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Technical Memorandum 33-553

Elements of Cost Comparison for Planetary Missions With Advanced Propulsion

J W Stearns

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JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

July 1, 1972

JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103

July 31, 1972

Recipients of Jet Propulsion Laboratory
Technical Memorandum 33-553·

Please note the following correction to Technical Memorandum 33-553, Elements of Cost Comparison for Planetary Missions With Advanced Propulsion, by J. W. Stearns, dated July 1, 1972:

The second paragraph of the CONCLUSIONS section on page 10 should begin "For ΔV from Earth orbit of 10 km/s" instead of "For ΔV for Earth orbit of 10 km/s."

Very truly yours,

John Kempton, Manager
Publications Section

Telephone 354-4321 Twx 213-449-2451

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July 1, 1972

PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

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CONTENTS (contd)

FIGURES (contd)

ABSTRACT

Cost and performance comparisons are made between chemical propulsion and nuclear electric propulsion for planetary missions at Jupiter and beyond. Nuclear rocket comparisons are made for performance only. Titan, Saturn, and Space Shuttle launch are evaluated, utilizing advanced propulsion upper stages Appendixes include a performance analysis of multiple Shuttle launches, with assembly in Earth orbit, and a discussion of nonrecurring costs.

I. INTRODUCTION

Chemical propulsion continues to be the conventional basis for achieving low Earth orbit. For propulsion beyond Earth orbit, however, alternatives are proposed for several types of advanced propulsion. Principal among these are advanced chemical rocket stages, solar electric propulsion, nuclear rocket stages, and nuclear electric propulsion (NEP). Cost and performance of launch vehicles is thus recognized as a factor common to the economics of all forms of advanced propulsion.

For current planetary missions at moderate energy levels, however, the cost of propulsion to Earth orbit is only a fraction of the total cost of propulsion. Furthermore, the total cost of propulsion is only a fraction of the total mission cost. But mission energy requirements are rising. In the future, the cost of propulsion -- and particularly that part beyond Earth orbit -- may become an increasingly significant portion of the mission cost.

Early studies of advanced propulsion have shown that significant performance advantages may be expected from low-thrust NEP for missions to the outer planets when mission velocity increment out of Earth orbit exceeds 10 km/s (Refs. 1-4) Costs are discussed in this report, to a large extent appearing to correlate with performance advantages.

Further improvements of performance and cost are expected by the development of the Space Shuttle. In the early study phases of that program, however, caution should be exercised to prevent making too many parametric extrapolations and simplifying assumptions. For example, until the Shuttle can be augmented by a "space base" type of operation, multiple launches and assembly in orbit of large vehicles may not be altogether practical. Costs of such operations appear to be impossible to estimate now and could not be expected to be negligible. Discussion of multiple launch systems with orbital assembly are therefore relegated to Appendix A, where performance tradeoffs are shown for the chemical rocket, nuclear rocket, and nuclear-electric rocket. Any attempt at this time to evaluate cost tradeoffs for multiple launch would be futile.

Areas for performance tradeoffs between advanced forms of propulsion have not yet been completely mapped, since each type of propulsion tends to be presented for only those missions where obvious advantages predominate. Thus, for instance, for unmanned missions to Jupiter, chemical rockets are shown usually for flyby or high elliptical orbiters for small payloads. Solar-electric spacecraft are shown usually for somewhat larger payloads and more circular orbits but still utilize chemical rockets for planetary orbit retropropulsion. Nuclear rockets are expected to start with much greater mass in Earth orbit, delivering larger mass with shorter flight times. Nuclear-electric propulsion, starting with modest mass in Earth orbit, is considered for close-in circular orbiters and landers at Jupiter and its satellites (utilizing chemical propulsion only for landing) with large payload mass.

The unmanned planetary missions are unique in many of their characteristics. Major emphasis is toward obtaining basic information throughout a wide part of our solar system. Net spacecraft mass as low as 500-1000 kg is needed, growing to perhaps 5000 kg for the later, more ambitious missions. Mission times are measured in years. Thus the constraints imposed within this report are not necessarily applicable to nonplanetary missions, such as the manned space exploration program or Earth satellite and lunar missions.

Comparisons in this report are made for high-energy outer planet orbiter missions (i. e., Jupiter and beyond) Such missions are expected to be of importance during the 1980s and 1990s, a time period consistent with several advanced propulsion developments. Missions are to be categorized in terms of velocity increment from Earth orbit, and comparisons then made of the cost of the propulsion system for payload delivered.

A single launch from Earth is assumed, utilizing one of three vehicles. the Titan IIID(7), the Saturn V, or the Space Shuttle. For chemical propulsion missions, the launch vehicle will have as upper stages a Centaur stage, followed by an F_2/H_2 kick stage. Finally, one or two OF_2/B_2H_6 (space storable) retrostages are provided, depending upon the mission needs. For NEP missions, the launch vehicle will operate to a 270-nm orbit for purposes of nuclear safety. The NEP will then operate to spiral out from Earth orbit, make a heliocentric transfer to the destination planet, and then spiral into final orbit at the planet. If high-thrust maneuvers are needed at the planet (such as landing), space storable retropropulsion would have to be provided from the net spacecraft mass. Nuclear rockets are considered in Appendix A and are not included in this discussion since they require multiple launch. Also, solar electric propulsion, because of large distances from the Sun, is not suitable to most of the missions studied.

Evaluation of the cost of launch vehicles and upper stages is, in most cases, concerned with propulsion that is not yet developed Both the production cost and vehicle performance are subject to error. If we were to go further and attempt to introduce nonrecurring costs as well into a quantitative consideration, there might be a tendency to obscure the main issue of comparison in this report. Arguments concerning nonrecurring cost are provided in Appendix B.

Where possible, performance information in this report is based on the NASA projections contained in the OSSA Code SV launch vehicle reference documents (Ref. 5). A summary of the vehicle and upper stage propulsion costs appears in Table 1 (Refs. 6-10) Recurring costs include launch operations and support. Saturn V is estimated for a "de-manrated" version not presently available. Since cost estimates are quite sensitive to production and launch rates, their assumptions in this report are also shown in the table.

II. CHEMICAL PROPULSION SYSTEMS COST ANALYSIS

Chemical propulsion performance is seen to be exponentially decreasing with increasing mission ΔV. In Fig. 1, payload mass fraction for chemical upper stages is illustrated for a specific impulse of 470 s and staging at equal velocity increments. The ΔV requirements for several planetary and interplanetary missions of interest are also marked on this figure. By comparison with present space missions, these missions require the achievement of large velocity increments out of Earth orbit, and thus, large initial propulsion mass and several upper stages, leading to high cost and complexity.

