[4] Montgomery, H. E. and Paddack, S. J., "EGO Launch Window and Orbit," Doc. X-640-63-119, July 1963, NASA.

[5] Paddack, S. J. and Shute, B. E., "IMP-C Orbit and Launch Time Analysis," Doc. X-643-65-40, Jan. 1965, NASA.

[6] Shute, B. E., "Prelaunch Analysis of High Eccentricity Orbits," TN D-2530, Dec. 1964, NASA.

[7] Shute, B. E. and Chiville, J. A., "The Lunar-Solar Effect on the Orbital Lifetimes of Artificial Satellites with Highly Eccentric Orbits," *Planetary and Space Science*, Vol. 14, 1966, pp. 361–369.

[8] Leroy, R. and Pacé, H., "HEOS: Etude de Stabilité d'Orbite," SEREB Doc. ESRO 89/65, St. Aubin, April 1965, European Space Research Organization.

[9] Leroy, R., Pacé, H., and Mauroy, V., "HEOS: Etudes Complémentaries," SEREB Doc. ESRO 88-65, St. Aubin, Dec. 1965, European Space Research Organization.

[10] Renard, M. L., "HEOS-A Orbit," ESRO Int. Doc. DSP/65, June 1965, European Space Resesearch Organization.

[11] Roth, E. A., "Launch Windows for HEOS-P," ESTEC Int. Note 47, Sept. 1966, European Space Research Organization.

[12] Göllnitz, H. and Renard, M. L., "Orbital Restraints on the Release of a Body Along a Highly Eccentric Orbit," Rept. 28/66, Oct. 1966, Max Planck Institute for Extraterrestrial Physics, Munich.

[13] Göllnitz, H. and Renard, M. L., "Release Windows for the Ejection of a Body Along a Highly Eccentric Orbit," *Astronautica Acta*, Vol. 14, No. 1, Nov. 1968, pp. 23–46.

[14] Moe, M. M., "Solar-Lunar Perturbations on the Orbit of an Earth Satellite," *ARS Journal*, Vol. 30, No. 5, 1960, pp. 485–487.

[15] Pragluski, W., Stricker, J., and Miessner, W., "Launch Window Study and Analog Orbit Stability Program," Rept. ER 13634, Oct. 1964, Martin-Marietta Corp.

[16] Stricker, J. and Miessner, W., "Launch Window Program," *Simulation*, Vol. 7, No. 3, 1966, pp. 134–141.

[17] Renard, M. L., "Approximate Stability Criteria for Highly Eccentric Orbits About the Earth," *Proceedings of the 19th International Astronautical Congress*, 1969, Pergamon Press, pp. 13–25.

[18] Lidov, M. L., "The Evolution of Orbits of Artificial Satellites of Planets under the Action of Gravitational Perturbations," *Planetary and Space Science*, Vol. 9, 1962, pp. 719–759; Transl. *Isk. Sputniki Zemli*, Vol. 8, No. 5, 1961.

[19] Renard, M. L. and Sridharan, R., "Launch Window of a Highly Eccentric Satellite in an Orbit Normal to the Ecliptic: IMP-G," Preprint 9th Semi-Annual Astrodynamics Conference, Goddard Space Flight Center, April 1969.

[20] Paddack, S. J., "IMP-G Orbit and Launch Time," Doc. X-724-69-252, June 1969, NASA.

[21] Kovalevsky, J., "Sur la Théorie du Mouvement d'un Satellite à Fortes Inclinaison et Excentricité," Reprint, International Astronomical Union, Symposium No. 25, 1966.

[22] Lidov, M. L., "On the Approximated Analysis of the Orbit Evolution of Artificial Satellites," *Proceedings of the 14th International Astronautical Congress*, 1964, Springer-Verlag, pp. 168–179.

OCTOBER 1970 J. SPACECRAFT VOL. 7, NO. 10

Alternative Space Transportation Systems for Several Potential National Space Programs

ROBERT SALKELD*

410½ Landfair Avenue, Westwood Village, Los Angeles, Calif.

A general analytical structure for comparing total costs of alternative space transportation system families is formulated against the background of traffic requirements for several potential national space programs. First, payload capabilities and cost characteristics of existing and projected transportation systems are explored to identify which constitute meaningful families. Next, traffic requirements are projected for a range of possible space programs, including cases where emphasis is on near-orbit or far-orbit operations or both, and for different levels of national effort. Then, analytic expressions are written for the total recurring and nonrecurring costs for each system combination, breakeven conditions are determined, and regions of economic preference are plotted, against which are shown projected traffic requirements. The outcome can be quite sensitive to the near-orbit vs far-orbit traffic fraction, as well as to the projected size of the national space program. If only one system is to be developed, there are strong indications that it should be in a medium size range.

Nomenclature

C = total (development plus operational) cost
c = operational cost/lb in near orbit
D = system development cost
F = funded space transportation system
P = projected space transportation system
t = time from initial system operation
W = total weight placed in orbit

Subscripts

f = large (>250,000 lb in near orbit)
l_m = funded system (medium)
f_s = funded system (small)
m = medium (25,000–250,000 lb in near orbit)
p = projected system (large)
pm = projected system (medium)
ps = projected system (small)
s = small (10,000–25,000 lb in near orbit)

Received November 3, 1969; revision received May 18, 1970.
* Consultant. Associate Fellow AIAA.

