Economy of Large Launch Vehicles Including Orbital Labor Cost

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Some economic aspects of orbital assembly of deep space vehicles vs delivery of the complete, operational vehicle from the ground are investigated. The operating cost of an orbital assembly operation comprises the logistic operation and the orbital operation. The cost of orbital labor is treated in detail, because this aspect can be generalized more readily than that of development and material supply. It is shown that orbital labor should be valued at \$1000 to \$2000 per hour. The effects of success probability of orbital delivery, mating, and fueling are discussed. As far as recurring costs are concerned, orbital assembly is found in the long run to be economically inferior to delivery in operational condition because of the effect of limited reliability on the procurement level of redundant launch vehicles and their payloads and the high cost of orbital labor and orbital operation in general. The results offer an added incentive to invest in a large payload (10^6-lb) launch vehicle, the development cost of which would be justified by long-range astronautical mission requirements corresponding to a useful launch-vehicle life of 15 yr or more.

Nomenclature

C = total cost of establishing an orbital installation, \$
C' = over-all operating cost per launch of ELV, \$
C^* = over-all operating cost effectiveness, \$/lb payload
C_{DD}^* = direct cost of delivery per pound of net payload, \$/lb payload
C_{GO}^{**} = average daily cost of ground operations, directly charged to the orbital operations budget, \$/day
C_{ID}^* = indirect cost effectiveness, \$/lb payload
c_{liv} = specific cost of living, Eq. (12c), \$/labor-hr
C_{log} = cost of logistic operation, \$
C_{OH} = cost of orbital housing for the labor force, excluding development cost, \$
C_{OHM} = cost of orbital housing maintenance, \$
C_{op} = over-all operating cost per operation, \$
C_{orb} = cost of orbital operation (orbital burden rate), \$
C_{train} = cost of special training of person for his orbital job, \$
C_{transp} = transportation cost per person into orbit and back, (\$)
$C_{\text{transp},\,c}$ = transportation cost of cargo into orbit, \$
C_Y = annual over-all operating cost
c_{hous} = specific housing cost, Eq. (12d), \$/labor-hr
$\bar{C}_{\text{prod}}^*$ = mean production cost of orbital facility, \$/lb
C_{lab} = hourly labor rate, Eq. (11), \$/labor-hr
c_{lab} = specific labor cost, Eq. (11), \$/labor-hr
c_{train} = specific training cost, Eq. (12a), \$/labor-hr
c_{transp} = specific transportation cost, Eq. (12b), \$/labor-hr
c = labor cost per hour
C^{**} = cost per day
ELV = earth launch vehicle
f_w = fraction of 24-hr period spent working
ISV = interorbital space vehicle
j = redundant deliveries of modules
K_{prod} = production cost of ELV hardware, \$/lb
k = redundant matings
m = number of successful matings
N_L^* = cumulative number of launches per total installation
N_L = number of launches
N_D = number of orbital duty periods T_D of a given person during the period of orbital operation T_{op}
$\bar{N}_p$ = average number of personnel in the particular labor force
n = number of successful launchings
n_D = $n + j$
$P^* = P_D^* P_M^*$ = associated over-all success probability
P_D = over-all probability of successful orbital delivery
P_d = probability of successfully demating two modules
P_M = probability of successfully mating two modules
P_M^* = cumulative probability of successful mating
$P_p^* = (P^*)^p$ = over-all success probability
P_S = orbital tanking success probability
p = number of complexes in total installation
q = tanking redundancy
r = ratio of indirect to direct operating cost
R_{ELV} = over-all reliability of earth launch vehicle
$R_{\text{E-7}}$ = reliability of payload separation system
$R_{\text{E-8}}$ = reliability of rendezvous maneuvering system of payload propulsion and flight control system (transtage)
s = number of successful tankings
T_D = orbital duty period, time between ascent into orbit and return, days
T_{op} = period of particular orbital operation, days
T_{op}/T_D = number of trips to and from orbit per man (if not an integer, next higher integer is used)
W_d = dry weight of ELV, lb
W_{OH} = weight of orbital housing, lb
W_P = average weight of person and personal equipment, lb
W = net payload of ELV, lb
$\dot{w}_F$ = daily consumption of food to be replaced by supply from earth (mostly solid, since water is recycled), lb/man-day
$\dot{w}_W$ = water loss person per day, lb/man-day
$\dot{w}_X$ = expendables per person per day (hygienic and medical supplies), lb/man-day
Y = number of years
y = exponent in indirect cost effectiveness relation [Eq. (6)]
z = exponent defined by Eq. (3)
v = production number

Presented as part of Preprint 63-277 ("Nexus-Concept of a Large Reusable Launch Vehicle") at the AIAA Summer Meeting, Los Angeles, June 17–20, 1963; revision received September 4, 1964. The author is obligated to B. Brown for his cooperation and to G. L. Dugger, Editor-in-Chief of the Journal of Spacecraft and Rockets, for his valuable help in proofing and condensing the original manuscript.

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Table 1 Sequence of events for earth-to-orbit delivery

Event	2-stage ELV (Saturn V)	1-stage ELV
E-1	Launch	Launch
E-2	Cutoff S-IC	Cutoff some engines
E-3	Staging	Jettison fairing
E-4	Ignite S-II	Cutoff all engines
E-5	Jettison fairing	
E-6	Cutoff S-II	
E-7	Separation of payload	
E-8	Rendezvous maneuver of payload	

Introduction

A TRANSPORT system to the moon or to planets will preferably use two vehicles unless very advanced propulsion systems are available: an earth launch vehicle (ELV) and an interorbital space vehicle (ISV). The ISV can either be assembled in earth orbit (orbital vehicle-assembly mode OVAM) or launched into orbit in operational condition for immediate space flight (direct flight mode, DFM). The OVAM offers flexibility in handling a variety of deep space delivery missions and is less dependent on the types and capabilities of launch vehicles available. Moreover, the rendezvous or orbit-matching technique is of fundamental importance for manned space operations far beyond the payload delivery operation considered here, i.e., rescue missions, maintenance and supply missions to far-out orbits or extra-terrestrial bases, missions to small moons, asteroids, or comets require it. For these reasons, the OVAM and the associated orbital launch facility are important steps. Justifications for ELV's with large payload capability have therefore been based essentially on improvement of transport cost effectiveness. This brief study shows that, because of the expense of orbital operations, reduction of orbital assembly operations and, hence, of the number of successful launches required, is an added important reason for developing large ELV's and improving the economy of routine missions to the moon and beyond.