Table 2 is a listing of performance and cost estimates for the Titan IIID(7), Saturn V, and Space Shuttle, with several combinations of upper stages. The F_2/H_2 kick stage assumes a specific impulse of 470 s and a stage factor λ_s of 0.85. The retrostages assume a specific impulse of 400 s and a stage factor of 0.90. Use of space storables eliminates the need for cryogenic storage of hydrogen propellant for long periods of time, thus eliminating several disadvantages. Not only is hydrogen tankage large because of the low specific mass, but also boil-off mass (and/or hydrogen leaks) over a mission period of several years may seriously degrade mission performance, and the disturbance forces from boil-off or leaks would lead to excessive guidance errors.

Launch costs to Earth orbit and to Earth escape are shown in Figs. 2 and 3, in terms of dollars per kilogram of delivered "payload." Note that the propulsion cost per kilogram to Earth escape is approximately double that for Earth orbit if there are no added stages. This is because of the reduced payload at the higher energy. The addition of an upper stage increases cost, but it may be necessary to the effective delivery of payload.

The exponential nature of high-thrust chemical propulsion systems continues to reflect into reduced payload and increased number of upper stages as mission velocity increment continues to increase. The sets of data from Table 2 are plotted in Fig. 4 to show approximate per-unit cost of propulsion to deliver payloads with the Titan IIID(7), the Saturn V, and the Space Shuttle as launch vehicles, plotted as a function of mission velocity increment beyond Earth orbit. As listed in Table 2, upper stages have been assumed as necessary to meet the performance required. If we evaluate chemical propulsion cost at a ΔV = 10 km/s, the Titan III will deliver up to 1000 kg of net spacecraft mass at a propulsion system cost of \$33 to \$43 million. This amounts to \$33,000 to \$43,000 per kilogram of net spacecraft. Similarly, the Saturn V will deliver 5600 kg of spacecraft mass at a propulsion system cost of \$130 to \$196 million. This is \$23,000 to \$35,000 per spacecraft kilogram. The Space Shuttle, starting with 27,000 kg in Earth orbit, may deliver 1300 kg at a propulsion cost of \$21-45 million, for a per-kilogram cost of \$17,000 to \$35,000, provided that cargo dimensions are not exceeded. Beyond a ΔV of 10 km/s, the per-unit cost of chemical propulsion rises very rapidly

III. NUCLEAR-ELECTRIC PROPULSION SYSTEMS COST ANALYSIS

For comparison of nuclear electric systems with the systems described above, two launch modes are considered: launch to Earth orbit and launch to Earth escape. The Titan IIID(7)/Centaur as a launch vehicle (for approximately $26 million) will deliver 20,000 kg to Earth orbit, or 7300 kg to Earth escape. This initial mass is to be divided between the NEP system and the "net spacecraft."

Missions such as those to Jupiter circular orbit, if performed by chemical propulsion, would be characterized by a ΔV larger than 10 km/s. Beyond Jupiter, missions of interest lie in a broad band from a ballistic ΔV of 10 km/s to that of 30 km/s or greater. It will be shown that, where relatively high energy missions and/or large payloads are desired, the NEP system offers great potential. (Under particular circumstances, the nuclear rocket may offer advantages. However, these missions, which are not possible with a single launch from Earth, must be considered under a different set of constraints.)

Launch of NEP spacecraft to Earth escape by chemical means is not an optimal utilization of nuclear energy. There are, however, several identifiable missions where this launch mode is satisfactory, usually associated with low power levels. In such an operational mode, flight time is shortened by the amount of time necessary for a low-thrust spiral escape (on the order of 100 days), but the payload is quite radically reduced thereby. Except for very short mission times, the low-thrust spiral Earth escape appears to provide a more cost-effective mission and is therefore considered in this report.

It is difficult to compare NEP missions in a format developed for chemical propulsion missions, that is, over a range of ΔV. The method provided below is an approximation based on average mission energy for a number of outer planet missions. The low-thrust missions are not usually expressed in terms of ΔV because of their relatively complex time-integral interrelationship between kinetic and potential energy. The high-thrust ballistic propulsion ΔV is introduced hyperbolically utilizing planetary gravitational fields, while the NEP energy is introduced mainly during the heliocentric portion of flight.

An additional penalty is imposed on the NEP craft when it is operating with a low-thrust spiral planetary escape and capture For low-thrust trajectories, there is no energy difference between elliptic and circular orbits having the same semimajor axis. Any such energy difference is a feature of hyperbolic trajectories rather than low-thrust trajectories

Table 3 summarizes the high-thrust ΔV calculations for several planetary missions of interest. This becomes the reference frame for the low-thrust mission evaluation.

Performance potential for the Titan-NEP and the Space Shuttle-NEP to the outer planets is shown in Figs. 5 and 6. Flight time as a function of distance from the Sun is shown in Fig. 5 for planetary orbiters. Orbital payload is plotted based on a planetary spiral at the destination to a semimajor axis of 19-20 planetary radii. Figure 6 illustrates a number of NEP missions from Jupiter outward, plotted as a function of ballistic ΔV for equivalent missions Note that elliptic and circular orbits with the same semimajor axis have the same payload because they require the same energy. However, since ΔV is different for the high-thrust frame of reference, low-thrust payload appears constant over a range of ΔV. The median value of ballistic equivalent ΔV is approximated from these data, as indicated, and is the value utilized in the cost comparisons that follow.

A set of estimated recurring costs of the NEP system and its chemical launch vehicle is shown in Table 4. A single NEP "stage" includes the thrust subsystem (electric thrusters, actuators, switching and power conditioning, and propellant storage and distribution) and the power subsystem (nuclear reactor and controls, shielding, cabling, and heat rejection radiators). Minimum recurring cost estimates represent a "consensus" from discussions with personnel at AEC, NASA, and JPL.

The NEP power subsystem, with its lower limit of reactor criticality, has only a small cost difference between a 200-kWe and a 300-kWe subsystem. Because of great uncertainty in cost estimating of this subsystem, the author also provides, in the comparisons that follow, a second per-unit cost estimate which is arbitrarily set at a factor of 3 higher than the minimum estimate, thus yielding what is believed to be a conservative band of cost projections.

The thrust subsystem cost per kWe is expected to drop significantly as the power level increases. For the 10-kWe solar-electric system now in pre-prototype test at JPL, the cost is estimated at \$150,000/kWe (Ref. 12). At

100-300 kWe, the cost should be no greater than \$70,000/kWe, and this value is used as a minimum estimate. For conservatism, however, a second estimate is also given at \$150,000/kWe.