Introduction

WHATEVER the scope, scale, and growth rates of the national space program beyond the Apollo lunar landing project, it is clear that analytical studies to identify the most economical families of space transportation systems will be a central space planning task. The requirement for such studies was stressed by Heiss and Morgenstern.[1] Recent work in this area, as represented in Ref. 2, has included some treatment of the general question of comparison between alternative systems. It is a complex question, which can

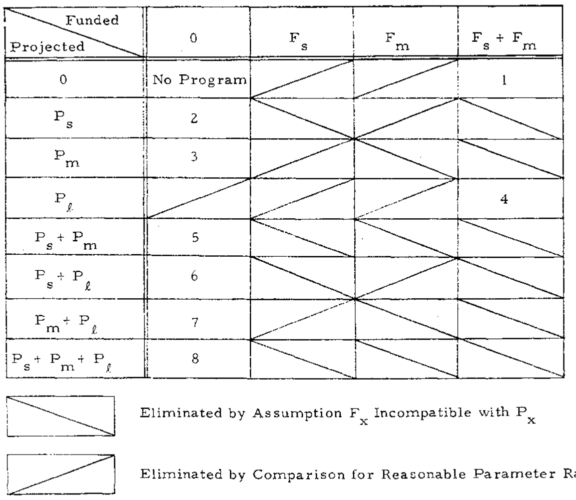

Fig. 1 Matrix of funded and projected space transportation systems.

encompass considerations of versatility, operational factors and system development approach, as pointed out by Morris.[3] Its mathematical treatment can be greatly elaborated as in Stroup.[4]

The purpose of this study is to formulate a simplified, tractable analytical structure for comparing the economics of possible post-1975 families of space transportation systems. The approach is to compare the parametric cost expressions for programs involving several likely system combinations, including both funded and projected systems, against the background of a number of possible space transportation requirements to obtain analytical trends indicating which future transportation system development efforts, if any, are economically preferable. The structure is framed to show in particular the sensitivity of the outcome, to the near-orbit vs far-orbit traffic fractions.

Space Transportation Systems

For purposes of classifying mission requirements, space can be divided into three regions; near-orbit space (100–500 naut miles altitude), for which round-trip transportation velocity gains (ΔV) in the order of 26,000 fps plus losses are required; the magnetosphere (500 $\sim$ 50,000 naut miles altitude), 26,000–40,000 fps plus losses; and far-orbit operations (beyond $\sim$50,000 naut miles altitude), 40,000–45,000 fps plus losses (Table 1). For each region, four typical kinds of missions and equivalent near-orbit payloads can be roughly identified: 1) unmanned spacecraft, $\leq$15,000 lb; 2) manned shuttle payloads, 10,000–25,000 lb; 3) manned stations, 25,000–250,000 lb; and 4) lunar and interplanetary payloads, >250,000 lb. Corresponding size categories of space transportation systems are: 1) unmanned, 2) small, 3) medium, and 4) large, respectively. Typical vehicles of the unmanned category would be the Atlas/Agena, Thor/Agena, and many others. A typical small launch vehicle already funded (F_s) would be the Titan III-C. As technology advances, F_s may be superseded by some projected small system (P_s), such as a reusable shuttle vehicle. A typical medium launch vehicle already funded (F_m) is the Saturn V. This may eventually be superseded by a P_m, perhaps involving nuclear propulsion and partial or total reusability. There is at present no funded large vehicle (F_l), although Saturn V may (in up-rated versions) be capable of partially assuming this role; P_l have been visualized, including such concepts as Nova and Orion.

No manned missions are shown in the magnetosphere in Table 1 because it is difficult to visualize a requirement sufficiently strong to justify the heavy weight penalities which would be associated with Van Allen belt shielding. Because of the higher ΔV associated with far-orbit operations, each vehicle category can be associated with the next lower payload range in far orbit than in near orbit.

Table 2 lists the orbital payload capabilities, operating costs and development costs to be associated with the two funded and three projected space transportation systems. The costs associated with the funded vehicles are reasonably well-known. The costs assumed for the three projected vehicles are thought to be representative of typical results of prior studies by others, and they will be varied parametrically later.

Figure 1 shows all possible combinations of the aforementioned systems. In evaluating the realism of some of these combinations, it is assumed that it would not be meaningful to program a family of boosters containing both a funded and projected vehicle system in the same size range. Such cases are therefore eliminated from consideration. In addition, certain other elements of the matrix can be eliminated as economically undesirable by quantitative comparison of their costs over reasonable parameter ranges. Finally, the case representing no space program at all is eliminated as trivial. After these eliminations, eight candidate national booster families remain.

Space Traffic Projections

Two basic areas of uncertainty are 1) the total level of effort the nation will decide to invest, and 2) which regions of space will be shown to be most appropriate for what types of operations. For example, whereas near-orbit space has lower transportation costs and satellite power requirements and higher photographic resolution for Earth surveillance, far-orbit operations have better line-of-sight coverage of the Earth, lower maneuvering velocity requirements, and reduced vulnerability to ground fire.

