon, but has very nearly the same density.
3. Io, the second smallest satellite, and the Moon are almost identical twins in both size and mass.

TABLE I

GALILEAN SATELLITES: BASIC PHYSICAL PARAMETERS

Satellite Number	I	II	III	IV
Satellite Name	Io	Europa	Ganymede	Callisto
Mass (in 10^{25}g)	7.22 ± 0.57	4.70 ± 0.09	15.45 ± 0.19	9.64 ± 0.76
Radius (in km)	1800 ± 163	1549 ± 98	2621 ± 367	2389 ± 389
Mean Density (in g/cc)	3.0	3.0	2.1	1.7
Escape Velocity (km/sec)	2.33	2.01	2.80	2.32

TABLE II

MOON, MERCURY AND MARS: BASIC PHYSICAL PARAMETERS

Celestial Body	Moon	Mercury	Mars
Mass (in 10^{25}g)	7.35	31.68	63.95
Radius (in km)	1738	2420	3400
Mean Density (in g/cc)	3.343	5.3	3.95
Escape Velocity (km/sec)	2.38	4.2	5.0

Consequently, their mean densities are nearly equal.

4. Callisto, the second largest satellite, is nearly as large as Mercury but with only one-third its mass. Its mean density is only one-half that of the Moon.
5. Ganymede, the largest satellite, is slightly bigger than Mercury, but with only one-half its mass. Its mean density, while being larger than that of Callisto, is much less than that of the Moon.
6. The mean densities of the satellites decrease with increasing distance from Jupiter.

On the basis of these conclusions, Io and Europa are probably rocky bodies similar to the Moon. On the other hand, because of their much lower densities, Ganymede and Callisto are probably very different from the Moon, being composed of a mixture of rock and ice. Studies of the composition and internal structure of the Galilean satellites will provide data essential for studies of both the mode of formation of the smaller planetary bodies in the solar system and the origin of satellite systems. Comparison of their physical properties with those of the Moon and smaller planets may well provide a link between studies of the Inner and Outer planetary groups.

Information on the physical properties of the satellites may be obtained most effectively by soft-landing instruments at strategically located points on their surfaces. To make the most effective use of each lander the following instrumentation should be on board:

1. Soil sampler: to determine surface composition, electrical and thermal conductivities.
2. Seismometer: to study the internal structure of the satellite.

3. Magnetometer: to determine the strength of the intrinsic magnetic field of the satellite.
4. Thermal flow meter: to study the internal properties of the satellite.
5. Atmospheric monitor: to study the composition, pressure and temperature of any atmospheres surrounding the satellites. Such atmospheres would be very tenuous, since none has yet been detected by astronomical spectroscopy.
6. TV system: for imaging of the surface environment in the vicinity of the landing point.

2.2 Observation of Jupiter from the Surfaces of the Satellites

The surfaces of the Galilean satellites provide extremely stable platforms from which remote observations of Jupiter could be made. To study the usefulness of the satellites in this regard a review of their orbital parameters is relevant. These parameters are listed in Table III. These data have been taken from Allen (1963) and Melbourne et al (1968). The relative dimensions of the orbits of the satellites with respect to Jupiter are shown in Fig. 1.

Strong evidence indicates that the periods of rotation of the satellites are equal to their periods of revolution. The main evidence comes from the published work on the variation in the brightness of each satellite with position in its orbit, reviewed by Harris (1961). Additional evidence is provided by visual observations of surface markings on the satellites, reviewed by Dollfus (1961). The latter observations indicate that for each satellite its axis of rotation is very nearly perpandicular to the plane of its orbit. The equality in the periods of rotation and revolution is not unexpected. The tidal influence of Jupiter should produce just such an effect.

Since the periods of rotation and revolution of the satellites are apparently equal, and their orbits are very nearly

TABLE III

GALILEAN SATELLITES: ORBITAL PARAMETERS

Satellite Number	I	II	III	IV
Satellite Name	Io	Europa	Ganymede	Callisto
Semi-major axis of orbit (in 10^6kms)	0.422	0.671	1.070	1.883
Semi-major axis of orbit (in Jovian Eq. Radii)	5.9	9.4	15.0	26.4
Eccentricity of orbit	~0	0.0003	0.0015	0.0075
Inclination of plane of orbit to Jovian Equatorial plane (in degrees)	~0	~0	~0	~0
Sidereal Period of Revolution (in days)	1.769138	3.551181	7.154553	16.689018