Integration of the NEP system with the net spacecraft operation is expected to be greater than for standard chemical systems, because of the more intimate relationship of the spacecraft to the NEP system, the latter representing about 80-90% of the spacecraft mass. Additional integration and test with NEP is anticipated to increase recurring costs by roughly \$8 to \$10 million.

Also recognized are large offsetting cost advantages because the nuclear power plant will also supply auxiliary electric power for operation of the spacecraft. For chemical propulsion, the payload includes a substantial mass for auxiliary power. A kilowatt of RTG power, for instance, represents more than 400 kg at present, with future projections being no lower than 200 kg/kWe. This compares with 20-25 kg/kWe for fast reactor power subsystems. But in addition to the mass saving for auxiliary power, the anticipated cost savings for the high energy missions under consideration is expected to be in excess of \$8 to \$10 million. Since these savings approximately equal the cost of spacecraft integration discussed above, the numbers cancel in Table 4.

Figure 7 is an overlay of NEP cost estimates in comparison with the chemical cost curves from Fig. 4. The median performance curves of Fig. 6 were utilized rather than the maximum potential of the NEP spacecraft. This median performance is shown over the range of minimum to maximum cost from Table 4. Both the Titan IIID(7)/Centaur and the Space Shuttle are considered as launch vehicles. Shaded areas in the NEP curves of Fig. 7 represent the spread between the minimum and maximum NEP cost estimates. However, maximum performance at the maximum cost projection are also illustrated for comparative purposes.

The flatness of the NEP curves out to much higher mission ΔV results from the very high NEP rocket exhaust velocity, typically of the order of 50-60 km/s. However, because of the high cost of a large nuclear-electric energy source, NEP is relatively unattractive for missions characterized by a ΔV of less than about 6-8 km/s.

IV. NEW LAUNCH CONCEPTS

Unmanned planetary exploration is presently conducted with fairly small spacecraft. Good science experimentation can be accomplished when the spacecraft mass at its destination approaches the order of 500 to 1000 kg. With chemical propulsion, if net spacecraft mass is held constant, launch vehicle size must increase as the mission characteristic velocity increases. Conceptually, this would require a full spectrum of launch vehicles (for example, the Titan "building block" concept).

An alternative approach to launch size variability would be a space base/shuttle capability. This would allow the assembly and test of upper stages and payloads in Earth orbit. The extent of the cost savings for this approach is unknown, as discussed earlier, because the total logistics picture must be taken into account. Manned operations in Earth orbit are bound to be expensive.

The main advantage of cost reduction for launch to Earth orbit is to the Earth-orbiting satellite operations. The principal cost of propulsion for these missions is the basic launch vehicle without additional upper stages.

When multiple stages of propulsion must be provided beyond Earth orbit, the cost of propulsion increases rapidly. At 10 km/s ΔV from Earth orbit, the launch vehicle to Earth orbit is roughly 50% of the total propulsion cost. At the same time, the net spacecraft mass delivered to 10 km/s is on the order of 5% of the Earth-orbit mass. The cost of propulsion per kilogram of delivered spacecraft mass is therefore at least a factor of 40 greater at a ΔV of 10 km/s than at Earth orbit ($\Delta V = 0$). A 20-30% reduction of launch vehicle cost will reduce total propulsion cost by approximately 10-15%.

At a ΔV of 10 km/s, NEP cost (including launch vehicle) for each kilogram of delivered payload is on the order of that of chemical systems. Launch vehicle cost is roughly 20-40% of the NEP cost. A 20-30% reduction of launch vehicle cost will reduce total propulsion cost by 4-12%. However, with single Shuttle launches, NEP does not limit payload to less than 1000 kg at ΔV's beyond 10 km/s, as do chemical stages. For median NEP performance, 1000 kg or greater can be carried out to a ΔV of approximately 20 km/s for outer planet missions. Performance equivalence for chemical systems would require up to eight Shuttle launches, as discussed in Appendix A.

V. CONCLUSIONS

Even with forseeable improvements, chemical propulsion by itself is probably not economically attractive for application to complex, high-energy missions with velocity increments much beyond 10-12 km/s out of Earth orbit. This is the energy level at which detailed exploration (close orbit and landing) at the outer planets and their natural satellites begins to be possible.

For ΔV for Earth orbit of 10 km/s out to at least 20 to 30 km/s, NEP is presently indicated as a more economical method (based on recurring costs) of performing planetary exploration. Incentives appear great enough to begin a more detailed study of NEP missions at the outer planets and to pursue the development of a total system technology. Unless flight times are increased and the mission requires very large payloads, nuclear electric propulsion does not appear to improve mission economy for a ΔV from Earth orbit much below 8-10 km/s.

Improved Earth-orbit launch capability, expected to be available with the Space Shuttle, could be important to near-Earth missions but will improve the high-energy planetary mission cost effectiveness of propulsion by less than 15%. NEP mission spacecraft, also boosted to Earth orbit chemically, will obtain improvement of cost effectiveness similar to that of chemical systems.

For missions equivalent to a ΔV of 10 to 12 km/s, nuclear-electric propulsion costs are $10,000 to $30,000 per spacecraft kilogram. This is only slightly lower than the cost of chemical propulsion. Since spacecraft programs for planetary missions presently cost between $200,000 and $300,000 per spacecraft kilogram, exclusive of propulsion costs, propulsion is less than 20% of mission cost. Beyond 10 km/s out of Earth orbit, however, chemical propulsion costs are rapidly rising and could approach the cost of the spacecraft, and thus double program total cost.

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12. Kerrisk, D. J., JPL internal communication, November 1971.

Table 1. Launch vehicle cost estimates[a] (Refs. 6-11)

Launch vehicle or stage	Cost estimate			Production rate per year	Launch rate per year	Size of buy
	Hardware	Launch and support	Total			
Atlas (SLV3C)	4.1	0.8	4.9	4	4	3
Titan IIID(7)	12.7	5.2	17.9	4	4	12
Saturn V			180 ± 30			
Shuttle	10 ± 5	2.5 ± 2.5	12.5 ± 7.5			
Centaur	5.5	2.9	8.4	4	4	6
Kick (H_2/F_2)			7 ± 2			
Retro (OF_2/B_2H_6) (1 or 2 stages)			5 ± 3			

[a]All costs given in millions of dollars.