To attempt to bracket these uncertainties, Table 3 includes three levels of effort, denoted I, II, and III in order of increasing effort. For each level of effort, general emphasis may be placed on near- or far-orbit operations, or approximately divided between the two. Thus, nine potential space programs are considered. For each program, a number of launches is

Table 1 Classes of space missions and transportation systems

Region	Unmanned satellites, $\leq$15 klb	Manned shuttle, 10–25 klb	Manned station, 25–250 klb	Lunar, interplanetary >250 klb
Near orbits ($\Delta V \sim$ 26,000 + losses)	Atlas/Agena (typical)	F_s(T-IIIC) P_s	F_m(S-V) P_m	F_m(S-V) P_l
Magnestosphere ($\Delta V \sim$ 26–40,000 + losses)	Atlas/Agena (typical) F_s(T-IIIC)	...	...	...
Far orbits ($\Delta V \sim$ 40–45,000 + losses)	F_s(T-IIIC) P_s	F_m(S-V) P_m	F_m(S-V) P_l	(P_l)

Table 2 Near-orbit payloads (W) and operating (c) and development (D) costs for funded and projected space transportation systems

System	W, 10^3 lb	c, \$/lb	D, 10^9 \$
F_s (Titan III-C)	25	500	1
F_m (Saturn V)	250	250	3
P_s (Reusable? H_2-O_2)	25	100?	3?
P_m (Reusable? H_2-O_2)	125	50?	5?
P_l (Nova, etc.)	1000	25?	5?

postulated for flights to near orbits, far orbits, and lunar and interplanetary missions. Only manned or man-related launches are considered, since they are assumed to play the dominant role in the space program. Any extensive unmanned interplanetary program is assumed to require manned orbital platforms for assembly, checkout, and launch, and its transportation requirements are assumed to be included in the total logistics activity shown for such studies. That reduced space transportation costs enhance the economic desirability of manned servicing of unmanned equipment, is demonstrated in Ref. 5. The range of traffic requirements embraced by Table 3 is thought to be sufficiently broad to include virtually the full spectrum of national level-of-effort projections currently under serious consideration. For each region of space operations, space launches of these three types (shuttle, station, and logistic) are listed, and the class of booster required for each is indicated by a letter in parentheses.

The projected large launch vehicle (P_l) has been left out since, as will be shown subsequently, it is doubtful that development of P_l represents a reasonable course of action, even for the heaviest launch weights assumed. Also, for case I no manned interplanetary activities and only a very minimal lunar program are visualized. In general, the number of flights assumed for case II is approximately twice the number for case I, and the number required for case III is approximately three times that required for case II. These assumptions result in a spectrum of national space programs involving from 16 to 22 manned launches per year for case I, to 184–241 manned launches per year for case III.

Table 4 converts the number of flights per year as given in the preceding chart to number of pounds launched per year, simply multiplying by the appropriate orbital payload capability of each launch vehicle. This results in annual manned launch rates from about one million lb/yr for case I to nearly 30 million lb/yr for case III.

Analysis

For each of the eight candidate system families shown in Fig. 1, total cost may be expressed as follows:

$$C_1 = 0 + c_{fs}W_s + c_{fm}W_m + c_{fm}W_l \quad (1)$$

$$C_2 = D_{ps} + c_{ps}W_s + c_{ps}W_m + c_{ps}W_l \quad (2)$$

$$C_3 = D_{pm} + 5c_{pm}W_s + c_{pm}W_m + c_{pm}W_l \quad (3)$$

$$C_4 = D_{pl} + c_{fs}W_s + c_{fm}W_m + c_{pl}W_l \quad (4)$$

$$C_5 = D_{ps} + D_{pm} + c_{ps}W_s + c_{pm}W_m + c_{pm}W_l \quad (5)$$

$$C_6 = D_{ps} + D_{pl} + c_{ps}W_s + c_{ps}W_m + c_{pl}W_l \quad (6)$$

$$C_7 = D_{pm} + D_{pl} + 5c_{pm}W_s + c_{pm}W_m + c_{pl}W_l \quad (7)$$

$$C_8 = D_{ps} + D_{pm} + D_{pl} + c_{ps}W_s + c_{pm}W_m + c_{pl}W_l \quad (8)$$

In the cases where P_m is utilized to launch small payloads, a factor of 5 penalty is taken since only about one-fifth the total payload capability of the vehicle is utilized in these cases. Neither F_m nor P_l is used to launch smaller payloads than those for which it is intended, since these cases can be shown to be unsound economically because of the high operating costs of F_m and P_l. Where payloads are launched in segments by smaller vehicles, some weight penalties must inevitably be allowed for assembly and refueling. Such a penalty is not shown in these expressions, but is introduced later in the study.

If Eqs. (1–8) are set equal, the resulting expressions give the corresponding break-even conditions. The equation for break-even between, for example, system family A and system family B expresses in effect the total weight which must be placed in orbit by, say, system A before the difference in development costs of A and B can be amortized by the savings per pound in orbit associated with A. The plot of this equation forms the boundary between the regions of economic preference for A and B.