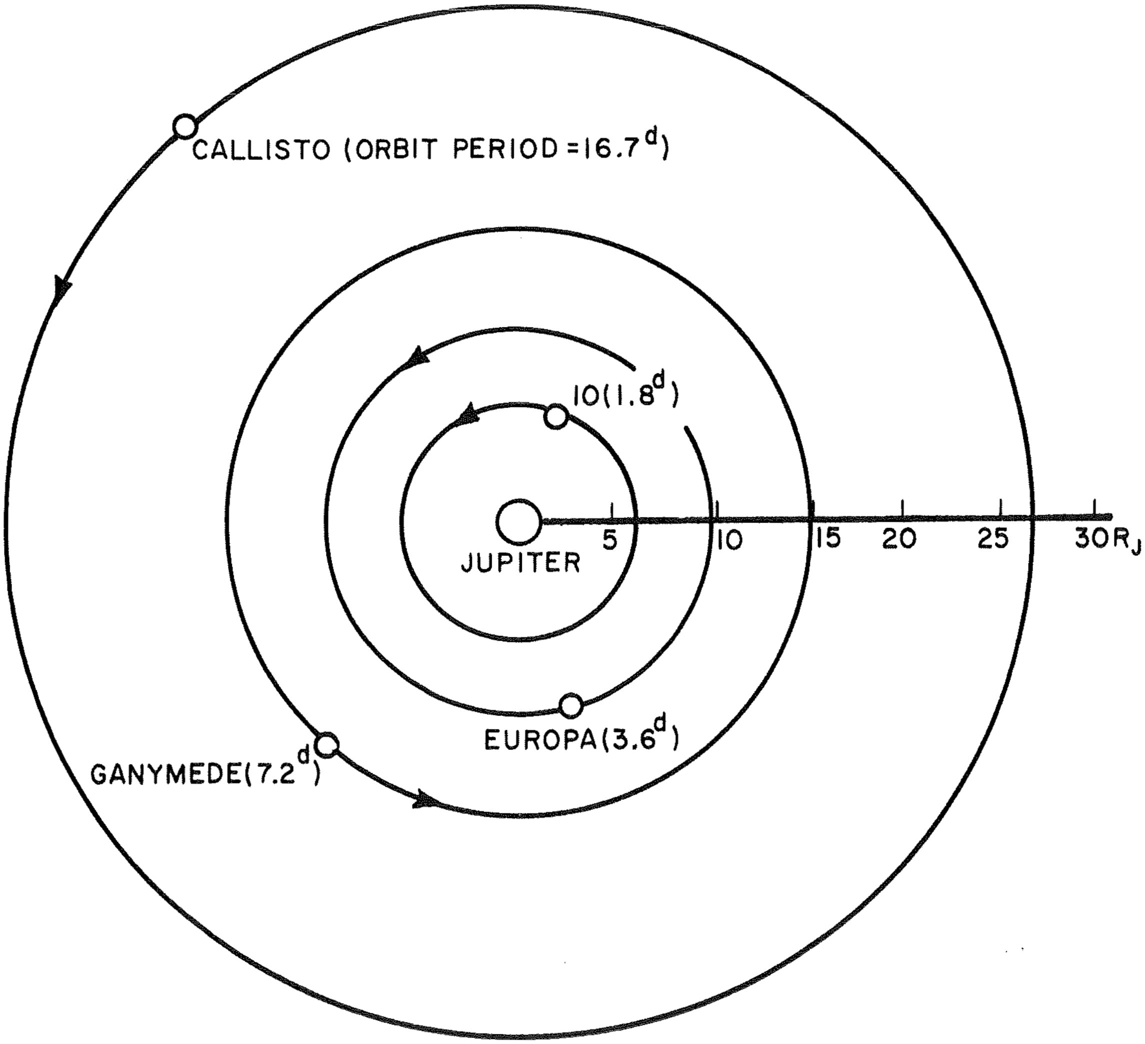

FIGURE 1. THE ORBITS OF THE GALILEAN MOONS OF JUPITER, ALL ORBITS IN JOVIAN EQUATORIAL PLANE.

R_J = JOVIAN EQUATORIAL RADIUS = 71372 KM) circular, it follows that as viewed from Jupiter libration is negligible. In addition, the circularity of the orbits ensures that variation in the apparent angular diameter of Jupiter as seen from each satellite will be very small.

The data in Table III have been used to calculate the apparent angular diameter of Jupiter, as seen from each satellite, together with the linear distance at the sub-satellite point on the planet's equator which corresponds to an angular resolution of 1 second of arc (1"). The results are listed in Table IV. Data on the Jovian equatorial radius and the ellipticity of the planet were taken from Allen (1963). For comparison, note that, as seen from Earth, the Moon subtends an angle of close to 0.5 degrees.

The synchronous orbits which correspond to the two rotation periods ($9^h\ 50^m.5/9^h\ 55^m.4$) of the equatorial/temperate regions of the Jovian cloud level have semi-major axes of 2.230/2.242 Jovian equatorial radii. All four satellites are, however, at much greater distances from the planet. Consequently, features on Jupiter will appear to revolve under them rapidly. It would not be possible to observe individual features for periods longer than about five hours without interruption.

On the basis of geometrical considerations alone, the Jupiter-turned face of each satellite could serve as a very useful base for remote study of the planet. Ideally, soft landings of remote sensing instruments should be made at the sub-Jupiter point on each satellite. Here Jupiter will be in the zenith, and observing conditions will be optimum.

2.3 Measurement of the Physical Properties of the Jovian Magnetosphere from the Surfaces of the Satellites

Recently Warwick (1967) has reviewed present knowledge of the interplanetary environment in the immediate vicinity of Jupiter. Results from radio astronomy indicate that Jupiter has Van Allen-type

TABLE IV

JUPITER AS VIEWED FROM THE GALILEAN SATELLITES

Satellite Number	I	II	III	IV
Satellite Name	Io	Europa	Ganymede	Callisto
Angular Polar/Equatorial diameters of Jupiter (in degrees)	18.2/19.4	11.4/12.2	7.2/7.6	4.1/4.3
Distance at sub-satellite point on Jovian equator which corresponds to 1" of arc resolution (in km)	1.70	2.91	4.84	8.78

radiation belts surrounding it, which suggests that the planet may have an essentially dipole magnetic field with probable strength at the Jovian cloud layer of order 10-20 gauss. Observations indicate that the axis of the dipole is inclined about ten degrees to the rotation axis of the planet. The maximum density of the charged particles in the belts appears to occur at approximately two Jupiter radii from the center of the planet. Almost all the accumulated particles lie within about five Jupiter radii from the planet.

At first sight the satellites appear to be useful observation points for monitoring particle densities and field strengths in the vicinity of Jupiter. Since the periods of revolution and rotation of the satellites are apparently equal, each body presents the same face permanently turned towards its direction of motion in its orbit. An ideal location for the soft-landing of particle/field detectors to monitor the environment of Jupiter would, therefore, appear to be on the "forward" face of the satellite, ninety degrees from both the rotation axis and the sub-Jupiter point. There are, however, several reasons why the satellites are unsuitable as bases for the study of the Jovian magnetosphere:

1. All four satellites revolve around Jupiter well outside the most intense regions of the radiation belts.
2. Since the satellite orbits are essentially circular it would not be possible to study variations in particle densities and field strengths as a function of distance from the center of the planet.
3. Even if the particle/field detectors had been soft landed on the "front" face of each satellite interpretation of their measurements would be difficult. The instruments could not make "pure" measurements of the radiation belts because interaction of the charged particles with the satellite itself would almost certainly drastically modify the local and

non-local particle/field environment of the lander. The severity of the interaction would, of course, depend on the conductivity of the satellite and the magnitude of its magnetic field. Very likely the instruments would be measuring the interaction of the satellite with the outer regions of the radiation belts, rather than the belts themselves. The latter information would of course, be of great interest, but only after a thorough physical understanding of the belts had already been obtained.

Spatial and temporal measurements of particle densities and field strengths in the vicinity of the Jupiter would be better made using either a spacecraft in a highly elliptical orbit in the plane of the Jovian magnetic equator or a series of Pioneer-type fly-by missions.

3. TRAJECTORY AND PAYLOAD ANALYSIS

The objective of this section is to define the propulsion systems required to land a useful payload of 1000 lbs. on each of the Galilean satellites. In this context, useful payload is not the total landed weight but only the weight of the scientific instrument package and support equipment. The total landed weight includes the landing gear, descent propulsion system and terminal guidance electronics, and must be scaled for each particular satellite.

A comparison of the various types of advanced propulsion systems which have been proposed has been made on the basis of the flight time necessary to complete the mission. To facilitate the comparison the soft-lander mission has been divided into four phases:

1. Departure from Earth.
2. Interplanetary (Earth-Jupiter) transfer.
3. Braking maneuver for gravitational capture by the satellite.
4. Terminal descent to the surface of the satellite.

A schematic representation of the four mission phases is shown in Figure 2.

The different types of propulsion systems studied were chemical high thrust (solid, space-storable and cryogenic), low thrust (nuclear-electric and solar-electric) and nuclear high thrust. All these types of propulsion systems are not applicable to all four of the mission phases. Consequently each mission phase is described individually with the appropriate propulsion system.