Table 2. Estimated payloads from multiple upper stages launched by Titan IIID(7), Saturn V, and Space Shuttle

Parameter	Value							Launch vehicle cost[a]
ΔV km/s from Earth orbit	2	4	6	8	10	12	14	
V_c, 10^3 ft/s	32.5	39.0	45.6	52.2	58.7	65.3	71.8	
C_3, km^2/s^2 hyperbolic excess	-	18.5	75	128	195	272	356	
Launch vehicle	Payload mass, 10^3 kg							
Titan IIID(7)								18
Titan IIID(7)/Centaur	10.8	5.3	1.6					26
Titan IIID(7)/Centaur/kick[b]			3.4	1.6	0.6			33 ±2
Titan IIID(7)/Centaur/kick/retro[c]				1.9	1.0	0.6	0.3	38 ±5
Saturn V	68	35	15					180 ±30
Saturn V/Centaur			19	10.5	5.0			188 ±30
Saturn V/Centaur/retro[c]				10.0	5.6	2.6		193 ±33
Saturn V/Centaur/kick[b]					5.5	2.5		195 ±32
Saturn V/Centaur/kick/retro[c]						2.9	1.4	200 ±35
Shuttle/Centaur		6.2	2.3					21 ±7.5
Shuttle/Centaur/retro[c]			4.0	2.0	1.0			26 ±10.5
Shuttle/Centaur/kick[b]		7.6	4.3	2.2				28 ±9.5
Shuttle/Centaur/kick/retro[c]				2.4	1.3	0.7	0.3	33 ±12.5

[a] All costs given in millions of dollars. Cost variations are strongly dependent upon production rate.

[b] Kick stage assumes I_s = 470 s, λ_s = 0.85, cost = \$7M ±2M.

[c] Retro assumes I_s = 400 s, λ_s = 0.90. One or two stages assumed; cost depends on number of stages and test items required

Table 3. Outer planet missions ΔV summary

Planet	Flight time, days	Flyby ΔV, km/s	Retro ΔV		Total ΔV	
			2 × 38 orbital radii, km/s	20 × 20 orbital radii, km/s	2 × 38 orbital radii, km/s	20 × 20 orbital radii, km/s
Jupiter	600	7.1	2.1	6.7	9.2	13.8
Saturn	1000	9.4	3.7	8.7	13.1	18.1
	1500	8.0	1.5	4.8	9.5	12.8
	2000	7.6	1.0	3.7	8.6	11.3
Uranus	1500	11.4	8.2	16.1	19.6	27.5
	2000	9.7	5.2	10.7	14.9	20.4
	2500	9.1	3.5	7.8	12.6	16.9
Neptune	2000	14.1	10.8	18.6	24.9	32.7
	2500	12.1	8.6	15.2	20.7	27.3
	3000	11.3	6.6	12.4	17.9	23.7

Table 4 Nuclear-electric propulsion cost estimates[a]

Item	System cost			
	200 kWe		300 kWe (with Centaur)	
Launch vehicle = Titan III	18		26	
Power subsystem (minimum)	25		30	
(maximum)		75		90
Thrust subsystem (minimum)	14		21	
(maximum)		30		45
System integration	8		8	
Auxilary power	-8		-8	
Totals	57	123	77	161
Launch vehicle = Shuttle (minimum)			5	
(maximum)				20
Power subsystem (minimum)			30	
(maximum)				90
Thrust subsystem (minimum)			21	
(maximum)				45
System integration			8	
Auxiliary power			-8	
Totals			56	155

[a]All costs given in millions of dollars.