The technique of orbital assembly and fueling of ISV's was conceived some 40 years ago, when propulsion systems appeared to be limited to the liquid chemical types. The OVAM approach has become deeply ingrained in space flight thinking, obscuring the fact that it was originally conceived as a crutch for our feeble means to reach targets in deep space. However, the advent of nuclear engines offers hope of keeping the orbital departure weight and size of interorbital vehicles within limits which may be practical for future ELV's (1 to 2 $\times 10^6$ lb), thus permitting extended use of DFM. The present study indicates that OVAM is economically inferior to DFM, as far as recurring costs are concerned, primarily for the three following reasons: 1) limited reliability of orbital delivery tends to raise the launch vehicle procurement faster, if the required number of successful launches is large; 2) the procurement level of reserve payloads is higher; and 3) orbital operations are significantly more costly than ground operations. These considerations offer a strong incentive to reduce the extent of orbital assembly operations by investing in a large-payload ELV for the long run.

An orbital operation is defined here as a process in the establishment, maintenance, or servicing of an orbital installation; that is, a "permanent" space station or temporary lunar or planetary vehicle. Since the transportation requirements for servicing and maintenance are generally below those needed for the initial establishment, the latter will pace the expansion of the ELV capacity. The job of the ELV is defined as the payload transfer from launch pad to the rendezvous condition obtained when the vehicle moves into the immediate vicinity (20 to 100 ft) of the completed or partially completed orbital operations establishment at near-equal values of instantaneous radial velocity and angular momentum. The sequences of principal events during delivery are summarized for both a two-stage vehicle (exemplified by Saturn V) and a more advanced single-stage vehicle in Table 1. The mission of the ELV proper is completed with the successful separation of the payload. The ELV may deliver the payload into an intermediate parking orbit or directly into the target orbit in a near-rendezvous condition. A propulsion system attached to the payload section carries out a comparatively small terminal maneuver to complete rendezvous. The over-all probability of payload delivery is

$$P_D = R_{ELV} R_{E\text{-}7} R_{E\text{-}8} \quad (1a)$$

where,

$$\left. \begin{aligned} R_{ELV} &= \prod_{E\text{-}1}^{E\text{-}6} R_E \text{ for 2-stage ELV} \\ R_{ELV} &= \prod_{D\text{-}1}^{E\text{-}4} R_E \text{ for 1-stage ELV} \end{aligned} \right\} \quad (1b)$$

The reliabilities are assumed to vary with cumulative launches between 1970 and 1990, as shown in Fig. 1. The curves are based on component reliability estimates and on experience curves for various ballistic missiles and space boosters.[1] (These particular curves represent one of several reliability models that will be used in the subsequent cost analysis.) The curve for the one-stage ELV is based on the use of advanced all-chemical (O_2/H_2) propulsion with initial operational availability in 1975; since the number of principal operation events during delivery is smaller for a one-stage vehicle, a higher rate of growth is indicated.

Operating Cost of Establishing an Orbital Installation

The total (direct + indirect) cost C of establishing an orbital installation is the sum of the total operating costs of the logistic operation $C_{\log}$ (of which the cost of delivery is the major part) and the orbital operation C_{orb}:

$$C = C_{\log} + C_{orb} \quad (2)$$

Numerous cost analyses have been prepared in the past five years for the development and operation of launch vehicles of various sizes (see, e.g., Refs. 2–4). Approximately 90% of the direct operating cost (d.o.c.) for expendable, land-launched vehicles of the Saturn V-type is the vehicle production cost; hence the variation in d.o.c. can essentially be reduced to a discussion of production cost. This cost decreases with increasing cumulative production (learning curve), but for a given production level, cost increases with time, because of both rising labor and material costs and continued product improvement of vehicle subsystems and components. In the current transition from missiles to spacecraft, a trend toward reduction in production numbers will result in more man-hours per unit weight, the demand for higher product quality and reliability, further increase in the proportion of

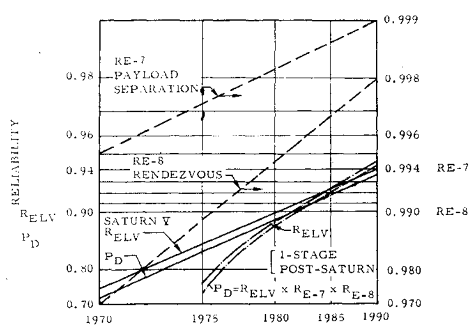

Fig. 1 Assumed reliability of Saturn V and post-Saturn payload separation and rendezvous events.

Table 2 Cost effectiveness and annual launch cost of Saturn V for various orbital payload levels in the 1970–1985 period

Rates and costs		1970–1975 A	1970–1975 B	1975–1980 A	1975–1980 B	1980–1985 A	1980–1985 B
Total orbital payload, Mlb	$W_\omega = 250k$	15	30	30	65	65	130
	$W_\omega = 220k$	13.2	26.4	26.4	57.1	57.1	114.2
$\bar{K}_{prod}$, \$/lb		48	44	48	44	50	45
r, Eq. (6)		0.77	0.7	0.64	0.61	0.54	0.475
For $P_D = 1.0$:							
Total launches, $N_{op} = 5\bar{N}_y$		60	120	120	260	260	520
C^*, Eq. (7), \$/lb payload	$W_\omega = 250k$	166	145	157	137	150	130
	$W_\omega = 220k$	189	165	178	156	171	147
Cost/launch, C', \$M		41.5	36.4	39.2	34.3	37.6	32.6
$C_{op} = C'N_{op} = 5\bar{C}_y$, \$M		2500	4360	4700	8,930	9,800	16,900
For varying P_D:							
P_D		0.792	0.792	0.87	0.87	0.93	0.93
$N_{op} = 5\bar{N}_y$		76	152	138	300	280	560
$C_{op} = 5\bar{C}_y$, \$M		3165	5525	5405	10,300	10,550	18,200
C^{**}, \$/lb payload	$W_\omega - 250k$	210	183	181	158	160	140
	$W_\omega = 220k$	240	209	200.5	180	183	158

electronic and other high cost equipment and material (heat shields, etc.), and a further rise in average salaries because of an increase in the proportion of highly skilled personnel all the way from analysis, research, and design through manufacturing and testing.