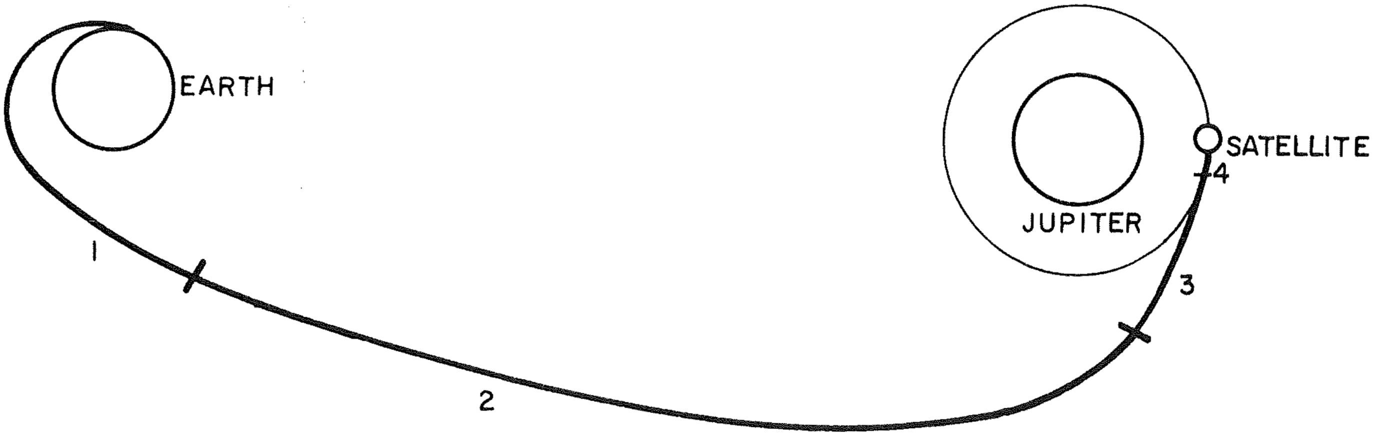

FIGURE 2. MISSION PHASE REPRESENTATION (NOT TO SCALE):

1.) EARTH LAUNCH
2.) INTERPLANETARY TRANSFER
3.) CAPTURE RETRO MANEUVER
4.) TERMINAL DESCENT MANEUVER

3.1 Earth Departure

Various multi-stage chemical launch vehicle systems were studied for the launch phase of the mission. These ranged from the seven-segment Titan up to the Saturn V/Centaur. Data for these vehicles were obtained from the Launch Vehicle Estimating Factors Handbook (1969).

3.2 Interplanetary Transfer

For the Earth-Jupiter transfer phase ballistic flight mode data are given in Table V. The launch energies and approach velocities are averaged over any period encompassing eleven successive launch opportunities. The data are somewhat optimistic since it is assumed that the spacecraft would be launched at the optimum time in any given launch opportunity.

In the case of the low thrust flight mode two propulsion systems were considered, solar-electric and nuclear-electric. The characteristics of the solar-electric propulsion system which have been adopted here were taken from Horsewood (1969). These characteristics are listed in Table VI. Note that ranges in the values of the design parameters are given corresponding to ranges of flight time for each launch vehicle considered. Within these ranges, the initial spacecraft weight necessary to land a 1000 lb. package on each satellite was determined. From these initial spacecraft weights the necessary flight times were then determined. If the Titan 3F/Centaur launch vehicle is used the interplanetary trajectory is indirect i.e. the spacecraft makes more than one revolution around the Sun before encountering Jupiter.

In the case of the nuclear-electric propulsion system certain assumptions have been made which are listed in Table VII. These data on nuclear-electric spacecraft (NES) performance requirements have been used to determine flight times to all four of the Galilean satellites. The NES-A has standard Earth escape

TABLE V

TYPICAL BALLISTIC FLIGHT MODE EARTH-JUPITER TRANSFER DATA

FLIGHT TIME (days)	LAUNCH ENERGY		HYPERBOLIC JUPITER APPROACH VELOCITY (km/sec)
	V_c (ft/sec)	C3 (km^2/sec^2)	
500	50180	128	12.76
600	48200	94	9.66
700	47330	86	7.65
900	47330	86	5.86

TABLE VI

CHARACTERISTICS FOR SOLAR-ELECTRIC LOW THRUST FLIGHT MODE

DESIGN PARAMETER		
Launch Vehicle	Titan 3F/ Centaur	SIC/SIVB/Centaur
S/C Initial Weight, lbs.	$8787 \leq W_o \leq 9111$	$15,964 \leq W_o \leq 19,756$
Powerplant Weight, lbs.	$3132 \leq W_{pp} \leq 3454$	$4696 \leq W_{pp} \leq 8911$
Propellant Weight, lbs.	$3100 \leq W_{prop} \leq 3408$	$2888 \leq W_{prop} \leq 6980$
Tankage & Structure Weight, lbs.	$93 \leq W_t \leq 101$	$86 \leq W_t \leq 209$
Propulsion System Specific Mass kg/kwe	30.0	30.0
Power at 1.A.U., kwe	$47.4 \leq P_e \leq 52.2$	$71.0 \leq P_e \leq 134.7$
Total Flight Time, days	$1500 \leq TF \leq 1800$	$600 \leq TF \leq 1200$

TABLE VII

ASSUMPTIONS FOR NUCLEAR-ELECTRIC LOW THRUST FLIGHT MODE

Conceptual Nuclear-Electric Spacecraft (NES)

DESIGN PARAMETER	NES - A	NES - B
Launch Vehicle	Titan 3F/Centaur	Titan 3F
Starting Condition	Earth Escape	300 n.m.Earth Orbit
Power	100 kwe	200 kwe
Total S/C Weight	17,000 lbs.	35,000 lbs.
Powerplant	7,200 lbs.	10,800 lbs.
Tankage (5% W_{pmax})	300 lbs.	1,000 lbs.
Guidance and Control	500 lbs.	500 lbs.

Powerplant Weight, $W_{pp} = 3600 + \alpha P$ where

$\alpha = 36$ lbs/kwe

P = Exhaust power, kwe

Powerplant Includes Reactor, Shield, Radiator, Power Conditioning Thrustors and Structure.

Total Power Efficiency, η, varied with vehicle design and performance index, J, between the limits:

$$0.67 \leq \eta \leq 0.84$$

initial conditions, whereas the NES-B utilizes a spiral Earth escape phase. Both NES vehicles, however, make a spiral approach to the orbit of the satellite prior to the capture retro maneuver.

3.3 Retro Maneuver for Satellite Capture of Spacecraft

Details of the propulsion systems appropriate for the required braking maneuver are listed in Table VIII.