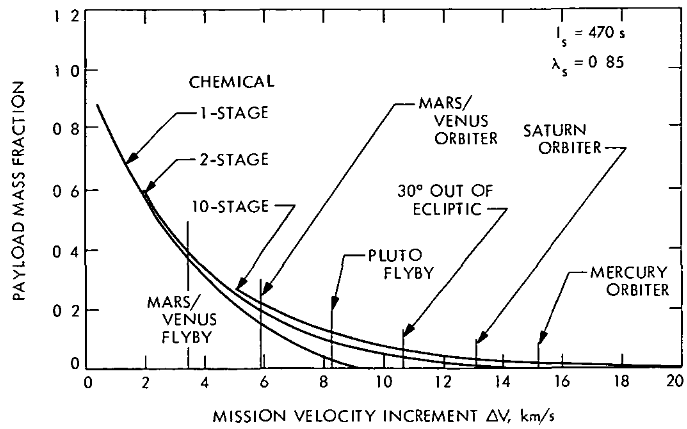

Fig. 1. Chemical propulsion mission performance

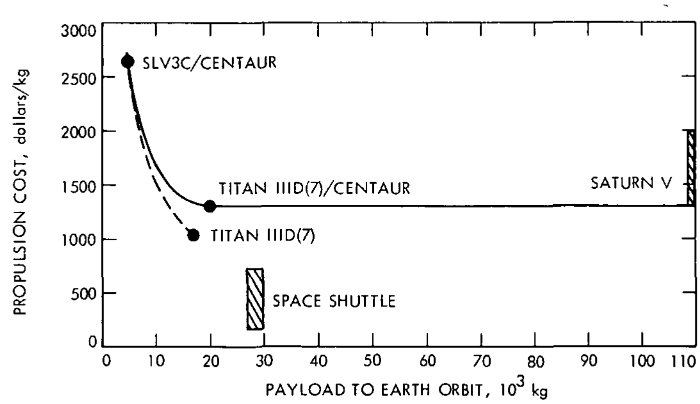

Fig. 2. Propulsion cost per unit payload to Earth orbit

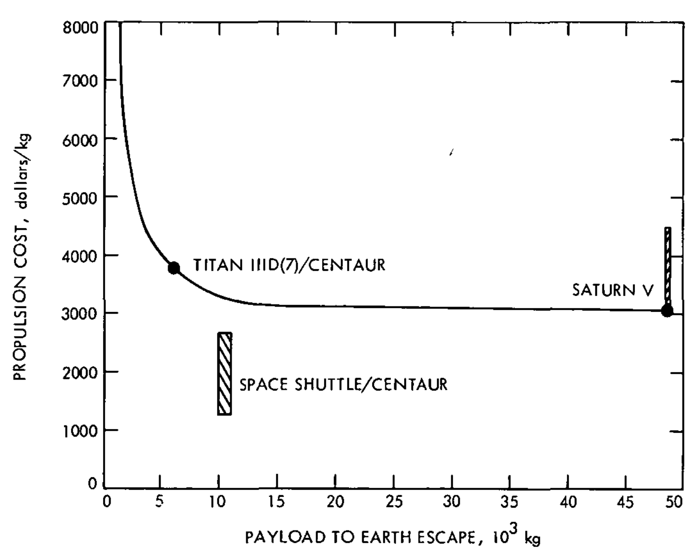

Fig. 3. Propulsion cost per unit payload to Earth escape

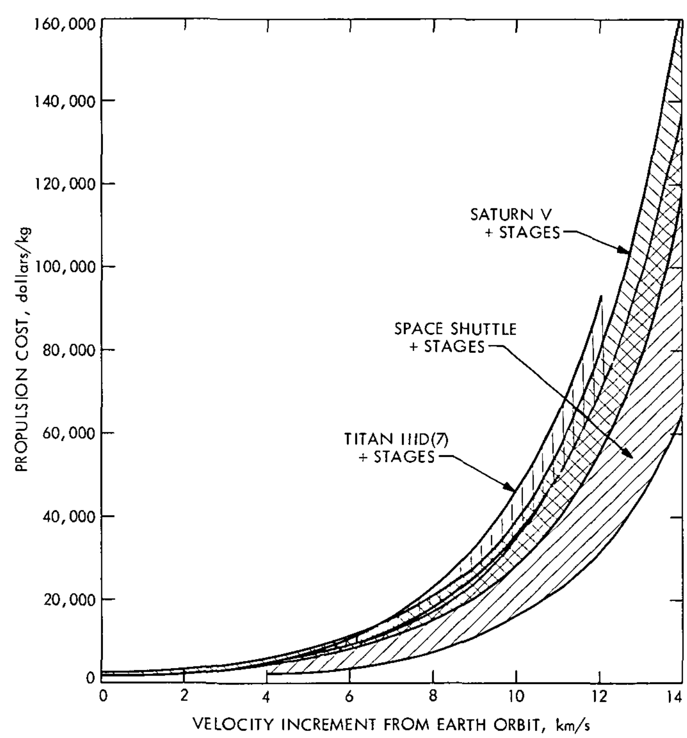

Fig. 4. Propulsion cost comparisons per unit payload beyond Earth orbit (chemical propulsion)

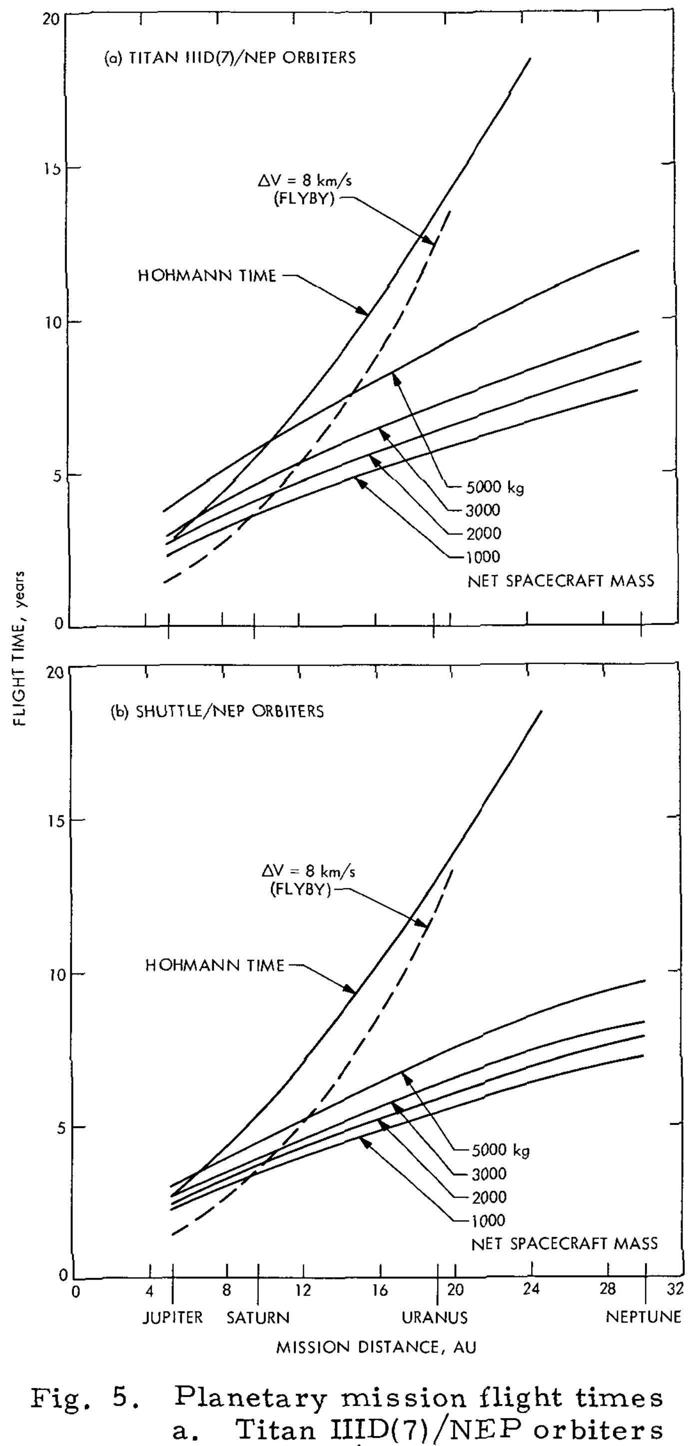

Fig. 5. Planetary mission flight times
a. Titan IIID(7)/NEP orbiters
b. Shuttle/NEP orbiters