Figure 2 shows the regions of economic preference for the eight candidate system families for various combinations of total cumulative weight in orbit for small payloads, medium payloads, and large payloads (W_s, W_m, and W_l). Both W_s and W_m are allowed to vary between 0 and 100 million lb and W_l is allowed to vary from 0 to 400 million lb. For $W_l = 0$, it is seen that in the small triangular region near the origin corresponding to W_m <20 million lb and W_s <8 million lb, there will be insufficient launch activity for a projected transport system to pay for its own development costs, so that the least-cost alternative would be to develop no new boost sys-

Table 3 Numbers of flights per year for alternative national space programs for three levels of effort (I-III) and three emphasis categories

		I			II			III		
	Mission[a]	Near	Both	Far	Near	Both	Far	Near	Both	Far
Near orbits	Manned shuttle (s)	15	10	5	25	15	5	75	45	15
	Space station (m)	2	1	0	5	2	0	15	6	0
	Logistic (m)	1	1	0	2	1	0	6	3	0
Far orbits	Manned shuttle (m)	0	2	5	2	5	10	6	15	30
	Space station (m)	0	0	0	0	5	10	0	15	30
	Logistic (m)	0	1	2	0	2	5	0	6	15
Lunar	Manned shuttle (m)		2			5			15	
	Space station (m)		0			0			1	
	Logistic (m)		2			5			15	
Interplanetary	Manned shuttle (s or m)		...		10 (s)	10 (s)	10 (m)	30 (s)	30 (s)	30 (m)
	Space station (m)		...		1	1	5	3	3	15
	Logistic (m)		...		10	10	25	30	30	75
Total flights	F_s or P_s	15	10	5	35	25	5	105	75	15
	F_m or P_m	7	9	11	30	36	75	91	109	226

[a] Letter in parentheses shows size of F or P required.

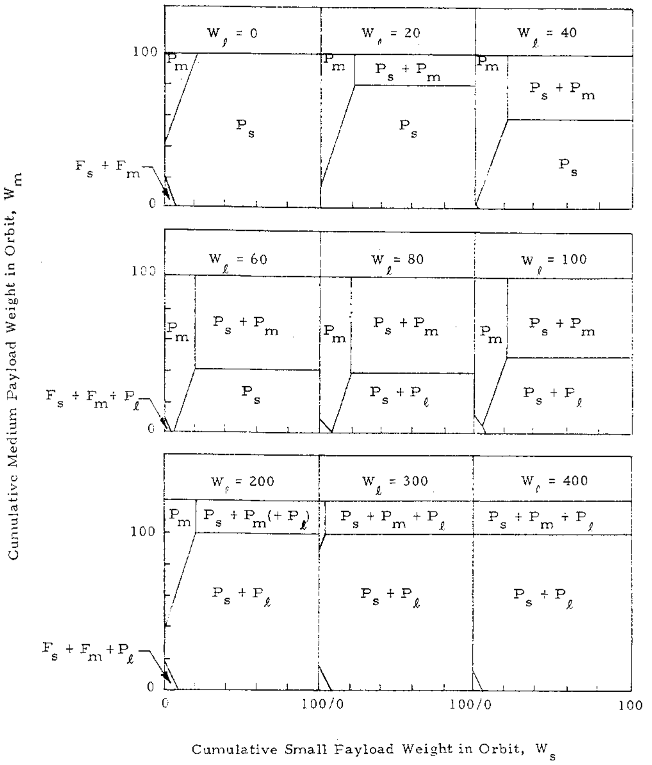

Fig. 2 Regions of economic preference (referred to total equivalent weights in near orbit, in millions of lb).

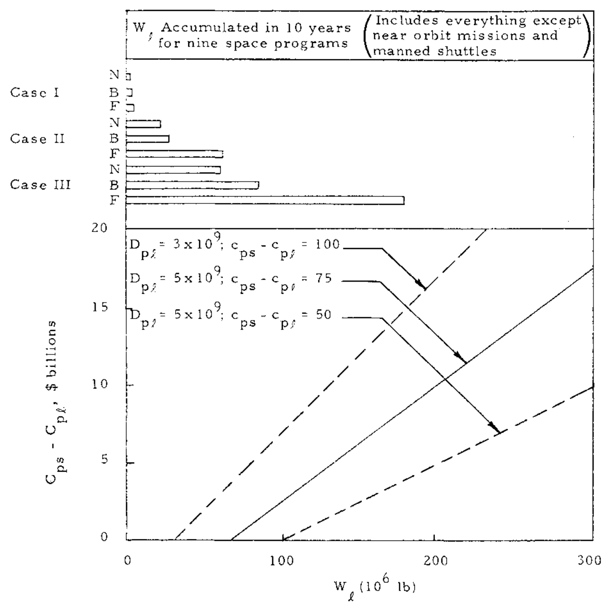

Fig. 3 Cost savings using ($P_s + P_l$) instead of (P_s) $C_{ps} - C_{ps+pl} = D_{pl}(c_{ps} - c_{pl})W_l$.

tem and to continue to use F_s and F_m. As W_s and W_m increase beyond this small region, the development of P_s becomes preferable. For W_s <20 million lb, as W_m increases past the 40 to 100 million-lb level, it becomes economically desirable to develop P_m. For $W_s > 20$ million lb and for $W_m > 100$ million lb, it is economically preferable to develop both P_s and P_m. The remaining material in Fig. 2 shows that as W_l increases, there are expansions of the regions of economic preference for booster families containing P_m and eventual appearance of regions for families containing P_l.