Boundary conditions for all cases were an initial deceleration of approximately one Earth gravity, together with a final velocity of 250 m/sec directly towards the center of the satellite.

The mass fraction for all cases includes losses for finite burning time. The stage inert weights were obtained from the Launch Vehicle Estimating Factors Handbook (1969) for the solid and space-storable chemical cases, and from Chadwick (1968) for the cryogenic case. A powerplant weight of 3500 lbs. was assumed for the nuclear rocket case, including 10% propellant weight for tankage and plumbing and 8% propellant weight for insulation and propellant losses.

3.4 Terminal Descent Maneuver

For the terminal descent maneuver a variable thrust chemical propulsion system was assumed with a throttle ratio ~5. The propellant was Earth-storable N_2O_4 - Aerozine 50 with an I_{sp} of 310 secs. The initial condition was taken to be a 250 m/sec radial descent towards the surface. The equation used to calculate the total landed weight W_L, from the total useful scientific payload, W_{PL}, was:

$$W_L = \frac{W_{PL} + 50}{1 - 0.2 \left[\frac{1 - R}{R}\right] - 0.1 \left[1 + \frac{2\, g_{sat}}{g_{Moon}}\right]}$$

TABLE VIII

SPACECRAFT SYSTEMS APPROPRIATE FOR RETRO MANEUVER

Propellant Propulsion/System	Chemical	Cryogenic	Nuclear	Chemical (Solid)
Propulsion System	Restartable Pressure Fed	Pump fed	200 MW Nuclear Reactor	Solid Motor
Propellant	Space-Storable OF_2-B_2H_6	F_2-H_2	Hydrogen	Solid
Propellant, I_{sp} (secs)	385	468	833	300
Number of Stages	Two	Callisto- One Io- Europa - Two Ganymede -	One	One

where $R = W_L/W_o = \exp(-\Delta V/g\, I_{sp})$ is the characteristic mass ratio, g_{sat} and g_{Moon} are the surface gravities of the satellite and the Moon, respectively, and 50 lbs. has been included for an altitude/velocity control unit.

Useful payload is defined, as before, as the weight of the scientific instrument package with its support equipment, while total landed weight includes the landing gear, descent powerplant and terminal guidance unit. For the present study, useful payload was taken to be constant at 1000 lbs., and the total landed weight was calculated for each satellite accordingly. The landed weights range from 1430 lbs. at Callisto to 1594 lbs. at Io, reflecting the dominating influence of the gravitational field of Jupiter over that of the satellite.

The above equation was derived following experience gained in soft-landing Surveyor spacecraft on the Moon.

3.5 Flight Mode/Propulsion System Combinations

Table IX lists the various flight mode/propulsion systems which were considered. The first three combinations listed utilize a ballistic interplanetary transfer. The combination labeled "Storable Retro" has a two-stage space-storable chemical retro maneuver. The next combination, labeled "Cryogenic Retro", has a single-stage chemical cryogenic retro at Callistro and two-stage retro at the other three satellites. The combination "Nuclear Retro" uses a nuclear rocket retro maneuver. The last two combinations have low-thrust interplanetary transfers. The first, labeled "SE & Storable Retro", combines solar-electric low-thrust with a two-stage space-storable chemical retro. The last combination, labeled "NE & Solid Retro", combines nuclear-electric low-thrust with a single-stage chemical solid retro. All combinations use a multi-stage chemical launch system and a variable thrust earth-storable chemical descent stage.

TABLE IX

MISSION PHASE-FLIGHT MODE/PROPULSION SYSTEM COMBINATIONS

Mission Phase / Combination	Launch	Interplanetary Transfer	Retro-Capture Maneuver	Terminal Descent
Storable Retro	Multi-Stage Chemical	Coast	Two-Stage Chemical-Storable	Variable Thrust Chemical
Cryogenic Retro	Multi-Stage Chemical	Coast	Single-or Two-Stage Chemical Cryogenic	Variable Thrust Chemical
Nuclear Retro	Multi-Stage Chemical	Coast	Nuclear	Variable Thrust Chemical
SE & Storable Retro	Multi-Stage Chemical	Solar-Electric Low Thrust	Two-Stage Chemical-Storable	Variable Thrust Chemical
NE & Solid Retro	Multi-Stage Chemical	Nuclear-Electric Low Thrust	Single-Stage Chemical Solid	Variable Thrust Chemical

Note that all possible combinations were not considered. Some, such as nuclear retro atop nuclear-electric low-thrust, were unnecessarily powerful. Others, such as cryogenic retro atop solar-electric low-thrust, were unnecessarily complex utilizing a mixture of advanced technologies.

Figures 3, 4, 5, 6 and 7, with the proper combination label at the top, indicate the flight time requirements to each satellite using a variety of launch vehicles.