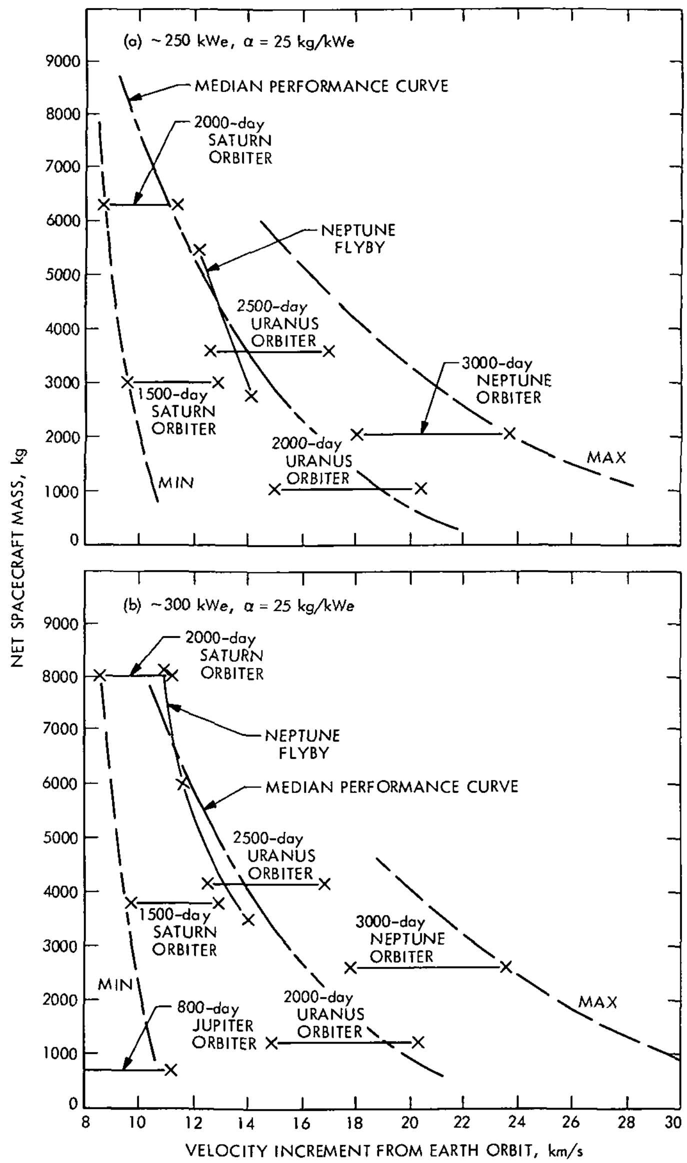

Fig. 6. NEP missions, spiral Earth escape
a. With Titan IIID(7)/Centaur
b. With single Shuttle launch

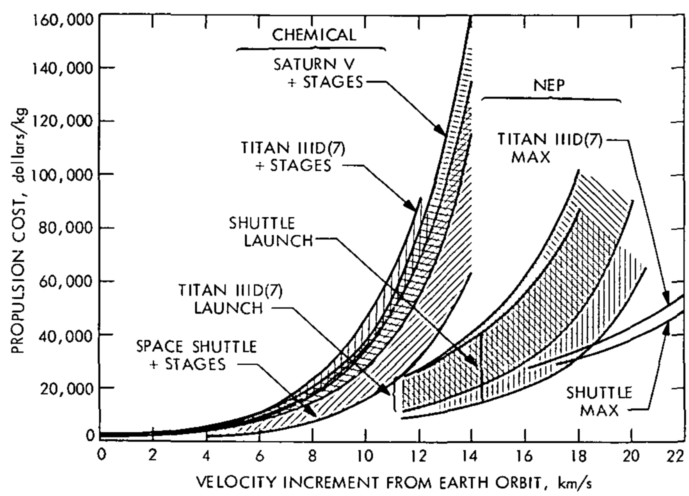

Fig. 7. Propulsion cost comparisons per unit payload beyond Earth orbit

APPENDIX A. MULTIPLE LAUNCH PERFORMANCE ESTIMATES

I Propulsion Comparisons

The exact requirements for assembly and checkout of large planetary vehicles in Earth orbit, in terms of orbital facilities, tools, manpower, control systems, and the like, have not yet been studied. The magnitude of the logistics problem is therefore unknown, and assessment of cost is not possible. However, if performance incentives for assembly of large planetary vehicles in Earth orbit can be shown, other studies will follow.

The Space Shuttle, presently in preliminary study phases, is conceptually capable of delivering a series of packages to Earth orbit. Characteristics assumed are a cargo mass of 27,000 kg and an envelope size of 4.6 m (dia) × 18.3 m. However, since this envelope is limiting to the hydrogen propellant of the nuclear rocket, we will also assume the ability to carry hydrogen fuel tanks external to the Shuttle. This will allow maximum weight utilization. We still expect the nuclear rocket itself, with its shielding, startup tank, and instrument package, to ride inside the Shuttle.

Comparative performance curves for chemical propulsion, nuclear rocket propulsion, and nuclear-electric propulsion are shown in Fig. A-1. Using net spacecraft mass as a parameter, the number of Shuttle launches to provide that payload to a given ΔV is plotted. Note that, by using chemical retropropulsion with the nuclear rocket for payloads between 1000 and 5000 kg, the crossover in the number of shuttle launches, i.e., where it becomes advantageous to use nuclear rocket stages rather than chemical stages, is never greater than three Shuttle launches.

Details of the three systems compared in Fig. A-1 are discussed below.

II. Chemical Propulsion

The optimization of chemical propulsion for planetary missions is strongly dependent upon the optimization of staging. The performance improves as the number of stages increases. Also, excepting launch to Earth orbit, a basic rule of thumb for multistage vehicles is to attempt to stage at velocity increments proportional to the exhaust velocity of the rocket. So long as the thrust acceleration of successive stages does not drop much below 0.5 g, gravity losses can be ignored.

One of the specific features of planetary missions is the need for long-term storage of propellant for retropropulsion at the destination planet. High-energy cryogenics, as was discussed above in Section II, have too many disadvantages to make them desirable for this purpose. Therefore, storable liquids are assumed with staging designed to meet the needs of retropropulsion velocity.

Dependent upon the details of mission design, a typical vehicle for planetary orbiter missions may appear somewhat as illustrated in Fig. A-2. A central, multistage core, with 1000-kg payload, is launched by a single Space Shuttle. Attached around this core are several 27,000-kg stages, with the number of stages dependent upon the C_3 requirement of the mission.

The two-stage retropropulsion assumes $I_s = 400$ s and $\lambda_s = 0.9$. The cryogenic stages for boost out of Earth orbit are assumed at $I_s = 470$ (potentially available F_2/H_2 rockets), and a stage fraction λ_s of 0.90. Because of an additional instrument package for guidance and control on the final cryogenic stage, the λ_s of that stage is expected to drop to 0.85.

It should be noted that the retropropulsion velocity requirement ΔV at the planet is arbitrarily assumed to be 6 km/s. Any variations around this nominal figure may be accommodated by further variation of payload.

Table A-1 shows the ΔV for each stage, utilizing the following expression for payload fraction:

$$\frac{M_L}{M_0} = \frac{1}{\lambda_s}\left[\exp\left(-\frac{\Delta V}{V_{ex}}\right) - (1 - \lambda_s)\right]$$

By appropriate adjustment of stage masses, payload may be scaled upward. That is, a net spacecraft mass of 2000 kg requires just double the number of Shuttle launches as for 1000 kg, and so forth. Thus a family of performance curves is generated, as in Fig. A-1.