This cost-increasing trend is taken into account for the 1970/1985 time period by means of an exponential function e^z. For Saturn V,

$$z = 0.009 + 0.027Y + 2.2 \times 10^{-4}v\,Y^{-2} - 8 \times 10^{-8}v^2Y^{-6} \quad (3)$$

where Y represents the number of years, starting with mid-1970 (i.e., $Y = 1$ in mid-1971). The first (constant) term indicates that the increase in cost is not directly proportional to time, taking into consideration factors such as saturation of plants with highly skilled and experienced personnel and amortization of the investments in basic production capabilities and in other basic facilities. The third and fourth terms represent the time-correlated effect of the production number v; the third term accounts for the fact that the cost-reducing effect of increased production will be less pronounced in early years (because of tooling and facility investments and the production errors that occur with rapid increase in production of a new product), and the fourth term modulates the effect of v in the first year ($Y = 1$) and takes into account the fact that, for Saturn V, the year 1971 is not really "$Y = 1$." (The fourth term gives a greater cost-reducing effect for a very high production level in the first year than would be justified for a new product.)

The "learning curve" can mathematically be defined by av^{-b}. From data[3] for production numbers up to 1000 (on the V-2 rocket and various large aircraft), a value of $b = \frac{1}{6}$ is indicated. Most of the available data are obtained on time periods shorter than the 15 years considered here. Neglecting the fact that b is a function of time (since some of this, at least, already has been incorporated in z), the following relation is applied to the determination of the production cost per pound of hardware:

$$K_{prod} = av^{-b}e^z \quad (4)$$

where z is given by Eq. (3) for the Saturn V ELV. This relation is plotted in Fig. 2 for $a = 80$ and $b = \frac{1}{6}$. Increasing the production number is more effective in later years, since earlier investments are amortized by then, and the entire manufacturing and quality control process has been improved. To put it another way, the cost-increasing effects are more significant when there is prolonged manufacturing at a low production level.

The associated direct cost of delivery per pound of net payload (direct cost effectiveness) for Saturn V is

$$C_{DD}^* \approx (K_{prod}/0.9)(W_d/W_\omega) \quad (5)$$

where W_d is the dry weight and W_ω the net payload weight of the vehicle. The associated indirect cost effectiveness is

$$C_{ID}^* = r\,C_{DD}^* \approx [0.9 - (N - N_\sigma)^y]C_{DD}^* \quad (6)$$

where from cost studies of Saturn V and larger ELV's, in which it was assumed that the vehicles are not stockpiled in significant quantities, it is approximately $N_\sigma = 23$ and $y = 0.155$. The over-all cost effectiveness of payload delivery into orbit with Saturn V is, therefore, approximately

$$C^* \approx [1.9 - (N - 23)^{0.155}]K_{prod}W_d/0.9W_\omega \quad (7)$$

where $W_d \sim 440{,}000$ lb for both the first and second stage of Saturn V. The net payload is 250,000 lb or less. The various total operating costs are then

Per Launch

$$C' \approx C^*W_\omega \quad (8)$$

For a Given Operation

$$C_{op} \approx N_{op}C' \quad (9)$$

Per Year

$$C_Y \approx N_YC' \quad (10)$$

Two models of growth (A and B) of the Saturn V launch rate have been assumed; the associated numbers of launches for 5-yr operations are listed in Table 2. Model A assumes a comparatively moderate growth of cumulative payload in orbit, reaching 90 to 115 Mlb by 1985, and model B reaches

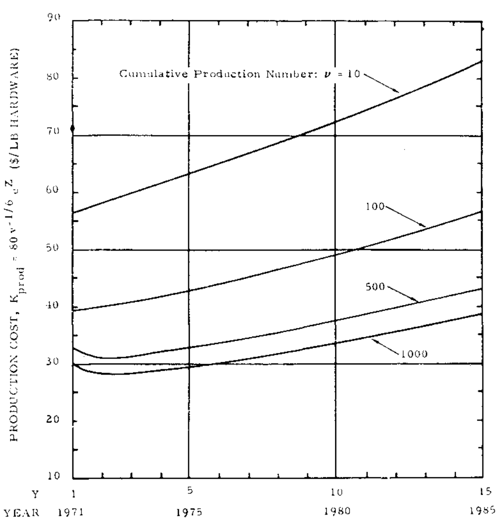

Fig. 2 Possible variation of specific production cost of Saturn V as function of time.

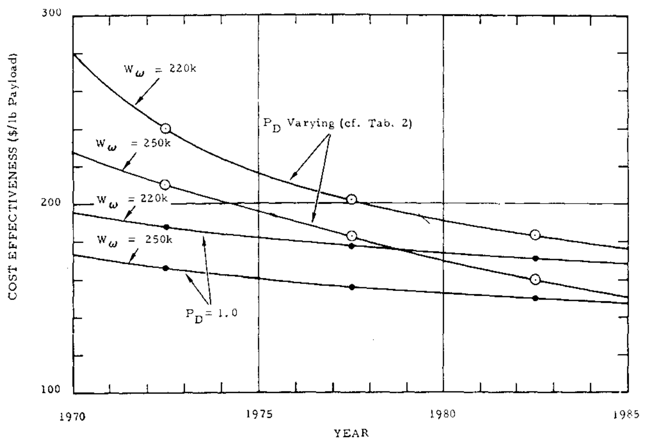

Fig. 3 Total cost effectiveness of Saturn V vs time, based on case *A* in Table 2.

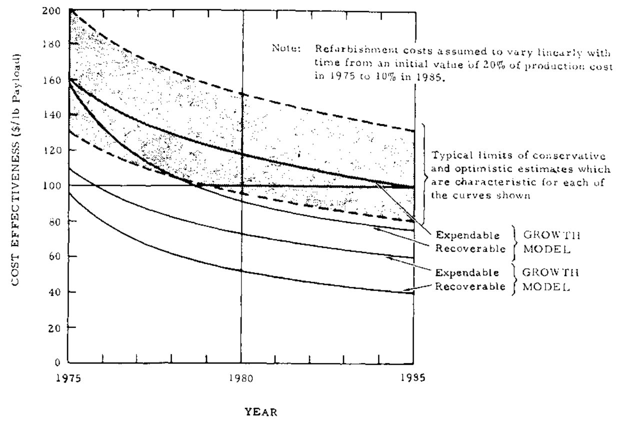

Fig. 5 Typical total cost effectiveness curves for a single-stage chemical ELV of 10^6-lb payload.

approximately twice this range. Mean total cost effectiveness and associated parameters are given for each of these models, based on Eqs. (7–10) and Figs. 1 and 2. The approximate variations of total cost effectiveness vs time are shown in Figs. 3 and 4 for these two models for two values of W_ω, with P_D fixed at unity or varying (according to Fig. 1).