Several indications arise at this point. First, the booster combination $P_m + P_l$ never appears economically preferable. Second, $F_s + P_m + P_l$ appears preferable only if the total cumulative weight of large payloads (W_l) is at least an order of magnitude greater than total cumulative weight of either the small (W_s) or medium (W_m) payloads, which seems unlikely. Third, $P_s + P_m + P_l$ appears preferable only if $W_l >$ 200 million lb, certainly an improbable projection for any 10 to 20 year evaluation period for which such a booster decision would be made. Fourth, $P_s + P_l$ appear preferable only if $W_l >$ 67 million lb. Whether or not this is a realistic condition is treated in Fig. 3.

Figure 3 shows the savings that can be obtained by utilizing $P_s + P_l$ instead of P_s, as a function of W_l. The nominal case is shown by the solid line (which becomes positive at $W_l = 67$ million lb), accompanied by dotted lines showing the results obtained with different combinations of development and operational cost parameters, that are thought to be representative of bounding conditions. The upper portion of the figure shows the expected values of W_l over a 10-yr period resulting from the nine potential national space programs discussed above. The expected values are thought to represent high estimates for W_l, since they were taken to include all launches shown on the nine potential space programs, except near orbit missions and manned shuttles.

Comparison of the two portions of the chart shows that for the nominal case, only one of the nine postulated space programs involves high enough launch rates to benefit signifi-

Table 4 Weight in orbit per year for alternative national space programs (near-orbit equivalent weights in millions of lb/yr)

		I			II			III		
	Mission[a]	Near	Both	Far	Near	Both	Far	Near	Both	Far
Near orbits	Manned shuttle (*s*)	0.375	0.250	0.125	0.625	0.375	0.125	1.875	1.125	0.375
	Space station (*m*)	0.250	0.125	0	0.625	0.250	0	1.875	0.750	0
	Logistic (*m*)	0.125	0.125	0	0.250	0.125	0	0.750	0.375	0
Far orbits	Manned shuttle (*m*)	0	0.250	0.625	0.250	0.625	1.250	0.750	1.875	3.750
	Space station (*m*)	0	0	0	0	0.625	1.250	0	1.875	3.750
	Logistic (*m*)	0	0.125	0.250	0	0.250	0.625	0	0.750	1.875
	Manned shuttle (*m*)		0.250			0.625			1.875	
Lunar	Space station (*m*)		0			0			0	
	Logistic (*m*)		0.250			0.625			1.875	
	Manned shuttle (*s* or *m*)		...		0.25 (*s*)	0.25 (*s*)	1.25 (*m*)	0.75 (*s*)	0.75 (*s*)	3.75 (*m*)
Interplanetary	Space station (*m*)		...		0.125	0.125	0.625	0.375	0.375	1.875
	Logistic (*m*)		...		1.250	1.250	3.125	3.750	3.750	9.375
Total wt/yr.	$\dot{W}_s$	0.375	0.250	0.125	0.875	0.625	0.125	2.625	1.875	0.375
	W_m	0.875	1.125	1.375	3.750	4.500	9.375	11.375	13.625	28.250

[a] Letter in parentheses shows size of *F* or *P* required.

cantly from the development of P_l. Even for the most optimistic assumptions about the development and operating costs of P_l, it is seen that significant cost benefits can be obtained by its development only in case III and possibly one of the case II programs. Further, it can be seen that this result would not change significantly even if a 15- or 20-yr operational period were considered. It is thus clear that barring some special unforeseen requirement, only for the most extreme assumptions about the scope and intensity of the national space program and about the development and operating costs of P_l, can the development of such a system be justified. The large launch vehicle will therefore be excluded from the remainder of the study.

Thus, four of the eight candidate system families drop from consideration, leaving four as primary possibilities, the total costs for which are expressed by Eqs. (1, 2, 4, and 5) which can be rewritten as follows:

$$C_{fs+fm} = (c_{fs}\dot{W}_s + c_{fm}\dot{W}_m)t \tag{9}$$

$$C_{ps} = D_{ps} + (\dot{W}_s + \dot{W}_m)\, c_{ps}\, t \tag{10}$$

$$C_{pm} = D_{pm} + (5\dot{W}_s + \dot{W}_m)\, c_{pm}\, t \tag{11}$$

$$C_{ps+pm} = D_{ps} + D_{pm} + (c_{ps}\dot{W}_s + c_{pm}\dot{W}_m)\, t \tag{12}$$

Using breakeven conditions derived from Eqs. (9–12), Fig. 4 superimposes 10-yr cumulative weights associated with the nine possible future space programs against the background of the previously discussed breakeven diagram. (Since P_l has been eliminated, the breakeven diagram assumes $W_l = 0$.)

The results indicate that for the space programs associated with case I level of effort, the cumulative weights involved are such that all three programs seem to fall just barely within the region of preferability for $F_s + F_m$, implying that use of funded systems and the development of P_s are essentially of equal economic preferability. The six potential programs associated with cases II and III levels of effort, however, clearly fall within regions favoring the development of one or more new systems. Specifically, case II favors the development of P_s except for the case where emphasis is placed on far-orbit operations, in which case P_m is indicated. For case III, the development of P_m is favored, except for emphasis on near-orbit operations, in which case the analysis favors development of both P_s and P_m.