III. Nuclear Rocket Propulsion

There are several different concepts of the nuclear rocket for multiple Shuttle launches. With so many options available, it is difficult to define a total concept that is generally applicable. The concept provided in this report is somewhat arbitrary. Extrapolation is made from existing solid-core rocket technology to a lightweight system. Since we are considering multiple propellant tanks, the rocket specific impulse must be penalized for long burn times. Chemical space-storable retropropulsion is utilized at the destination planet for smaller payloads, and this provides a much better tradeoff for the unmanned missions. A comparison of retropropulsion performance is shown in Fig. A-3. The nuclear rocket in this figure has also been penalized 3000 kg because it would be necessary to provide adequate cryogenic storage of hydrogen propellant by adding a nuclear-electric power topping cycle to operate compressors. The curves clearly illustrate the desirability of chemical retropropulsion. But even if a lesser penalty for cryogenic storage could be predicted, only small changes would be evident in the curves of Fig. A-3.

The nuclear rocket is assumed to have a specific impulse of 830 s and a system mass of 9000 kg. The hydrogen storage assumes a structural factor λ_s of 0.87. The 9000-kg system (including instrument package), plus 4000 kg propellant in the start tank, requires a separate Shuttle launch, since it fills the cargo volume available. The second Shuttle launch carries the payload package (spacecraft), the retropropulsion system, and a single filled hydrogen tank, with a total mass of 27,000 kg Additional Shuttle launches provide hydrogen propellant and tankage as strap-on modules at 27,000 kg each. Figure A-4 shows a possible system assembly.

Table A-2 presents a tabulation of ΔV for each "stage" for several payloads. At 5000 kg payload, retropropulsion may be assumed to be nuclear rocket, which Fig. A-3 shows to yield the same payload as the chemical retropropulsion at 6 km/s. (If there were no penalty for cryogenic storage, the 6 km/s crossover between chemical and nuclear retropropulsion would be at 4000 kg payload) For payloads in excess of 4000 kg, chemical retropropulsion requirements exceed second shuttle stage capability. At this point, configuration changes needed to support larger payloads would probably make use of nuclear rocket retropropulsion.

IV. Nuclear Electric Propulsion

Additional stages of nuclear electric propulsion are assumed to scale directly from the single Shuttle launch discussed in the main text of this report. Power plants may be operated in parallel, thus providing (at least in part) a redundancy which would tend to increase operational reliability.

Performance of NEP for multiple Shuttle launches is also included in Fig. A-1 for payloads up to 5000 kg. The spread between median and maximum chemical equivalent ΔV is illustrated. Curves are provided for purposes of comparison only. No attempt has been made to define the NEP missions for multiple Shuttle launches because single Shuttle launch already provides a very large increase in mission ΔV.

Table A-1. The ΔV capability of chemical stages with multiple shuttle launches

$$\left(\Delta V = -V_{ex} \ln \left[\lambda_s \frac{M_L}{M_0} + (1 - \lambda_s)\right]\right)$$

Stage	M_L, kg	M_0, kg	λ_s	V_{ex}, m/s	ΔV, m/s	$\Sigma \Delta V$, m/s
1 (Retro)	1,000	2,455	0.90	3924	2991	
2 (Retro)	2,455	6,045	0.90	3924	3000	6,000
3 (Core)	6,045	16,500	0.85	4610	3589	
4 (Core)	16,500	27,000	0.90	↓	1986	11,585
5 (Strap-on)	27,000	54,000	↓		2756	14,331
6 ↓	54,000	81,000			1644	15,975
7	81,000	108,000			1175	17,150
8	108,000	135,000			915	18,065
9	135,000	162,000			749	18,814

Table A-2. The ΔV capability of nuclear rocket stages with multiple shuttle launches

$$\left\{ \Delta V = -V_{ex} \ell n \left[\lambda_s \frac{M_L}{M_0} + (1 - \lambda_s) \right] \right\}$$

Net spacecraft (payload), kg	Stage	M_L, kg	M_0, kg	λ_s	V_{ex}, m/s	ΔV, m/s	$\Sigma\Delta V$, m/s
1000	1 (Retro)	1,000	2,455	0.90	3924	2991	
	2 (Retro)	2,455	6,045	0.90	3924	3000	6,000
	3 (Core)	15,045	40,000	0.87	8140	6388	12,388
	4 (Strap-on)	40,000	67,000			3514	15,902
	5	67,000	94,000			2341	18,243
	6	94,000	121,000			1757	20,000
	7	121,000	148,000			1407	21,407
2000	1&2 (Retro)	2,000	12,000	0.90	3924	6000	6,000
	3 (Core)	21,000	40,000	0.87	8140	4340	10,340
	4 (Strap-on)	40,000	67,000			3514	13,854
	5	67,000	94,000			2341	16,195
	6	94,000	121,000			1757	17,952
	7	121,000	148,000			1407	19,359
3000	1&2 (Retro)	3,000	18,000	0.90	3924	6000	6,000
	3 (Core)	27,000	40,000	0.87	8140	2705	8,705
	4 (Strap-on)	40,000	67,000			3514	12,219
	5	67,000	94,000			2341	14,560
	6	94,000	121,000			1757	16,317
	7	121,000	148,000			1407	17,724
4000	1&2 (Retro)	4,000	24,000	0.90	3924	6000	6,000
	3 (Core)	33,000	40,000	0.87	8140	1344	7,344
	4 (Strap-on)	40,000	67,000			3514	10,858
	5	67,000	94,000			2341	13,199
	6	94,000	121,000			1757	14,956
	7	121,000	148,000			1407	16,363

