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NEXUS
CONCEPT OF A LARGE REUSABLE EARTH LAUNCH VEHICLE

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ABSTRACT

Aspects of Earth-to-orbit delivery are discussed and a cost analysis of the logistic operation and the cost of orbital operations are presented. Probabilities of success of orbital delivery and the operational and economic aspects of establishing large orbital installations and maintaining a large transportation volume in the 1975/85 time period are compared for the two cases of using a large number of Saturn V versus a smaller number of 1-stage chemical Post-Saturn launch vehicles. Performance parameters of chemical, chemonuclear and nuclear launch vehicles are compared. The concept of a blunt launch vehicle configuration, referred to as NEXUS, is presented in detail. Applications of this configuration to chemonuclear propulsion and to a 50 ft diameter version of Saturn V with recoverable first stage are discussed.

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1. Introduction

The history of transportation technology shows that requirements imposed by the need for a growing transportation volume are met in three steps: First, the number of existing carriers is increased; second, the capacity of the individual carrier is raised until some practical size limit is reached; finally, through technological advances, a quantum jump is achieved, raising the carrier capacity through greater speed of transportation or by attaining a higher payload fraction or by achieving both simultaneously with a new and more advanced carrier.

This process occurs in response to a demand for growing transportation capacity on land, on sea and in the air. Space is no exception. Throughout many decades of the past, adequate prognosis of future transportation needs and careful planning of how to satisfy these needs has been of crucial importance to the competitive growth and survival of private transportation business in this country. As far as space transportation is concerned, Earth is "this country" and qualified nations represent the individual enterprises engaged in competition for technological eminence and the manifold benefits expected to result therefrom. The approach to the problem is, therefore, essentially the same.

It is the object of this paper to suggest a concept of how a growing demand for space transportation capability can be met in a timely and economical manner when it arises. The question, if it should arise in the first place, is not subject to discussion here. If and when it arises, it will have to be faced first in the field of Earth-to-orbit transportation. Therefore, Earth launch vehicle

(ELV) planning is necessarily the first order of business.

Applying the three steps of transportation volume growth, referred to above, to the ELV problem, they take the following form:

(1) Increase of the number of Saturn V launches per unit time.

(2) Develop a chemically powered Post-Saturn ELV of 4 to 8 times the orbital payload capability of Saturn V.

(3) Develop a chemonuclear or nuclear ELV of superior payload fraction (ratio of payload weight to lift-off weight).

This paper contains results of a Post-Nova launch vehicle study conducted since March 1962, and presently continuing, under the direction of the Marshall Space Flight Center, Future Projects Office. This study is one of the study series assisting in the selection and definition of the next large launch vehicle after Saturn V. It is primarily aimed at the question of probable operational life of the vehicle concept which is determined by the state-of-the-art expected during the late seventies and early eighties. Results of this study have produced conceptual designs for several promising launch vehicles, now transferred to the main NOVA studies. The chemical NEXUS concept presented in this paper is one of these configurations.

2. Orbital Operation

The Earth-to-orbit transportation volume is determined by the number and the extent of orbital operations. Orbital operation is defined here as a process of establishing or of maintaining and servicing orbital installations. Orbital installations can be "permanent" (space stations) or temporary (lunar or planetary vehicles). The four principal operational modes for establishing orbital installations are depicted in Fig. 1.

Servicing and maintenance becomes a significant factor only for permanent orbital installations and consists primarily of rotation of personnel, delivery of food and other expendable necessities; and, of delivery of spare parts and replacements. The transportation requirements for servicing and maintenance are always considerably below those needed for the initial establishment. The latter ones, therefore, pace the expansion of the ELV transportation capacity.

3. Earth-To-Orbit Delivery

Delivery is defined here as the process of payload transfer from the launch pad to a rendezvous condition with a point in the target orbit. The payload is in rendezvous condition when it moves in the immediate vicinity (20 to 100 ft distance) of the target point (e.g. orbital operations center, orbital launch facility or a partially completed orbital establishment) at very nearly the same instantaneous radial velocity and the same angular momentum as the target point. Successful establishment of planned rendezvous conditions completes the delivery process. Everything thereafter is categorized here as orbital operation (primarily, mating or fueling of modules).