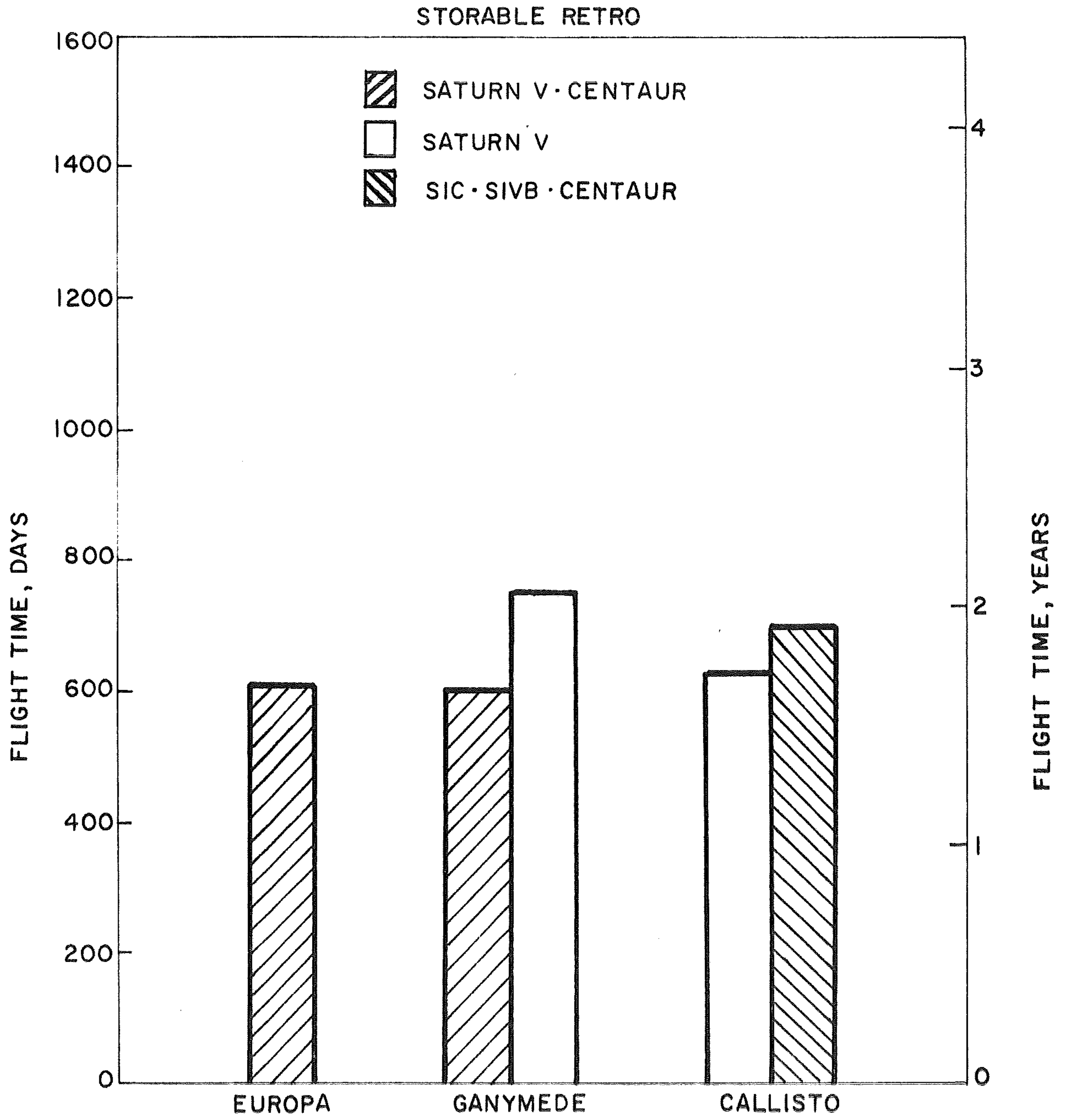

FIGURE 3. BALLISTIC FLIGHT TIME REQUIREMENTS TO LAND 1000 LBS. PAYLOADS ON THE MOONS OF JUPITER USING A TWO-STAGE CHEMICAL ROCKET CAPTURE PHASE.

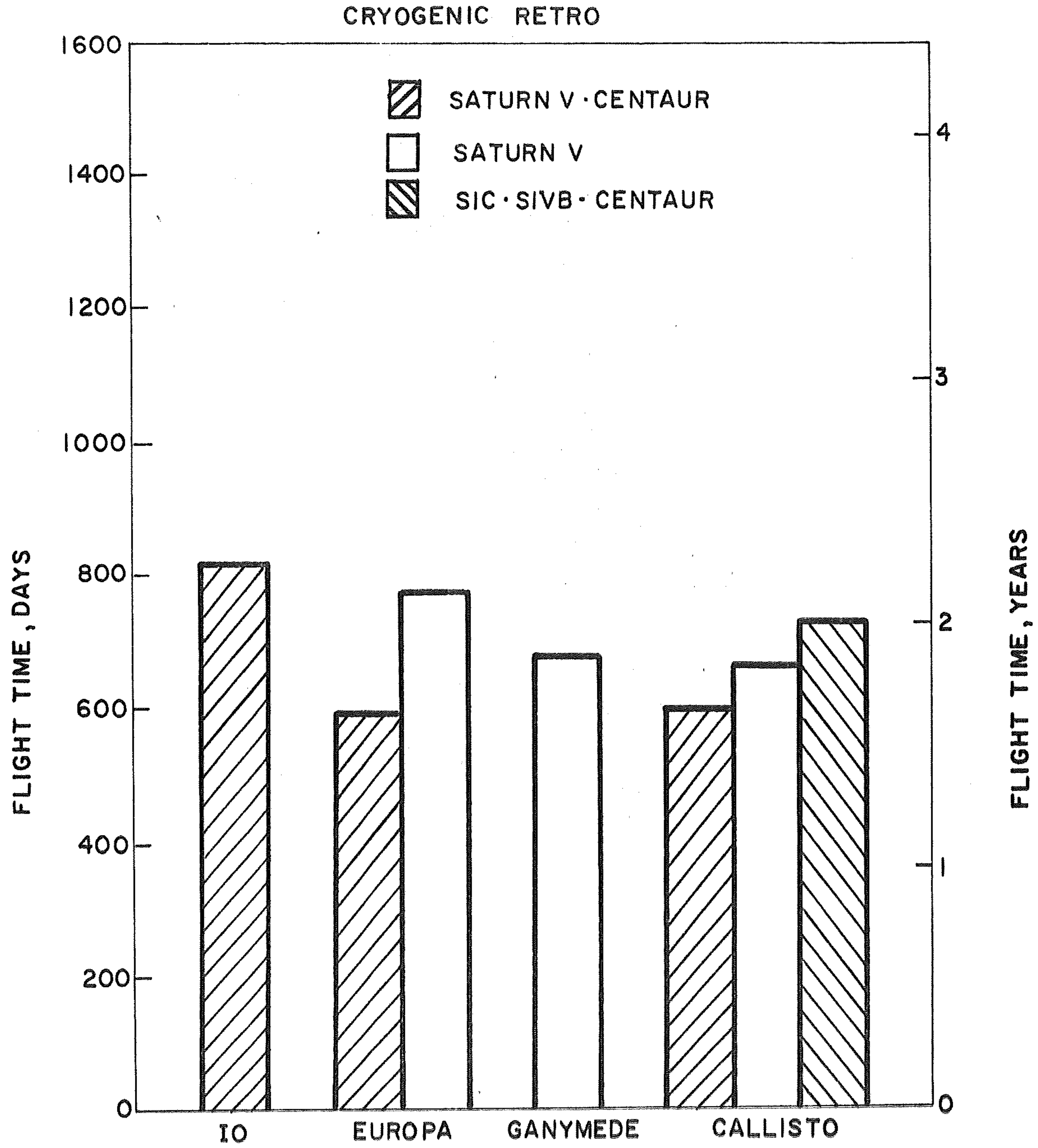

FIGURE 4. BALLISTIC FLIGHT TIME REQUIREMENTS TO LAND 1000 LBS. PAYLOAD ON THE MOONS OF JUPITER USING A CRYOGENIC CHEMICAL ROCKET CAPTURE PHASE (TWO-STAGE FOR IO, EUROPA, GANYMEDE, SINGLE-STAGE FOR CALLISTO).