For the post-Saturn vehicle, a payload capability into orbit of 10^6 lb has been assumed. A reusable version with an average operational life of 10 launches and an expendable version of a single-stage chemically-powered ELV have been considered. The same payload build-up as for Saturn V with 0.25 Mlb payload/vehicle in models *A* and *B* has been followed with the post-Saturn vehicle, for which 1975 has been assumed to be the first full year of operational state. The cost effectiveness of such a hypothetical vehicle can vary considerably (depending on many detailed assumptions that are beyond the scope of this paper), as shown in Fig. 5. Typical uncertainty limits (which would be characteristic for all curves) have been indicated for the upper curve, which is believed to be the most likely curve for the case in question. The total cost effectiveness figures for the expendable versions probably are on the conservative side; they indicate that reusability will pay off more in the later years (because reliability, permitting more vehicles to live through their full operational life of 10 launches, increases, and recovery and refurbishing operations are more routine).

Costs of Orbital Operations, Particularly Labor

The over-all cost of an orbital operation depends on the type of orbital facility used, the type of interorbital vehicle to be assembled, its fuel, the mode of assembly (i.e., how much mating and how much fueling has to be done), the degree of interchangeability of the modules and/or vehicles, the probability of success of each step, the cost of delivery of each module to orbit, the number of personnel maintained in orbit, and the type of maintenance and the duration of the orbital facility. For a particular mission, the orbital burden rate depends, in addition to the forementioned factors, on the consumption of fluids and other expendable materials, on the number of missions over which the basic costs can be prorated, and on any special preparations or training required.

The burden rate can be divided into 1) developmental and other nonrecurring costs and 2) recurring costs, which are subdivided into materials and orbital labor costs. The nonrecurring cost depends largely on whether a new capability is to be developed, or whether existing capabilities (Saturn I, Titan III, and Saturn V) will be utilized. The materials costs can be assessed realistically only in the framework of an over-all mission model that furnishes time distributions, types of ISV's, and the W_ω (and volume) and expected P_D of the ELV. An investigation of the materials costs of orbital operations for several mission modes is under way, but the present considerations will be confined to the orbital labor cost.

The hourly labor rate c_{lab} dollars per labor hour over the period T_{op} of the particular orbital operation is a function of: 1) the cost of special job training, 2) the cost of transportation to and from orbit, 3) the cost of living, and 4) the cost of housing and of operating and maintaining orbital housing:

$$c_{lab} = c_{train} + c_{transp} + c_{liv} + c_{hous} \quad (11)$$

$$c_{train} = C_{train}/24 N_D T_D f w \quad (12a)$$

where

$$c_{transp} = C_{transp}/24 T_D f w \quad (12b)$$

$$c_{liv} = C^*_{transp,\,c}\,(\dot{w}_F + \dot{w}_W + \dot{w}_X)/24\, fw\, T_{op} \quad (12c)$$

$$c_{hous} = (C_{OH} + C_{OHM})/24 T_{op} fw\, \bar{N}_p \quad (12d)$$

Based on the definitions and assumed values for the various parameters as given in the Nomenclature and in Table

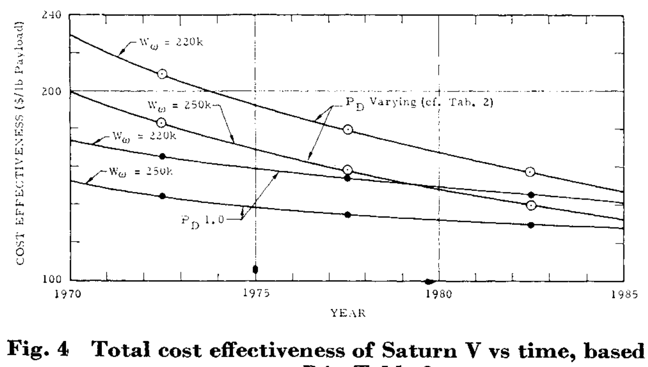

Fig. 4 Total cost effectiveness of Saturn V vs time, based on case *B* in Table 2.

Table 3 Inputs for a numerical analysis of orbital labor cost

f_w	$\frac{1}{3}$
C_{train}, \$	800,000
W_p, lb	200
C^*_{transp} \$/lb W_p	100
$\dot{w}_F$, lb/man-day	3.66
$\dot{w}_W$, lb/man-day	0.35
$\dot{w}_X$, lb/man-day	0.74
$C^*_{transp,\,c}$ \$/lb cargo	150
$\bar{N}_p$, men	50
W_{OH}, lb	200,000
$\bar{C}^*_{prod}$, \$/lb	80
C^{**}_{GO}, \$/day	10,000

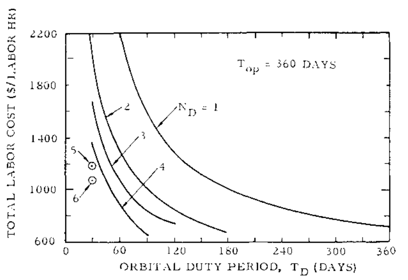

Fig. 6 Hourly orbital labor cost for an operational period of 360 days.

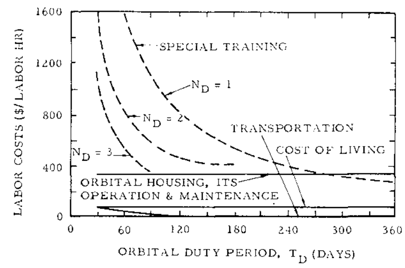

Fig. 7 Factors determining orbital labor cost for a 360-day operation.

3, the orbital labor cost has been computed for orbital operations lasting 180, 360, and 720 days. Results for 360 days are shown in Fig. 6. The breakdown by cost elements (Fig. 7) is typical also for the two other operational periods. From this figure it is seen that the cost of special training of the orbital labor force can dominate this cost group. If the orbital duty period is brief, the cost of special training remains the dominant factor even if the cost is only one-half or one-third of the $800,000 value assumed. The cost of personnel transportation (at $100/lb, round trip) is a comparatively small item in the framework of a 360-day orbital operation. However, Fig. 8 shows that it becomes significant when T_{op} becomes small or T_{op}/T_D becomes large.† The cost-of-living contribution nominally is not a function of T_{op}, since food requirements and number of labor hours vary in the same manner with T_{op}. The contribution of orbital housing exceeds that of transportation by a factor of 4 and higher, as shown in Fig. 8, for various average numbers of personnel $\bar{N}_p$.

These results for the hourly orbital labor rate (to which must be added materials costs and amortization costs as previously noted) can be summarized as follows:

1) For $T_{op} \geq 100$ days, personnel transportation costs play a comparatively minor role, provided that the number of crew rotations does not exceed 2 for a 100-day operation and 12 for a 720-day operation. (This conclusion is correct even when the assumed transportation cost of $100/lb is doubled.)