The sequence of principal events during delivery is summarized in Tab. 1 for a two-stage vehicle exemplified by Saturn V and for a more advanced single-stage vehicle. It is seen that in this model the mission of the ELV proper is completed--as far as delivery is concerned--with the successful separation of the payload. The ELV may deliver the payload directly into the target orbit into a near-rendezvous condition, leaving it to the propulsion system attached to the payload to carry out a comparatively small terminal maneuver to attain full rendezvous condition. If no direct delivery occurs, the payload either is launched into a parking orbit, or the method of intercept delivery (ref. 1) is applied: that is, the ELV enters an elliptic orbit, slightly overshooting the target orbit. Prior to intersection with the target orbit the payload is separated and, with its own propulsion system accomplishes rendezvous. In either case, the number of events remains the same for the ELV mission, while the number of principal maneuvers for the payload propulsion system is either one or two (Fig. 2). In the case of 1-burn (for payload propulsion system) intercept-delivery, the number of events is basically the same as for the sequence of events outlined above. The overall probability of delivery is

$$P_D = R_{ELV} R_{E-7} R_{E-8} \tag{1a}$$

The reliability of the events E-1 through E-6 directly related to the ELV is

$$\prod_{E-1}^{E-6} R_E = R_{ELV} \tag{1b}$$

The reliability R_{ELV} is assumed to vary as shown in Fig. 3 for the 2-stage Saturn V as the result of the cumulative launches between 1970 and 1990. The assumed reliability of events E-7 and E-8 is also shown in Fig. 3. These reliability curves are based on component reliability estimates and on experience curves for various ballistic missiles and space boosters (ref. 2). Since a reliability analysis is not the purpose of this paper, these curves are presented here as one of several reliability models which will be used in the subsequent cost analysis. The reliability curve for the 1-stage ELV is based on the assumption of all-chemical propulsion with initial operational availability in 1975. The propulsion system is assumed to consist of advanced O_2/H_2 engines and a configuration described as NEXUS configuration below. Since the vehicle does not stage and since the number of principal events involved in the delivery is, therefore, smaller, a higher rate of growth is indicated. It is believed that the reliability figure of 0.945 in 1990 for a 1-stage vehicle operational since about 1975, is conservative.

4. Operating Cost of Establishing an Orbital Installation

4.1 Total Operating Cost

The total operating cost, C, of establishing a particular orbital installation consists of the sum of the total operating cost of the logistic operation, C_{log}, of which the cost of transportation into orbit is the major part, plus the total operating cost of the orbital operation, C_{orb},

$$C = C_{log} + C_{orb} \tag{2}$$

The total operating cost is defined here, as in ref. 3, as being the sum of direct and indirect operating cost. The direct operating cost comprises the cost of article production, propellant, transportation from factory to launch site, launch cost, maintenance and repair or refurbishing, flight crew (if any) and other recurring costs. The indirect cost includes the cost of range operation, GSE per launch complex, launch facility, article development and other non-recurring cost. The term "article" refers to either the ELV or the net payload package and its associated propulsion system, needed for events E-7 and E-8 (Tab. 1). The individual cost elements listed above must, of course, be checked as to their applicability to the particular case under consideration.

The logistic operation consists of launch preparations and delivery, beginning with lift-off and terminating with rendezvous condition of the payload. Cost considerations enter both phases. Reliability is primarily a problem in the delivery phase and has been specified in Sect. 3 above.