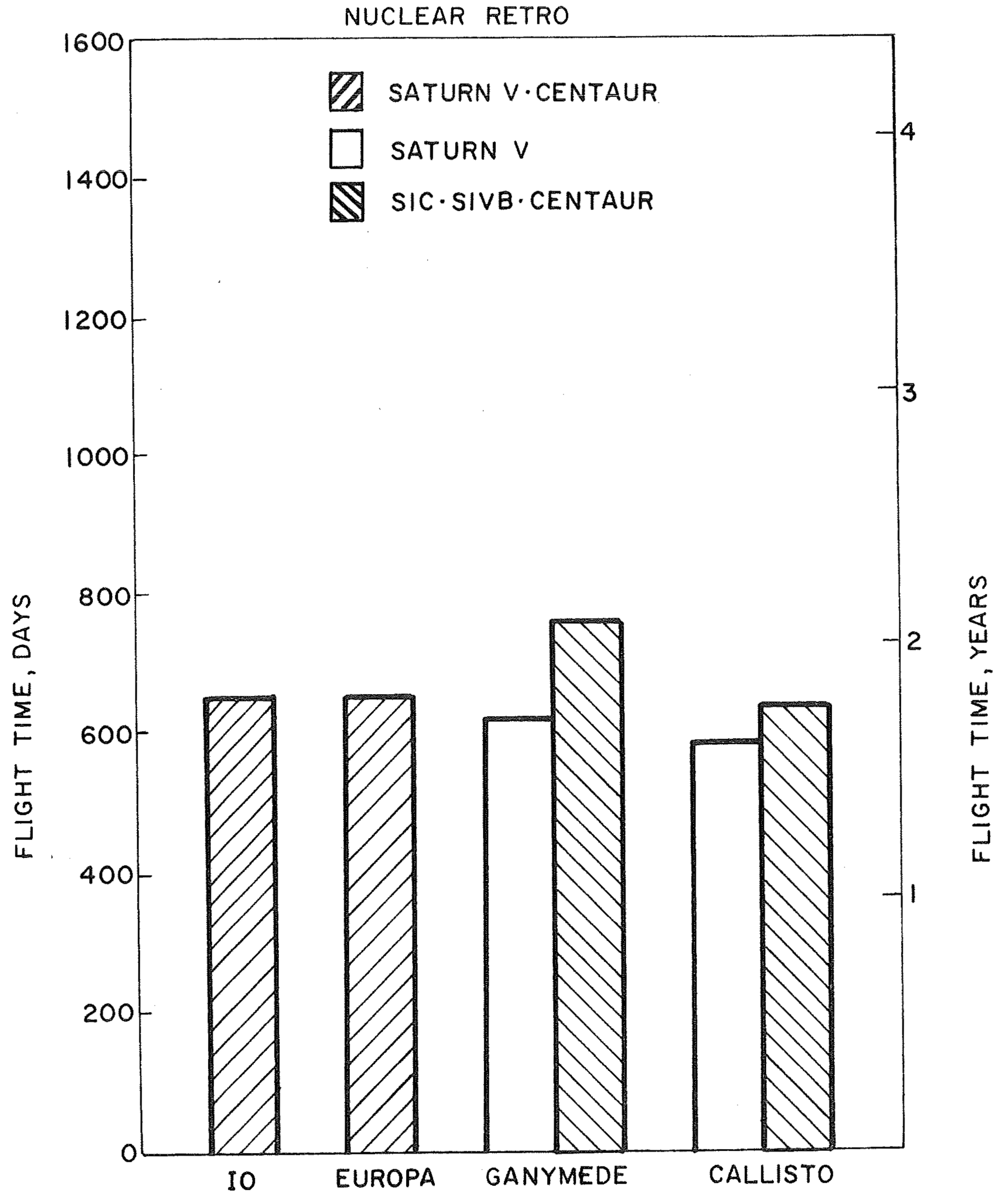

FIGURE 5. BALLISTIC FLIGHT TIME REQUIREMENTS TO LAND 1000 LBS. PAYLOAD ON THE MOONS OF JUPITER USING A NUCLEAR ROCKET CAPTURE PHASE.