2) The cost of supplying the orbital crew with food (3.66 lb/man-day), make-up water (0.35 lb/man-day), and miscellaneous expendables (0.74 lb/man-day) contributes approximately $89 to c_{lab}, based on a cargo transportation cost of $150/lb.

3) The principal cost item, aside from special training, is orbital housing and its maintenance. Even for an operational period of one year, its contribution to c_{lab} is between $350 and $850 for crew sizes between 50 and 20.

4) If the cost of special training of the individual (assumed here to be $800,000) is taken into account, the hourly labor cost varies within wide limits, depending upon the individual's cumulative duty time during the T_{op}. Unless the cost of such training can be reduced to the order of $100,000, it is of great economic importance to maintain long orbital periods of duty (at least 90 days) or, if this meets with difficulties from the standpoint of work efficiency, to assure at least three tours of duty ($N_D = 3$) of 30 days each.

Probability of Successful Establishment of Orbital Installations

In principle, any ELV can amass any amount of weight in orbit, given a sufficient number of successful launchings. In practice, the establishment of an orbital installation whose weight or volume exceeds the payload weight or volume capability of a single given ELV affects the cost of establishing the installation through the following parameters: number of deliveries required, probability of successful delivery, and probability of successful orbital mating and/or fueling. The number of launchings affects ground operation and ELV procurement cost, especially if the vehicles are expendable. The reliability of the over-all operation determines also the procurement cost of modules in excess of those basically needed, to replace losses during delivery failures and failures during orbital operation. Finally, level of effort, duration, and cost of orbital labor determine essentially the cost of the orbital operation during the establishment phase.

The total requirement on the transportation system is determined by the probabilities of success desired for the delivery operation and the orbital operation associated with the payload weight delivered. First, we shall assume that payload modules are to be assembled in orbit in one of two cases:

Case I: All modules delivered are to be mated into a single complex. Failure to mate one module to several modules already mated leads to the loss o f the two modules concerned, but not of the other modules.

Case II: The delivered modules are mated to individual complexes limited to 3, 4, or 5 modules each. In case of failure to mate, the same rules apply as in case I.

Cases I and II are identical where 3, 4, or 5 modules are concerned. They are different for larger numbers of modules. Case I applies primarily to the establishment of large space stations, case II to lunar or planetary space vehicles.

The probability of success in establishing an orbital installation is determined by the cumulative probability of delivery of a number of modules P_D^* multiplied by the

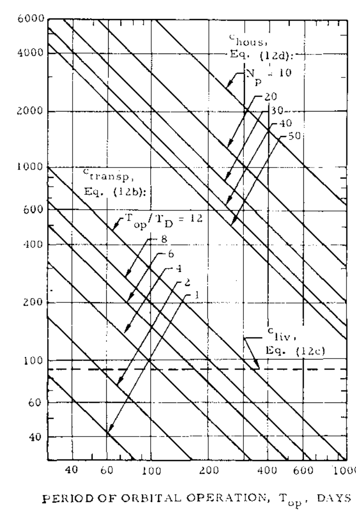

Fig. 8 Cost of orbital housing, its maintenance, associated ground tracking operations, and cost of living and personnel transportation.

† As far as transportation cost is concerned, it does not matter whether the same individual is involved in another period of duty during the same period of orbital operation; i.e., N_D has no effect on the transportation cost, only on the contribution of the special training cost to the hourly labor cost.

Table 4 Coefficient A_j in Eq. (15)

	A_j					
j	$n = 1$	2	3	4	6	8
0	1	1	1	1	1	1
1	1	2	3	4	6	8
2	1	3	6	10	21	36
3	1	4	10	20	56	120

cumulative probability of mating a given number of modules P_M^*. The probability of n or more successes in $n_D = n + j$ deliveries is

$$P_D^* = \sum_{n_D=n}^{n+j} A_j P_D^n (1 - P_D)^j \tag{13}$$

where P_D is given by Eq. (1a) and A_j is listed in Table 4. Thus, for 3 or more successful deliveries out of 5 attempts, i.e., $n_D = 3 + 2$, it is

$$P_D^* = P_D^3 + 3P_D^3(1 - P_D) + 6P_D^3(1 - P_D)^2 \tag{14}$$

and so forth.

The probabilities $P_{M,\ m}^*$ of m or more successful matings of $m + 1$ modules in m to $m + k$ attempts, under the ground rules specified for case I, are as follows:

$$\left.\begin{aligned}
k = 0:&\quad P_M^m \\
k = 1:&\quad P_M^m[1 + (1 - P_M)] \\
k = 2:&\quad P_M^m\left[1 + \sum_{k=1}^{2}(1 - P_M)^k\right] + (m - 1)P_M^m P_M P_d(1 - P_M) \\
k = 3:&\quad P_M^m\left[1 + \sum_{k=1}^{3}(1 - P_M)^k\right] + (m - 1)P_M^m P_M P_d \times (1 - P_M)[1 + (1 - P_M)] + (m - 1)P_M^m P_M P_d(1 - P_M)^2
\end{aligned}\right\} \tag{15}$$

where P_M is the probability of mating successfully two modules and P_d the probability of successfully demating a damaged module from a module aggregate. It is assumed in the preceding equations that P_M and P_d are the same for all modules or mating processes. The number of modules which must be delivered into orbit is always $(m + 1) + 2k$. This number, then, determines the possible number of successful launches required. Thus, if $m = 3$ and $k = 2$, preparations for the establishment of this 4-module orbital installation must plan for eight deliveries. If one delivery failure is included, a total of nine launch vehicles (if nonreusable) and of nine modules (or more, if not interchangeable) would have to be procured to attain the associated overall success probability:

$$P^* = P_D^* P_M^* = \sum_{8}^{9} A_1 P_D^8(1 - P_D) \times \left\{P_M^3\left[1 + \sum_{k=1}^{2}(1 - P_M)^k\right] + 2P_M^2 P_M P_d(1 - P_M)\right\} \tag{16}$$

In case II, Eqs. (13–15) are also applicable, but m is restricted to 5 or less, and the fact that the process of establishing these installations is to be repeated, say, p times, must be taken into account. Then the over-all success probability is

$$P_p^* = (P_D^* P_M^*)^p \tag{17}$$

The number of modules to be procured may have to be larger in this case than in case I if they are not interchangeable. A third case is also considered.

Case III: An orbital installation is to be supplied with fuel or other necessities. Failure to fuel does not destroy the module to be fueled and, therefore, requires only delivery of another supply vehicle (tanker) rather than two additional deliveries in the cases I and II. For case III, Eq. (13) applies also to the orbital operation. The probability of s or more successes in $p = w + q$ attempts to fuel or service the installation in any other manner is

$$P_S^* = \sum_{p=s}^{s+q} A_q P_S^s (1 - P_S)^q \tag{18}$$

where A_q is found from Table 4 for $q = j$ and $s = n$. The probability of success is then $P^* = P_D^* P_S^*$.