4.2 Cost of Logistic Operation

A large number of interesting cost analyses have been prepared in the past five years, regarding the cost of development and operation of launch

Tab. 1 SEQUENCE OF EVENTS MODEL FOR EARTH-TO-ORBIT DELIVERY

EVENT	2-STAGE VEHICLE (SATURN V)	1-STAGE VEHICLE
E-1	Launch of S-IC	Launch
E-2	Cut-off of S-IC	Cut-off of some engines
E-3	Staging of S-IC	Jettisoning of fairing
E-4	Ignition of S-II	Cut-off of residual engines
E-5	Jettisoning of fairings	Separation of payload
E-6	Cut-off of S-II	Rendezvous maneuver of payload
E-7	Separation of payload	
E-8	Rendezvous maneuver of payload	

vehicles of various sizes. Some of the related work and additional references are found in references 3 through 5. Moreover, cost and development time predictions become increasingly vague the more ambitious the project. For these reasons, and since detailed cost analysis is not the objective of this paper, approximations will be used which assure the development of a possible and perhaps likely cost model which can be used for parametric purposes and which takes into account the effect of increasing experience with large launch vehicles, and the effect of the rising cost of production and living.

The direct operating cost for vehicles of the Saturn V type which are expendable and land-launched, consists to about 90 percent of vehicle production cost. Therefore, for the present discussion, the variation in direct operating cost can essentially be reduced to a discussion of the production cost. This cost decreases with increasing cumulative production number due to growing experience and improving production efficiency. The cost increases with time, however, due to rising labor and material cost and due to continued product improvement of vehicle subsystems and components. Thus, the production cost is primarily a function of the cumulative production number and of time. From the volume of sales and deliveries of aircraft corporations in the 1950/60 period, it was shown in ref. 3 that the production cost, in terms of dollars per lb hardware delivered, increased almost by a factor of six during that decade, from $21 to $118. This includes the effect of transition from aircraft to missiles and, to a lesser extent, from missiles to spacecraft. The cost of airliner production roughly doubled during the past decade.

The effect of transition from missiles to spacecraft on cost will make itself felt in the 1960/70 period and will be caused primarily by a trend toward further reduction in production numbers resulting in more man-hours per unit weight, the (rightful) demand by NASA and DoD for higher product quality and reliability, by further increase in the proportion of electronic and other high cost equipment and material (heat shields, etc.), by a further rise in average salaries due to an increase in the proportion of highly skilled personnel all the way from design to manufacturing and testing and by other factors, connected with more studies, analysis and research. This trend may be expected to continue into the 1970/80 decade with the advent of nuclear propulsion, nuclear electric power generation, extensive application of cryogenic technology and, on the operational side, with the introduction of orbital facilities, lunar bases and manned planetary operations into the technological frame of reference.

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,

$$z = 0.03\ (0.9Y + 0.3) + 0.00022\frac{\nu}{Y^2} - 0.00000008\frac{\nu^2}{Y^6} \qquad (3)$$

where Y represents the cumulative number of years, starting with mid-1970 (i.e. Y = 1 in mid-1971). The term in parenthesis indicates that the first term, which represents the increase in cost with progressing time, is not directly proportional to time, modulating the growth of z, taking into consideration factors such as saturation of plants with highly skilled and experienced personnel (i.e. level-off trend in the process of transition in the personnel composition), amortization of the investments in basic production capabilities (for cryogenic fluids and special "space age" materials) and in other basic facilities (large simulators, special test facilities). The second term represents the time correlated effect of the production number ν. With increasing production, the cost per unit weight of hardware will decrease. However, this decrease will be different if a certain production number is to be attained during the "first" year (Y = 1) than two or three or more years later. In the first case, the cost-reducing effect will be less pronounced because of extensive tooling and facility investments and because rapid increase in the production number of a relatively young product is bound to cause mistakes which must be charged against the production cost. This effect, however, should diminish rapidly with time, as expressed by Y^2 in the denominator.

The third term modulates the effect of ν in the first year (Y = 1) and takes into account that for Saturn V the year 1971 is not really "Y = 1". The third term is designed to give the increase in production number to very high values of Saturn V in 1970 a greater cost-reducing effect than it would be justified for the first operational year of a new product.