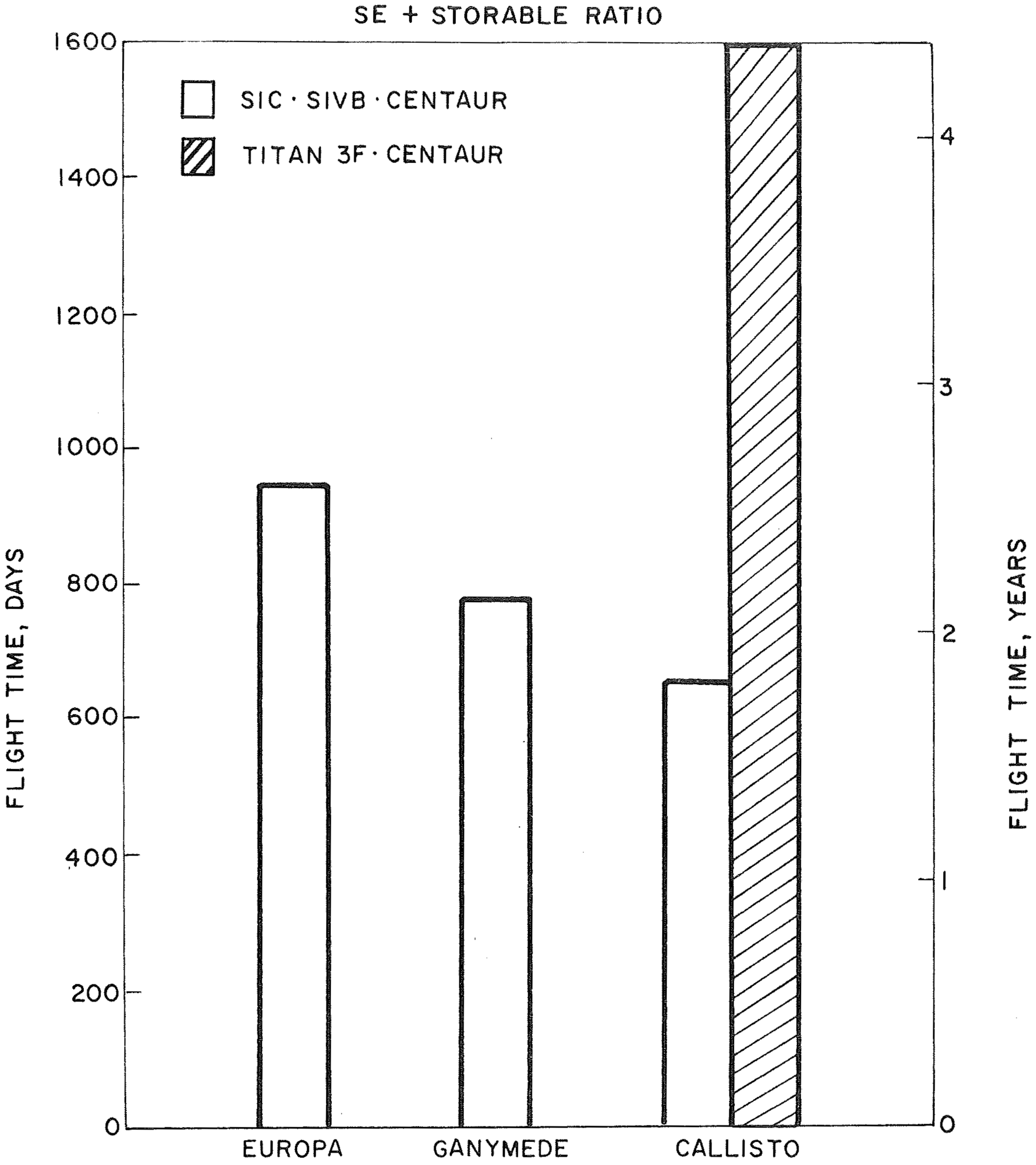

FIGURE 6. SOLAR-ELECTRIC LOW THRUST FLIGHT TIME REQUIREMENTS TO LAND 1000 LBS. PAYLOAD ON THE MOONS OF JUPITER USING A TWO-STAGE CHEMICAL ROCKET CAPTURE PHASE.

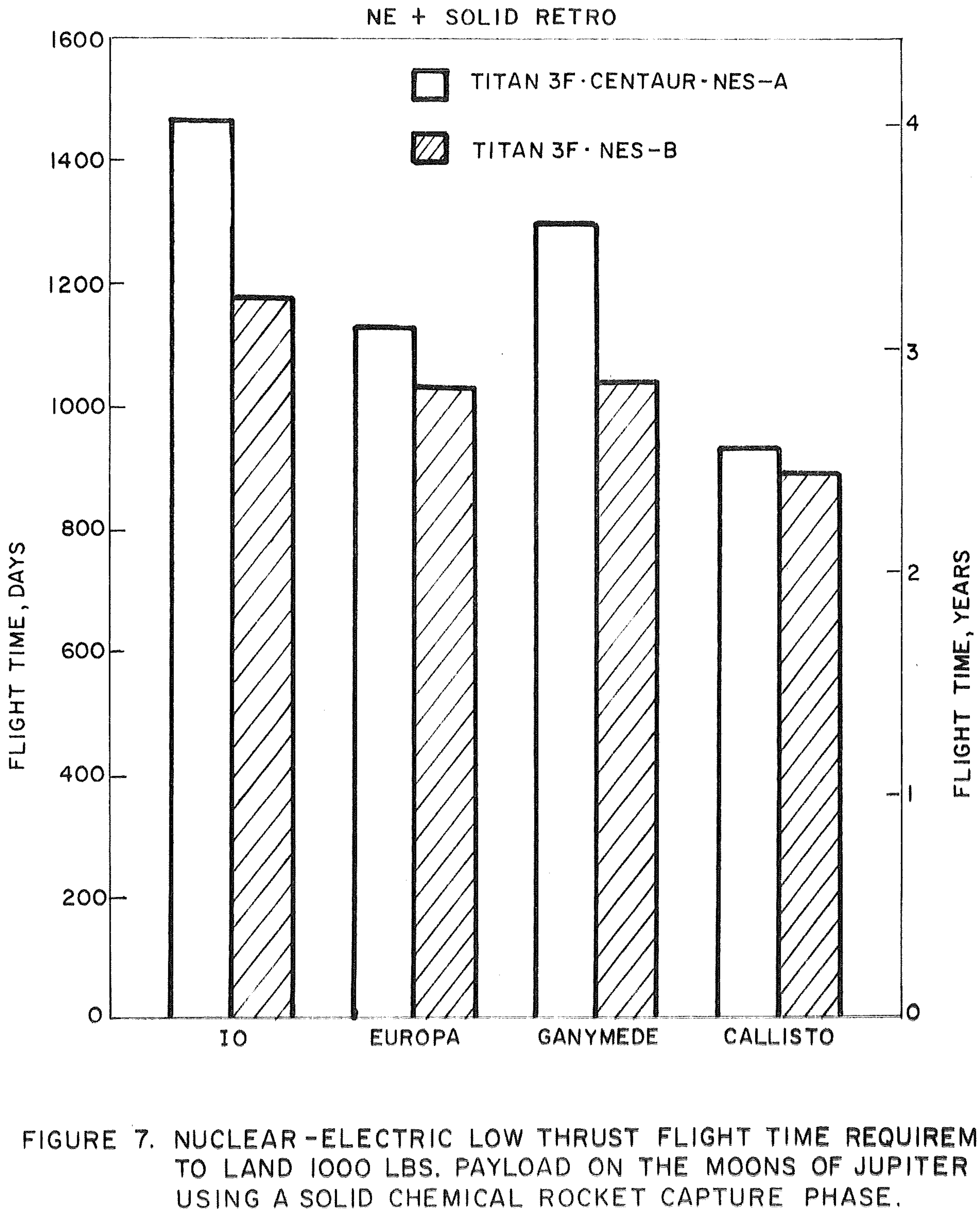

FIGURE 7. NUCLEAR-ELECTRIC LOW THRUST FLIGHT TIME REQUIREMENTS TO LAND 1000 LBS. PAYLOAD ON THE MOONS OF JUPITER USING A SOLID CHEMICAL ROCKET CAPTURE PHASE.

4. CONCLUSIONS

The major objectives for soft-landing spacecraft on the Galilean satellites would be:

1. To study them as individual and distinct planetary bodies.
2. To obtain data essential for the study of both the mode of formation of the smaller planetary bodies in the solar system, and the origin of satellite systems.
3. To compare the physical properties of the satellites with those of the smaller planets to develop a link between studies of the Inner and Outer planetary groups.

A secondary objective would be to use the satellites as bases for the remote observation of the Jovian cloud layer. Advantages of such bases would be:

1. The stability of the observation platform.
2. The proximity to the planet.
3. The expected long lifetime of the electronic components of the remote sensing instruments, since all four of the satellites revolve well outside the most intense regions of the Jovian radiation belts.

The flight time requirements for the soft-landing of a 1000 lb. useful payload on each of the Galilean satellites by utilization of all five flight mode/propulsion system combinations are summarized in Figure 8.