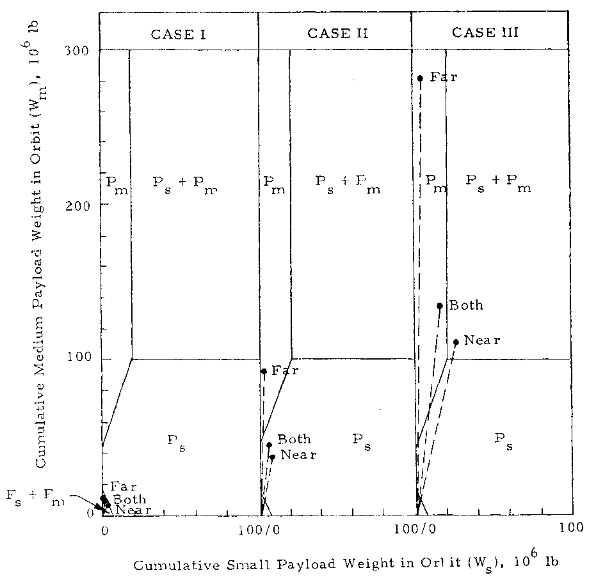

Fig. 4 Least-cost space transportation systems for nine potential national space programs (ten years of operation; D_{ps} = \$3 billion; D_{pm} = \$5 billion; no penalty for assembly).

In all of these cases, even for emphasis on near-orbit operations, the total cumulative launched weights associated with medium-sized payload (W_m) predominates.

If these diagrams were drawn for operational periods of 15 or 20 yr instead of the 10 yr shown here, the analysis would clearly favor the development of one or two new launch vehicles in every case. This is important to bear in mind, since it may not be unreasonable to require systems costing many billions of dollars to develop, to be useful for greater than a 10-yr period after their initial availability.

As emphasized at the outset, the values used for c and D are no more than assumptions; let us examine the effects caused by changing them. In the analysis to this point, DP_s and DP_m have been assumed to be 3 billion and 5 billion dollars, respectively. The following calculations will include changing these values to 2 billion and 3 billion dollars, respectively. The launch costs, c_{ps} and c_{pm} have been assumed to be \$100 and \$50 per lb in orbit, respectively, and the following calculations will assume also \$150 and \$100 per lb in orbit respectively. When using P_m to launch small payloads, it has been assumed that F_m increases by a factor of 5 to reflect the fact that only $\frac{1}{5}$ of the payload capability of P_m is used. In reality, however, it should be expected that if a P_m vehicle were developed with the intention of using it for small as well as medium payloads, the program would include development of a set of upper stages to be used with the medium first stage but optimized for small payloads. To allow for such a case, the following calculations will show the effects of increasing the basic c by a factor of 3 as well as a factor of 5. Finally, in order to reflect the inevitable penalties associated with assembly of payloads in orbit when small vehicles are used to launch medium or large payloads in segments, the effects of a 25% assembly weight penalty as well as zero penalty will be shown.

Against the background of two patterns of breakeven regions associated with these two sets of parametric assumptions, Figs. 5 and 6 show the cumulative weight conditions for the nine potential space programs after 10 yr of operations.

Condition A (Fig. 5) includes the high development and launch cost assumptions and no penalty for assembly or refueling. These assumptions are obviously the least favorable for

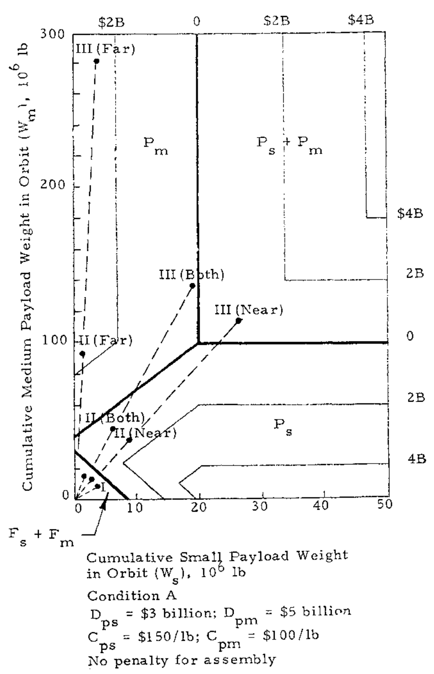

Fig. 5 Least-cost space transportation systems for nine potential national space programs (parametric Condition A; ten years of operations; P_m has both m and s upper stages).

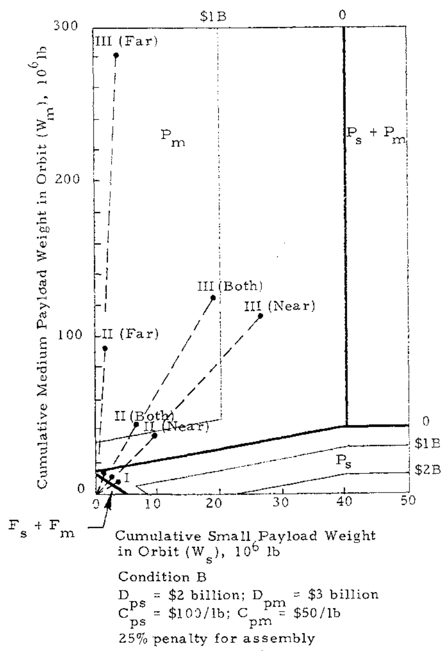

Fig. 6 Least-cost space transportation systems for nine potential national space programs (parametric Condition B; ten years of operations; P_m has both m and s upper stages).