Use of Many Saturn V ELV's vs Fewer Post-Saturn ELV's

Payload Procurement for 1975 Period

The purpose here is to show that associated costs of payload procurement and orbital operations, in addition to transport cost effectiveness, play important roles. The technique of comparison is illustrated by an example, which is listed in some detail in Table 5. The task is to establish, in 1975, an orbital installation of four complexes of 10^6 lb each. Saturn V, given a useful payload of 0.25 Mlb, is compared with a chemical post-Saturn vehicle of 1.0-Mlb useful payload.

For Saturn V, the task amounts to transporting 16 modules into orbit and mating them into four 1.0-Mlb complexes. Lines 1 through 7 in Table 5 determine, for the assembly of one of the complexes, the over-all probability of successful delivery (P_D^*), based on $P_D = 0.84$; the probability of successfully accomplishing four times three matings (P_M^*), based on $P_M = 0.95$ and $P_d = 0.99$; and the over-all probability of success P^*. The assumptions previously specified for orbital mating (rather than fueling) are used. Three alternatives are considered. First, in columns 1 through 3, no extra mating attempt beyond the minimum of three matings is planned ($k = 0$), whereas the number of extra delivery attempts (j) is increased; the delivery probability grows, therefore, according to Eq. (13), for $n = 4$ and $j = 0, 1, 2$ (i.e., 4 successful deliveries in 4–6 delivery attempts, respectively). In practice, if six delivery attempts are planned, and the first four are successful, then the fifth and sixth ELV's and their payloads would be available in case of a mating failure. However, this additional mating capability is not part of the procurement and launch plan represented by columns 1 through 3, which merely aims at maximizing the probability that the four required modules will actually be delivered. In columns 4 through 6, an additional mating attempt is specifically planned ($k = 1$). This means that the plan must provide for a minimum of 6 launches ($n = 6$) under the assumption that one failure to mate renders the two modules involved unsuitable against which j is again varied from 0 to 2 to increase the confidence level of successful delivery of six modules. In column 7, $k = 2$ and $j = 1$. Because P_M is larger than P_D, increasing j is more effective than increasing k. Thus, the highest confidence level is obtained with $j = 2$, but $k = 0$ (column 3). Trying to accumulate excess modules in orbit ($k = 0$) in case they are needed there degrades the over-all probability of success unless P_D^* is higher.

Lines 8–10 show the effect of carrying out 4 times each of the nine alternatives for establishing one complex (lines 1–7), on the procurement requirements and on the over-all probability, under the assumption that no additional attempt to assemble a complex is planned ($h = 0$). If one additional attempt is planned ($h = 1$), the figures in lines 11–13 are obtained. Lines 14–26 estimate the cost of delivery and of orbital labor, based on the procurement requirements (line 9) for $h = 0$. These procurement requirements represent the maximum numbers of interchangeable modules that could possibly be used; if they are not all interchangeable, then a significantly larger number than indicated in line 27 must be procured to be consistent with the over-all probability of success. The economic importance of having, in a planetary or lunar ship or in a space station, as many modules interchangeable as possible is so apparent that it will strongly influence the design philosophy in this direction (especially since interchangeability of modules of manned planetary ships is also of considerable practical importance in case of troubles en route). However, practice shows that this goal is never reached completely, and it can be expected that the majority, but not all, of the modules will be interchangeable. Since this tends to raise the "safe" procurement level, the numbers given in line 27 could possibly have to be met, even though the procurement of two extra modules for each mating failure is a conservative procedure.

In any case, for comparable success probability, the procurement cost for Saturn V is considerably higher than for a post-Saturn ELV. Although the individual delivery reliability of the latter is smaller, the confidence level attained with 6-Mlb-payload procurement ($j = 2, k = 0$) is significantly higher than that for Saturn V, 0.829 (line 7, column 10) vs 0.422 (line 10, column 3). Conversely, for a success probability of at least 0.75 for Saturn V (line 13, column 3), 7.5 Mlb of payload would have to be procured. The reason for this difference is, of course, that no orbital mating is required with the post-Saturn ELV; instead, preparation is done on the ground where it can be done more efficiently and far less expensively. For a given payload, e.g., 6 Mlb, the launch costs are $\frac{1}{3}$ higher for Saturn V, because each post-Saturn ELV costs only 3 times as much to launch as each of the equivalent total of four Saturn V's.

In summary, Table 5 indicates the following:

1) The best plan available to Saturn V, in terms of competitiveness with a post-Saturn ELV, would be a $n = 4$, $j = 2$, $k = 0$, $h = 1$ (column 3, lines 12 and 13).

2) This case compares with post-Saturn, $n = 4$, $j = 2$ (column 10) as follows: over-all success probability, 0.75 vs 0.829; maximum number of launches, 30 vs 6; maximum launch cost (expendable ELV), \$1200 × 10^6 vs \$720 × 10^6; and maximum payload weight procurement, 7.5 Mlb vs 6 Mlb.

3) If this payload is inexpensive (e.g., H_2), the last point is negligible. In this case, however, no housing would be available for the orbital crew of the post-Saturn ELV, which would bring the orbital labor cost roughly to the same level as listed for Saturn V. Thus, if inexpensive payload is hauled, the economic superiority would be based primarily on its higher cost effectiveness, resulting in a saving of the

Table 5 Comparison of Saturn V vs post-Saturn ELV for establishing four complexes @ 10^6 lb weight in orbit in 1975[a]