Counteracting this cost-raising trend is the fact that with increasing production number, independent of time, there is going to be a reduction in cost due to progress on the learning curve, more efficient production methods, smaller reject quantities and amortization of the production facilities and equipment proper. This trend can mathematically be defined by the experience curve $a\nu^{-b}$ which, in logarithmic form represents a straight line. From data concerning the V-2 rocket the B-29, B-47, B-52 and others for production numbers up to 1000, presented in ref. 3, a value of $b = 1/6$ is indicated, corresponding to about 90 percent learning. Most of the experience cases mentioned before are, however, based on time periods which are shorter than the 15 years considered here. In practice, progress on the learning curve makes b a function of time also. Neglecting this aspect here (since some of this, at least, already has been incorporated in z) we then apply the following relation to the determination of the production cost per lb of hardware

$$K_{prod} = a\nu^{-b} e^{z} \tag{4a}$$

which becomes, under the given assumptions for the Saturn V ELV,

$$K_{prod} (\$/lb) = a\nu^{-1/6} \exp \quad 0.03\,(0.9Y - 0.3) + 0.00022 \frac{\nu}{Y^2} - 0.00000008 \frac{\nu^2}{Y^6} \tag{4b}$$

This relation is plotted in Figs. 4 and 5 for a = 80. Fig. 4 shows the effect of varying the production number in a given year. For a fixed production number the increasing cost of living is a dominant factor. Increasing the production number is more effective, in terms of cost reduction, in later years, since by then earlier investments are amortized, the entire manufacturing and quality control process is more "debugged" and the capability of handling increases in production efficiently and without costly errors is increased. For comparison, the relation $a\nu^{-b}$ is shown, which does not take cost-increasing effects into account. Fig. 5 illustrates the effect of time on the production for given production number. As would be expected, the cost-increasing effects are most dominant at prolonged manufacturing at a low production level. This effect is less pronounced, and may even be reversed temporarily, at higher production numbers.

The associated direct cost of delivery per lb of net payload (direct cost effectiveness) is

$$C_{O,D}^{**} \approx \frac{K_{prod}}{0.9} \; \frac{W_d}{W_\omega} \text{ (\$/lb Pld)} \tag{5}$$

for the expendable, land-launched Saturn V, where W_d is the dry weight and W_ω the net payload weight of the vehicle. The associated indirect cost effectiveness is

$$C_{I,D}^{**} = m\, C_{O,D}^{**} \text{ (\$/lb Pld)} \tag{6}$$

where m = m(N), N being the annual launch rate. Cost analyses made in connection with the Post-Nova study indicate a trend as shown in Fig. 6, for m as function of the cumulative launches N, hence of ν, assuming that the vehicles are not stockpiled in significant quantities. The total cost effectiveness of payload delivery into orbit with Saturn V is, therefore, approximately

$$C^{**} \approx \frac{K_{prod}}{0.9} \; \frac{W_d}{W_\omega} \; (1 + m) \text{ (\$/lb Pld)} \tag{7}$$

Where $W_d \approx 440{,}000$ for both, first and second stage of Saturn V. The net payload is 250, 000 lb or less. The total operating cost per launch is then

$$C' \approx \frac{K_{prod}}{0.9} \; W_d \, (1 + m) \tag{8}$$

The total operating cost for a given orbit lift operation is,

$$C_{op} \approx N_{op} \, C' \tag{9}$$

where N_{op} is the number of launches required for a given transport volume. The annual total operating cost follows to be

$$C \approx N C' \tag{10}$$

where N is the number of launches per annum.

Two models of growth (case A and case B) of the Saturn V launch rate have been assumed and are shown in Fig. 7. They probably bracket the actual case. The associated cumulative net payload weight delivered into orbit is shown in Fig. 8 for three Saturn V payload levels. Case A assumes a comparatively moderate growth of cumulative payload in orbit, reaching 90 to 115 million lb by 1985. In case B, between 185 and 230 million lb will have been delivered into orbit by 1985. Mean total cost effectiveness and associated parameters have been determined for each of these cases, based on Eqs. (7) through (10) and Figs. 3, 4 and 6. They are listed in Tab. 2. Based on these values an approximate variation of total cost effectiveness of Saturn V versus time is shown in Figs. 9 and 10 for case A and B, respectively. All that can realistically be said about these figures is that they are likely and perhaps tend to be optimistic rather than conservative. This is done intentionally, because, if a larger, Post-Saturn ELV compares advantageously with Saturn V, such result is more conclusive if Saturn V is treated optimistically.