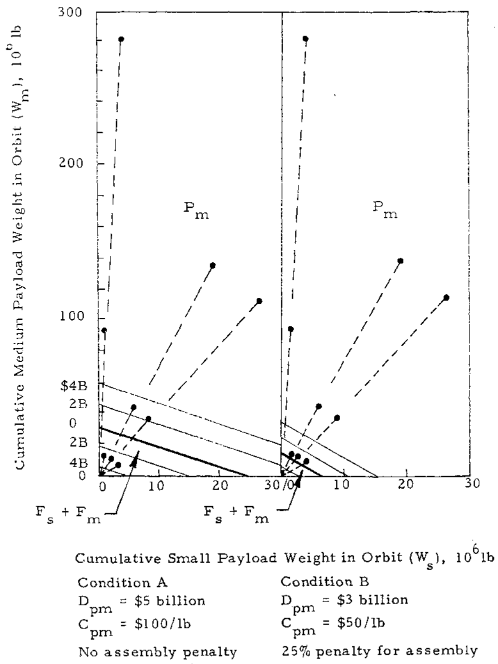

Fig. 7 Least-cost space transportation systems for nine potential national space programs (two parametric conditions; P_s excluded; ten years of operations; P_m has both m and s upper stages).

development of P_m because of the large difference between D_{pm} and D_{ps} and because P_s is not penalized for the assembly operations which will be necessary when it is used to launch medium payloads. The condition A assumptions also are less favorable to the development P_s in preference to the existing systems than the nominal case because of the high development and launch cost assumptions, which exert a stronger unfavorable effect toward P_s than the favorable effect caused by the zero assembly penalty.

Condition B (Fig. 6) includes the low development and launch cost assumptions and a 25% penalty for assembly and refueling. This set of assumptions is the most favorable for the development of P_m because of the reduced difference between D_{pm} and D_{ps} and because P_s is now penalized for the assembly operations required when it is used to launch medium payloads. Conditions B also increases the economic desirability of developing P_s in preference to existing systems because of the lower development costs, which exert a stronger favorable effect than unfavorable effect caused by the assembly penalty for P_s.

Figures 5 and 6 indicate that the region of economic preference for P_m can become dominant under a considerable range of assumptions. The general indication of which systems are preferable for which programs, however, is actually not strongly altered from the nominal case (for the 10-yr period) since the cost difference associated with the shift in regions between Conditions A and B is not great.

Also shown in Figs. 5 and 6 are lines of equal cost difference. These lines show how much costs are increased or reduced by decisions of whether or not to develop various system families, depending on how far a program point falls from a breakeven line dividing two regions. For example, the most significant indication for Condition A is that for the three programs involving case I levels of effort, developing P_s would increase total costs by up to one billion dollars in 10 yr. If, on the other hand, the actual case turns out to be closer to case II than case I, 4 billion dollars could be saved in 10 yr by developing P_s rather than continuing to utilize the existing systems. The exception to this occurs in the case where emphasis is placed on far-orbit operations, in which case 2.5 billion dollars could be saved by developing P_m instead of P_s.

The clear conclusion is that if equal uncertainties are involved as to whether case I or case II represents the more realistic projection of levels of effort, far less economic risk is entailed by development of P_s or P_m than by continuing to use existing boosters. Again, if time periods greater than 10 yr were considered, the development of new launch vehicles would clearly be preferable in every case.

For Condition B, (Fig. 6) there is a greatly expanded region of economic preference for P_m (although, as mentioned previously, the cost difference lines spread apart as the regions shift due to parametric changes; that is, the cost gradient is reduced in the P_m region). Under these assumptions all programs involving cases II and III levels of effort would require P_m. Although the three points representing case I levels of effort fall within the preference region of P_s, the three regions are so close to each other that there would be only a fraction of a billion dollars difference over a 10-yr period between $F_s + F_m$, P_s, and P_m.

The obvious indication is that for Condition B, P_m should be developed. If, for example, equal uncertainty were attached to cases I and II, P_m would increase total 10-yr costs by about 0.6 billion dollars, but if case II obtained instead, development of P_m would reduce 10-yr costs by about one billion dollars for near-orbit operations, 1.5 billion for a combined near-far program, and 5 billion for a primarily far-orbit program. The case for P_m becomes stronger if periods greater than 10 yr are considered.