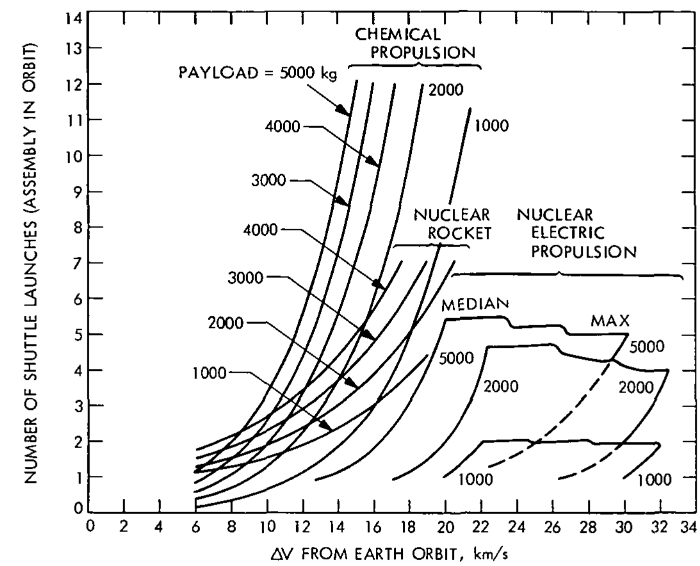

Fig. A-1. Propulsion performance comparisons for multiple Shuttle launches

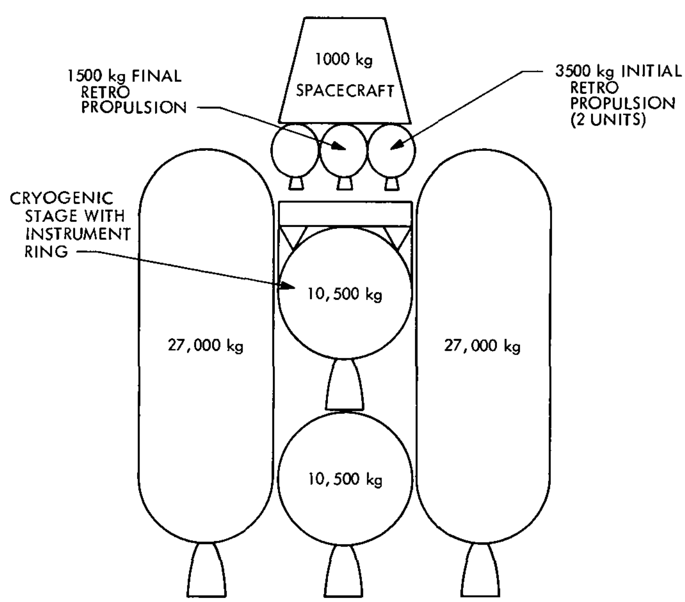

Fig. A-2. Chemical propulsion system concept for multiple Shuttle launches and assembly in orbit

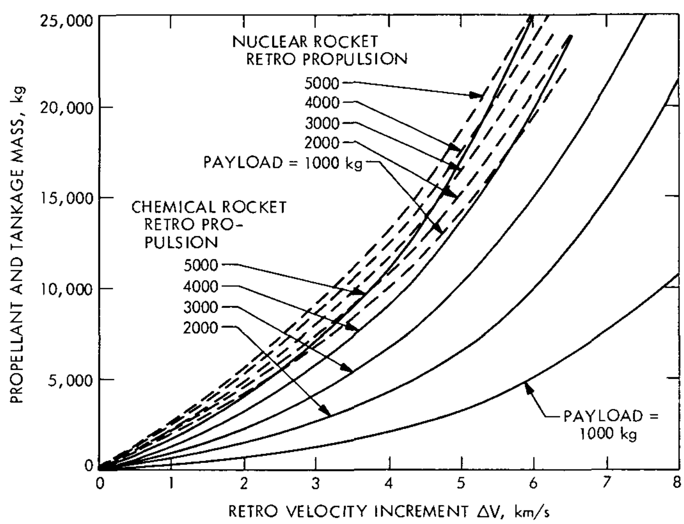

Fig. A-3. Planetary retropropulsion performance comparison, chemical vs nuclear rocket

Fig. A-4. Reusable nuclear stage multiple-tank concept

APPENDIX B. NONRECURRING COSTS

Arguments are sometimes presented, in the comparison of costs, wherein nonrecurring costs are a major concern. Generally, the problem appears when a vehicle is to be developed to replace an existing vehicle. In such a case, the new vehicle is expected to amortize its development costs according to some formula.

Allocation and amortization of technology and development costs were assumed by the author after private communications with several sources. A summary of launch vehicle and upper stage propulsion estimates is shown in Table B-1. For purposes of this comparison, all vehicles and stages were assumed to be equally available.

Multiple-shuttle-launch missions were considered for chemical propulsion assuming zero cost for manned Earth-orbital assembly operations. For comparable chemical and NEP payloads, a comparison of recurring costs, with and without nonrecurring costs, can therefore be shown as in Table B-2. The Titan and Shuttle are each listed as launch vehicles and, for these, the chemical propulsion and nuclear-electric propulsion are tabulated. Use is made of tables and figures in the main body of the report and in Appendix A in order to select recurring costs and net spacecraft mass at mission ΔV values of 10 and 12 km/s from Earth orbit.

The introduction of nonrecurring cost into propulsion comparisons makes little change in the overall picture for the amortization rates assumed. In all cases, with or without nonrecurring costs, the NEP per-unit cost advantage over chemical propulsion is on the order of 250-300%. However, costs are up approximately 50% during the amortization period.

Table B-1. Nonrecurring cost estimates of launch vehicles and upper stages[a]

Vehicle or stage	Number of flights to amortize	Nonrecurring costs		Total cost per flight, with recurring cost
		Total	Per flight	
Shuttle	1000	5,000 - 10,000	5-10	10-30
Titan IIID(7)	10	60 - 100	6-10	24-28
Centaur	0	0	0	8
Kick stage	10	40 - 100	4-10	9-19
Retro stage	10	10 - 20	1-2	3-10
NEP	10	300 - 600	30-60	81-195

[a]All costs given in millions of dollars.

Table B-2. Mission costs of propulsion, showing effect of nonrecurring cost[a]

Type of launch	ΔV = 10 km/s		ΔV = 12 km/s	
	Chemical	NEP	Chemical	NEP
Shuttle launch	(7 launches)	(1 launch)	(9 launches)	(1 launch)
Net spacecraft mass, kg	9100	9000	5850	6000
Recurring cost	\$140-322M	\$56-155M	\$180-414M	\$56-155M
Cost per kilogram	\$15-35K	\$6-17K	\$31-71K	\$9-26K
Recurring and nonrecurring cost	\$210-476M	\$91-225M	\$270-612M	\$91-225M
Cost per kilogram	\$23-52K	\$10-25K	\$46-105K	\$15-38K
Titan IIID(7) launch	(8 launches)	(1 launch)	(11 launches)	(1 launch)
Net spacecraft mass, kg	7600	7500	5170	5300
Recurring cost	\$264-344M	\$77-161M	\$363-473M	\$77-161M
Cost per kilogram	\$35-45K	\$10-21K	\$70-91K	\$15-30K
Recurring and nonrecurring cost	\$352-520M	\$113-231M	\$484-715M	\$113-231M
Cost per kilogram	\$46-68K	\$15-31K	\$94-138K	\$21-44K

[a]M = millions of dollars; K = thousands of dollars.

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16. Abstract

Cost and performance comparisons are made between chemical propulsion and nuclear electric propulsion for planetary missions at Jupiter and beyond. Nuclear rocket comparisons are made for performance only. Titan, Saturn, and Space Shuttle launch are evaluated, utilizing advanced propulsion upper stages. Appendixes include a performance analysis of multiple Shuttle launches, with assembly in Earth orbit, and a discussion of non-recurring costs.

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