Storable Retro: Missions using space-storable chemical propulsion for the retro maneuver are conceptually possible for Europa, Ganymede and Callisto with intermediate Saturn and Saturn V launch vehicles, with flight times of around 2 years. It should be pointed out that the requirements of direct approach to the satellite and large ΔV two-stage retro maneuvers raise serious

COMBINATION	IO	EUROPA	GANYMEDE	CALLISTO
STORABLE RETRO	—	SATURN V CENTAUR	SATURN V	SIC·SIVB CENTAUR
CRYOGENIC RETRO	SATURN V CENTAUR	SATURN V	SATURN V	SIC·SIVB CENTAUR
NUCLEAR RETRO	SATURN V CENTAUR	SATURN V	SIC·SIVB	SIC·SIVB CENTAUR
SE + STORABLE RETRO	—	SIC·SIVB CENTAUR	SIC·SIVB CENTAUR	SIC·SIVB CENTAUR *TITAN 3F·CENTAUR
NE + SOLID RETRO	TITAN 3F	TITAN 3F	TITAN 3F	TITAN 3F

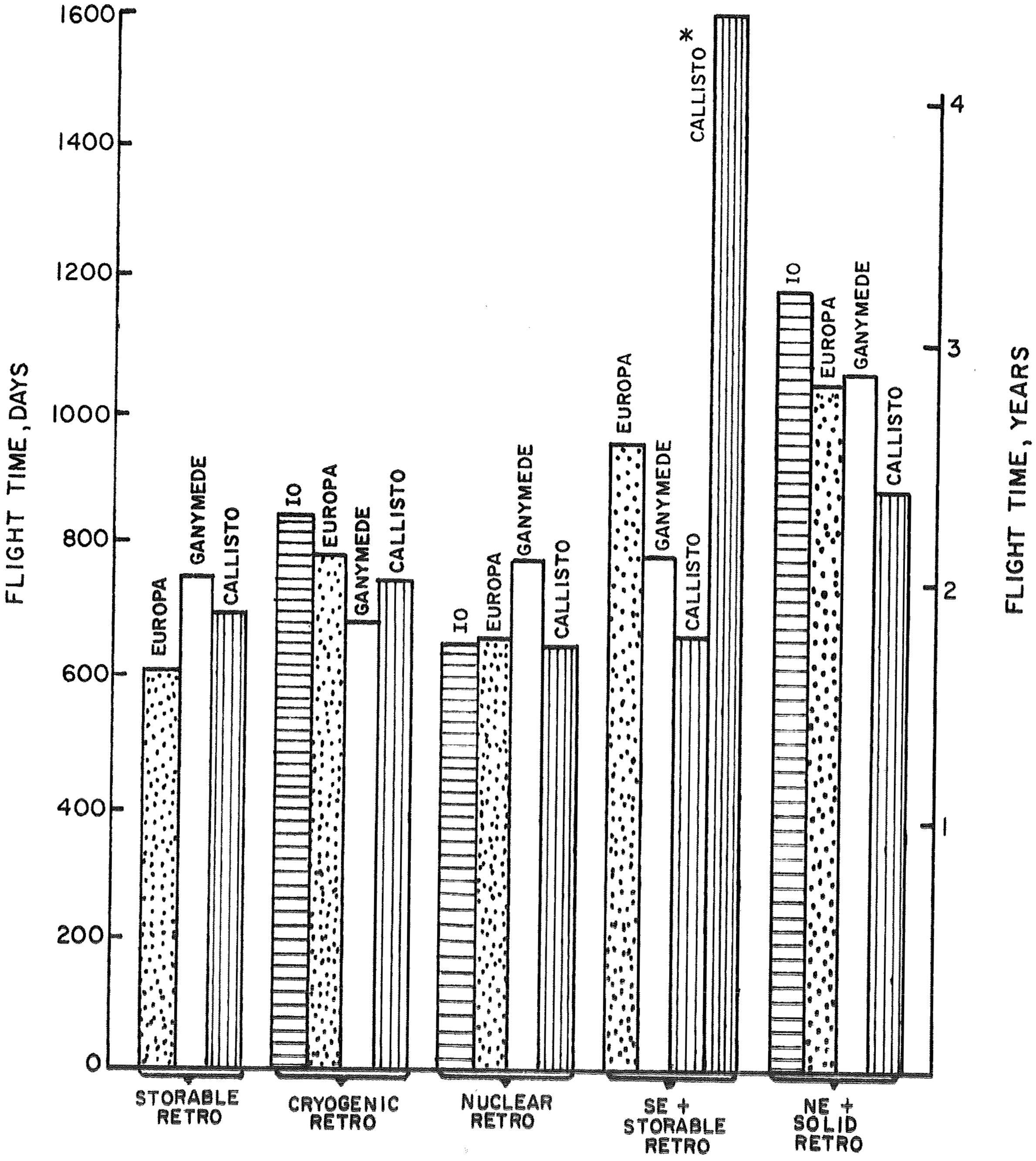

FIGURE 8. SUMMARY COMPARISONS OF FLIGHT TIME REQUIREMENTS FOR LANDING 1000 LBS. PAYLOAD ON THE GALILEAN MOONS OF JUPITER USING VARIOUS PROPULSION SYSTEMS.

questions concerning the feasibility and practicality of the chemical mission mode.

Cryogenic Retro: Utilization of a cryogenic propulsion system for the retro maneuver permits the possibility of an Io mission with a Saturn V launch vehicle and reduces the retro maneuver at Callisto to a single stage. Flight time requirements vary compared to a space-storable chemical propulsion system depending on the launch vehicle and the number of retro stages required. The reservations noted above still apply. In addition the problem of storing the cryogenic propellant in space for about 2 years must be considered.

Nuclear Retro: A nuclear rocket retro maneuver reduces the launch vehicle requirements of the chemical propulsion lander missions in the case of Ganymede. The flight time is about the same and Io landers are included. The most serious feasibility questions of this combination are the development of a small nuclear rocket stage and a guaranteed space hybernation period of about 2 years.

SE & Storable Retro: Solar-electric low thrust flight modes are possible (excluding Io) using the intermediate Saturn launch vehicle. Flight times are comparable to the chemical and nuclear flight for Ganymede and Callisto, but somewhat longer for Europa. The use of the Titan 3F Centaur launch vehicle was also investigated, but only Callisto missions were found to be possible, and then only with a flight time greater than 4 years. Feasibility questions again arise concerning direct satellite approach, two-stage retro maneuvers, and development of the low thrust stage.

NE & Solid Retro: Nuclear-electric low thrust flight modes give somewhat longer flight times of 2.5 to 3.5 years. There are a number of advantages to this flight mode including small Titan 3F launch vehicles, spiral approach to the orbit of the satellite, and a single stage retro-maneuver. The primary feasibility questions center on the development of the low-thrust stage.

It is concluded that while each flight mode/propulsion system combination is conceptually capable of landing 1000 lbs. useful payload on a Galilean satellite, each combination also raises technological questions which are unanswered at this time. Further analysis is necessary to evaluate the relative costs and difficulties of developing two-stage chemical retro stages versus single nuclear retro stages versus low-thrust propulsion systems. The results given here have also only considered direct satellite approaches to landing. Operationally, it would probably be more advantageous to land from an orbit about the satellite, allowing time for a surface survey from orbit to select a favorable landing site. The performance trade-offs between direct and out-of-orbit landing maneuvers should be studied. Finally, all the major satellites of the outer planets should be considered for potential soft-lander missions before a plan for satellite exploration is formulated.

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