Line	Column	Saturn V 1	2	3	4	5	6	7	Post-Saturn ELV 8	9	10
1	n	4	4	4	6	6	6	8	4	4	4
2	j	0	1	2	0	1	2	1	0	1	2
3	$m = 3$: k	0	0	0	1	1	1	2	No mating required		
4	$N_L = N_{mod}$	4	5	6	6	7	8	9	4	5	6
5	P_D^*	0.489	0.817	0.944	0.351	0.688	0.877	0.493	0.316	0.632	0.829
6	$P_M^*(P_M = 0.95;$ $P_d = 0.99)$	0.855	0.855	0.855	0.90	0.90	0.90	0.983	...	...	...
7	$P^* = P_D^* \cdot P_M^*$	0.425	0.699	0.806	0.316	0.619	0.79	0.484	0.316	0.632	0.829
8	$h = 0$:										
9	$N_L^* = N_{mod}^*$	16	20	24	24	28	32	36	...	...	...
10	$P_p^* = (P^*)^4$	0.033	0.239	0.422	0.01	0.147	0.389	0.055	...	...	...
11	$h = 1$:										
12	$N_L^* = N_{mod}^*$	20	25	30	30	35	40	45	...	...	...
13	P_p^* $(h = 1)$	0.109	0.527	0.75	0.037	0.371	0.716	0.168	...	...	...
14	Launch rate		1 per week (7 days) per launch pad						1 per 30d per launch pad		
15	Launch pads		4 + 1 spare = 5						3 + 1 spare		
16	Orbital crew, $\bar{N}_p$		40						20		
17	Launch period, days	28	35	42	42	49	56	63	30	40	50
18	T_{op}, days	38	45	52	52	59	66	73	40	50	60
19	Labor, hr × 10^{-2}	121	144	166	166	189	211	234	6400	8000	9600
20	Housing, \$/hr ($\bar{N}_p = 40$)	4200	3450	3000	3000	2630	2350	2140	No housing required		
21	Personnel transp.	40 (persons)·200 (lb/person)·100 (\$/lb) = \$800,000								\$400,000	
22	Labor cost, M\$	51.3	51.7	52.2	52.2	52.1	52.4	52.9	0.96	1.1	1.25
23	Labor rate, \$/hr	4350	3590	3140	3140	2760	2980	2260	150	136	130
24	C^{**}, \$/lb payload		160 (Fig. 3, 1975); \$40 × 10^6 per ELV						120; \$120 × 10^6/ELV		
25	Max. launch cost, M\$	640	800	960	960	1120	1280	1440	480	600	720
26	Total cost $w/0$ without payload, M\$	691	852	1012	1012	1172	1332	1493	481	601	721
27	Max. payload procured, M\$	4	5	6	6	7	8	9	4	5	6

[a] Notes (cf. text also):

Line 5: $P_D = 0.84$ for Saturn V; $P_D = 0.75$ for post-Saturn ELV.

Line 8: Process of mating four modules has to be repeated four times to obtain the required four complexes @ 10^6 lb; $h = 0$ means that no additional attempts to mate one more complex is planned. This results in the number of modules to be procured and probability of success indicated in lines 9 and 10.

Line 11: One redundant complex is planned ($h = 1$), resulting in improved probability of success (line 13) of obtaining the required four complexes, but at higher cost.

Line 17: Designates the period in which all launches take place.

Line 18: The orbital operation is ten days longer than the launch period to account for mating and/or checkout of the last module or complex via Saturn V or post-Saturn, respectively.

Line 19: Based on 8 labor-hr/day times T_{op} and $\bar{N}_p$(line 16).

Line 20: In the case of post-Saturn the crew is expected to live in the complex.

Lines 22, 23, 25: The cost of special training of the orbital crew is not included; but the cost of living at \$89/labor-hr is included.

Line 24: Cost effectiveness for post-Saturn is derived from 160·0.75 = 120; where \$160/lb is given in Fig. 5 (for the expendable version on the basis that its reliability is about 0.75). Since the effect of reliability has been considered here separately (lines 5 and 7), the cost effectiveness figure has been reduced to a value corresponding to100% reliability. The cost figures in Fig. 5 account for the effect of reliability statistically over large number of launchings, whereas the values in lines 5 and 7 refer to success probability for the given limited number of delivery attempts.

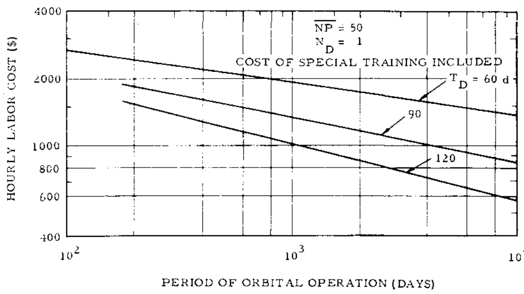

Fig. 9 Hourly labor rate vs period of orbital operation.

order of \$480 × 10^6 (30 Saturn V ELVs @ \$40 × 10^6 each minus six post-Saturn ELVs @ \$120 × 10^6 each) for the entire operation. The economic superiority of the post-Saturn ELV is not raised significantly if the cost of special training of the orbital crew is taken into consideration. At the level of \$0.8 × 10^6 man, this cost is \$16 × 10^6 higher for Saturn V, based on line 16 of Table 5.

4) If the payload is moderately expensive, say \$300/lb, the economic disadvantage of Saturn V is emphasized further, because, for reasons of mission success confidence, 1.5 Mlb more payload weight must be procured, adding \$450 × 10^6 to the \$480 × 10^6 in higher vehicle procurement and launch cost. Moreover, in this case, the payload is likely to possess accommodations for personnel (e.g., flight crew). Their temporary use by the orbital operations crew is likely to be more feasible in the post-Saturn case where no mating (only checkout of the complexes) is involved. Therefore, it is likely that no orbital housing will be required with the post-Saturn ELV, so that another \$50 to \$65 × 10^6 is added to the total cost difference for this comparatively small orbital operation, bringing it to the order of \$980 × 10^6 in favor of post-Saturn. It is important to note that approximately half of this advantage is due to lower transportation cost, and the other half results from lower payload weight procurement and simplification of the associated orbital operations. Even if the savings were only half as large, they would still be very significant. In reality, they will be even larger, because of the other elements of the orbital burden rate not considered here (cf. Fig. 5 for those considered).

The relative position of Saturn V can be improved if a mating technique is used in which failure to mate does not result in the destruction (or mission unfitness) of both modules concerned, but of only one, preferably the one to

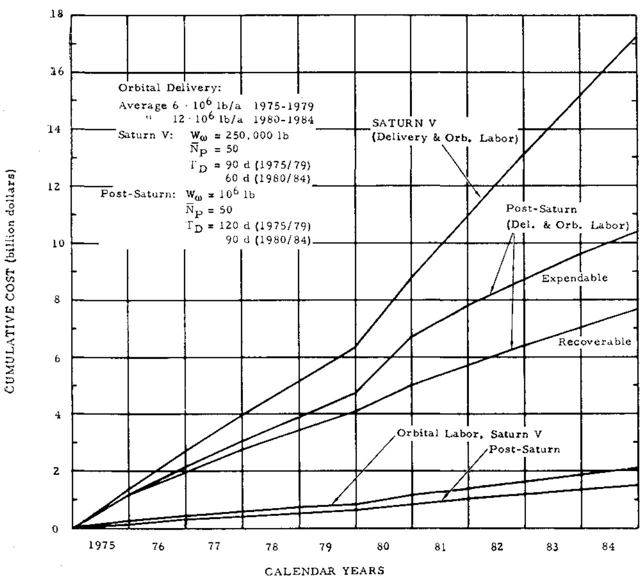

Fig. 10 Cumulative cost of delivery and orbital labor, 1975–1980.