Figure 7 shows the regions of economic preference between $F_s + F_m$ and P_m, which are not visible in Figs. 4–6, being hidden behind the P_s and $P_s + P_m$ regions. Figure 7 illustrates dramatically the cost savings and penalties associated with the decision of whether or not to proceed with such a development, assuming Condition B obtains. It is seen that, although for case I levels of effort development of P_m would produce total cost savings of only up to about 0.5 billion dollars over 10 yr, if case II levels of effort developed, then development of the P_m system would produce total savings of approximately 8 billion dollars over 10 yr if emphasis were placed on near- or both near- and far-orbit operations, and over 15 billion dollars if emphasis were on far-orbit operations. Thus, for an environment even approximating the

Table 5 Summary of least-cost systems

	Ten-year operations Case I	Case II	Case III	Twenty-year operations Case I	Case II	Case III
Near orbits	$F_s + F_m(P_s)$	$P_s(P_m)$	$P_s + P_m(P_m)$	P_s	P_m	$P_s + P_m$
Both	$F_s + F_m(P_s)$	$P_m(P_s)$	P_m	P_s	P_m	$P_s + P_m$
Far orbits	$F_s + F_m(P_s)$	P_m	P_m	$P_s(P_m)$	P_m	P_m

assumptions of Condition B, the development of P_m is clearly the preferable alternative.

Table 5 presents a summary of the least-cost system combinations for each of the nine potential national space programs, assuming that conditions A and B are considered equally likely. (Actually, it is thought that the development costs assumed in Condition B are probably optimistic for P_s and P_m.) The material in the left-hand table is assembled directly from the summary breakeven charts shown previously, which are associated with a 10-yr post-decision period. The material in the right-hand table represents the results of extending the total cumulative weights in orbit associated with each of the nine programs to 20-yr post-decision periods. In cases where economically preferable systems are different for Conditions A and B, the system or system combination producing the highest cost savings for either Condition is shown, with the other case being shown in parentheses.

The results show that for case I levels of effort the continued use of $F_s + F_m$ is preferable if a 10-yr period is considered and the development of P_s is preferable for a 20-yr period. For case II, the development of either P_s or P_m may be preferable. For case III, the development of either P_m or both of P_s and P_m may be preferred. As the considered time period increases, the development of both P_s and P_m is more strongly indicated.

It is evident that the economically preferred system or combination of systems depends more strongly on the projected levels of effort of the national space program than on which region or regions of space is expected to receive operational emphasis.

Observations

Assuming that ten years is the minimum operational time for which the cost effectiveness of a future family of transportation systems should be evaluated and that the actual use period probably will be longer, this study generally indicates an economic requirement for development of one, or possibly two new space transportation systems.

For what might be termed "minimum" post-1975 national space programs, it appears economically preferable to develop small projected systems having a near orbit payload capability about 25,000 lb. For "moderate" post-1975 programs (case II levels of effort), it appears preferable to develop a medium projected system having a near-orbit maximum payload capability of about 125,000 lb. For "heavy" post-1975 programs, (case III levels of effort), it appears preferable to develop a medium projected system, or both small and medium systems. A general indication emerging from this study is the broad promise associated with a wide range of possible launch requirements, for a new space transportation system in the medium size category, capable of placing up to 125,000 in near orbit.

At least five factors have not been considered in this study, the probable effects of which should be noted. 1) It is assumed throughout that the candidate system combinations can become operationally available at the same time (i.e., $t = 0$ at the same time). It is thought that the technological base is now developed sufficiently that this is a reasonable assumption, but if the larger or more costly systems did require more development time before initial operation, they would become correspondingly less attractive because of the high costs of continuing with existing systems after the earlier time when a less elaborate system could have attained operational capability and begun reducing costs. 2) The study assumes a spectrum of space programs characterized by constant launch rates which, although idealized, produced essentially the same conclusions as if the more realistic but cumbersome assumption were made that launch rates increased in such a way that cases I, II, and III could be considered time averages. 3) The cost of spacecraft and re-entry vehicles are not included. Accounting for them would affect the absolute but probably not the relative cost values, except that it might show the projected systems to be even more competitive to the degree that they turn out to involve integral vehicles for which the spacecraft costs cannot be accounted separately, and effectively are already included. 4) No account is taken of the fact that F_m (Saturn V) is quantized at about 250,000 lb in near orbit. This introduces a bias favorable to F_m, but this bias might be moderated if Saturn V were simplified and down-rated to be capable of performing some of the F_m missions. Finally, 5) it is not clear what effects on the study would result from consideration of advanced vehicles such as might involve nuclear or supersonic combustion propulsion.

References

[1] Heiss, K. P. and Morgenstern, O., "Planning Space Activities in the 1970's," AAS and ORSA Joint National Meeting, Denver, Colo., June 17–20, 1969.

[2] Chacko, G. K., ed., "Reducing the Cost of Space Transportation," *Proceedings of the 7th AAS Goddard Memorial Symposium*, Washington, D. C., March 4–5, 1969.

[3] Morris, D. M., "Evaluation Criteria for Space Transportation Systems Concepts," AIAA Paper 70-263, Cocoa Beach, Fla., 1970.

[4] Stroup, J. W., "Allocation of Launch Vehicles to Space Missions—a Fixed-Cost Transportation Problem," *Operations Research*, Vol. 15, Nov.–Dec. 1967, pp. 1157–1163.

[5] Salkeld, R., "Manned Maintenance and Refueling in Near- and Deep-Space Logistics," *Journal of Spacecraft and Rockets*, Vol. 6, No. 10, Oct. 1969, pp. 1186–1189.