Table 6 Establishment of four 10^6-lb complexes with Saturn V using fueling mode

Line	Column	1	2	3	4
	Vehicle (n = 1)				
1	j	0	0	1	1
2	$N_L = N_v$	1	1	2	2
3	$(P_D = 0.84)P_D^*$	0.84	0.84	0.97	0.97
	Tankers (s = 4)				
4	q	0	1	0	1
5	$N_L = N_T$	4	5	4	5
6	$(P_s = 0.95)P_S^*$	0.81	0.98	0.81	0.98
7	$(P_{DT} = 0.84)P_S^* \cdot P_{DT}^*$	0.41	0.73	0.41	0.73
8	N_L for 1 compl. vehicle	5	6	6	7
9	$P^* = P_D^* \, P_S^* \, P_{DT}^*$	0.34	0.62	0.39	0.71
10	$P_p^* = (P^*)^4$	0.01	0.14	0.02	0.26
11	N_L^*	20	24	24	28

be attached (so as to eliminate the need for demating a module). In that case, a mating failure results in a requirement for only one (rather than two) additional delivery. This raises the over-all probability of success significantly, even if the probability of mating success (P_M) is not raised.

The same conditions exist in the case of fueling if each complex is a lunar or interplanetary vehicle. It must further be assumed that the vehicle uses chemical propellants (O_2/H_2 or denser), since the size of a 1.0-Mlb nuclear-powered, hydrogen-carrying vehicle is too big for the presently specified payload volume of Saturn V (about 100,000 ft^3), which is limited by facility and design criteria. To account for problems connected with mounting the entire vehicle in the nose section and for insulation weights for the tanker atop Saturn V, it is assumed that in this case a minimum of five launches is required (n = 1 vehicle and s = 4 tankers). The success probability remains low, although it is seen that the allowance of an additional tanker (q = 1) raises the over-all success probability (e.g., columns 1 and 2, or 3 and 4, in Table 6), whereas allowance of an additional mating attempt (k = 1) actually reduces the over-all success probability (columns 1 and 4, line 10, Table 5), because an additional mating attempt requires two additional launches. These examples show that the concept of using a larger instead of a smaller number of ELV's suffers from a serious reduction of mission success probability, unless the delivery success probability (which is the main cause of this reduction) can be raised to 0.9 or higher.

Longer-Range Requirements

Although the preceding example indicates an impressive potential operational cost superiority for the post-Saturn ELV for the 1975 period, the difference is small as compared to the development cost of such a vehicle, which is expected to lie between \$5 and \$10 × 10^9. Therefore, a justification must be established on the basis of sustained long-range transportation requirements. For this purpose, a comparison can be made for case A transportation level (Table 2) with delivery costs and cost effectiveness values shown in Figs. 3 and 4 (P_D varying) and Fig. 5, and with orbital labor hourly rates plotted in Fig. 9. It will be assumed that the number of orbital personnel required in the second 5-yr period should be increased by 50% for Saturn V (corresponding to a 50% reduction of the nominal T_D) and by 33% for post-Saturn ELV's. The results are shown in Fig. 9 for the expendable and the recoverable versions of the post-Saturn ELV. The upper three curves show delivery plus orbital labor cost; the lower two curves show the orbital labor cost. (The cost effect of the two approaches on payload is not included, since it cannot be assessed in this general form, but the trend established by the example in Table 3 should apply.) Figure 10 shows that:

1) The cost superiority of the post-Saturn ELV is due to a) size, b) the gradually developing effect of reusability,

and c) savings in orbital labor cost (the least certain factor). If the other elements of the orbital operations cost are included in a more specific analysis, the effect of the orbital burden rate is likely to become more important even than reusability.

2) It is not necessary that the post-Saturn ELV attains reusability from the start; it is more important that it be designed so that a reusable mode of operation could be introduced during the first five years of operations.

3) If its development cost is taken as $\$6 \times 10^9$, it should be amortized during the first ten years of its operational life, even if no reusability is attained during this period; in case of reusability, amortization in eight years or less is indicated.

4) It is, therefore, important for the post-Saturn ELV configuration selected to have a low rate of obsolescence; this will be assured if the vehicle is characterized by: a) adequate orbital payload capability (i.e., ≥ 1.0 Mlb) to assure a useful life $\geq$ 15 yr; b) a shape which offers as few volume restrictions as possible to a payload weight of this magnitude; c) highest possible operational simplicity and reliability; and d) advanced chemical engines (high-pressure O_2/H_2) and a design that permits the vehicle to be adapted to more advanced propulsion systems (nuclear and/or air-breathing engines) as the state-of-the-art advances.

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Discussion by H. H. Koelle (see also accompanying paper by Koelle, p. 620)

Dr. Ehricke deserves the credit for discovering the fact that orbital labor rates can be substantial in extensive space operations. This factor has been neglected until now. He has opened the door for intensive investigations in this area which, hopefully, will lead to a better understanding of what we refer to as "orbital operations."

One of the strong points of his analysis is the consideration of actual reliabilities and reliability growth for all individual steps of orbital operations in a fairly sophisticated manner. This gives considerable insight into the actual problems of orbital operations. The introduction of several new parameters, describing individual orbital activities and supporting elements, bring out clearly the importance of individual assumptions and permit a ranking of these parameters according to sensitivities.

Since the original paper was written in early 1963, one might be cautioned in using the absolute figures given in the examples. For example, the Saturn V payload capability, considered for the 1970's, will probably be larger than those assumed, and the availability of a post-Saturn vehicle is now more likely around 1980 and not 1975 as assumed. But the sample calculations can be repeated as new data become available, and this fact does not reduce the importance of this paper.

A weak point of the paper is the fact that not all recognizable parameters have been introduced at that point in time. This was probably wise, as it kept the problem within manageable limits. On the other hand, some very important influence factors might not show up in this initial investigation. Parameters of this type are R&D cost for orbital support equipment, launch rate limitations, propellant requirements in orbit, and others. Most of these will shift the comparison of smaller launch vehicles with larger launch vehicles in favor of the larger launch vehicles. It is also to be expected that the permissable time for orbital operations will be less than half a year for a particular mission. Future studies will probably show that several other parameters, besides orbital labor rate and individual reliabilities, will be very influential in determining the total "orbital burden rate."

The author has to be congratulated for his pioneering paper, which not only will stimulate other investigators, but will also permit us to look at "orbital operations" more realistically than in the past.