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. Corresponding to the orbital transportation models A and B assumed in Fig. 8 for 250,000 lb payload, the same payload build-up has been

Tab. 2 COST EFFECTIVENESS AND ANNUAL LAUNCH COST OF SATURN V FOR VARIOUS ORBITAL PAYLOAD LEVELS IN THE 1970-1985 PERIOD

TIME PERIOD	1970/75		1975/80		1980/85	
CASE	A	B	A	B	A	B
Total orbital payload (W_ω = 250 k) (10^6 lb)	15	30	30	65	65	130
(W_ω = 220 k) (10^6 lb)	13.2	26.4	26.4	57.1	57.1	114.2
Mean production cost, $\overline{K}_{prod}$ (\$/lb)	48	44	48	44	50	45
Mean ratio of indirect to direct oper. cost, m	0.77	0.7	0.64	0.61	0.54	0.475
Probability of successful delivery, P_D	1.0	1.0	1.0	1.0	1.0	1.0
Total number of launches, N_{op}	60	120	120	260	260	520
Annual number of launches, N	12	24	24	52	52	104
Total cost of effectiveness, C^{**} (\$/lb Pld):						
W_ω = 250 k	166	145	157	137	150	130
W_ω = 220 k	189	165	178	156	171	147
Cost per launch, C' (10^6 \$)	41.5	36.4	39.2	34.3	37.6	32.6
Total operating cost, 5-yr period, C_{op} (\$)	2500	4360	4700	8930	9800	16,900
Annual total operating cost, (\$/a)	500	875	940	1780	1950	3,380
Probability of successful delivery, P_D	0.792	0.792	0.87	0.87	0.93	0.93
Total number of launches, N_{op}	76	152	138	300	280	560
Average annual number of launches, $\overline{N}$	15.2	30.4	27.6	60	56	112
Total operating cost, 5-yr period, C_{op} (\$)	3165	5525	5405	10,300	10,550	18,200
Annual total operating cost (\$/a)	634	1110	1080	2060	2,110	3,640
Total cost of effectiveness, C^{**} (\$/lb Pld)						
W_ω = 250 k	210	183	181	158	160	140
W_ω = 220 k	240	209	200.5	180	183	158

followed with the Post-Saturn vehicle (Fig. 11) for which 1975 has been assumed to be the first full year of operational state. The cost effectiveness of such more or less hypothetical vehicle can vary considerably, depending on many detailed assumptions which cannot be discussed here. Typical variations of the total cost effectiveness with time for the type of vehicle under consideration are shown in Fig. 13 for the cases A and B and for the reusable and the expendable version. Typical uncertainty limits whose range is characteristic for all curves have been indicated for the upper curve as the apparently most likely curve for the case in question. The total cost effectiveness figures for the expendable versions probably are on the conservative side. Reusability is indicated to pay off more on the long run than initially where lower reliability will permit fewer vehicles, if any, to live through their full operational life of 10 launches and where recovery and refurbishing operations are less routine.

4.3 Cost of Orbital Operation

The cost of the orbital operation is composed of the orbital labor cost and of the ground operational cost. The latter, consisting primarily of tracking the orbital installation and of associated data evaluation is small compared to the cost of orbital labor, because it is based on tracking facilities and crews which are also used for tracking other satellites and deep space vehicles, as well as in connection with Earth-to-orbit logistic operations.

The bulk of the direct cost of orbital operations is connected with the establishment and the maintenance of a human labor force in orbit for the duration of the particular orbital operation (i.e. primarily the establishment of an orbital installation as defined in Sect. 2). A small amount (approximately 10 to 15 percent of the orbital labor cost) will have to be added for maintenance and/or replacement of orbital support equipment (OSE, the analog of the GSE). This OSE and its transport into orbit constitutes the bulk of the indirect (non-recurring) cost of the orbital operation. Of all these cost items, the orbital labor cost appears to be by far the largest single cost item, although exceptions are possible. Fortunately, the orbital labor cost is comparatively most accessible to a general analysis. The cost of the OSE depends upon the type of orbital operation; the cost of maintaining and servicing the OSE is largely a function of the duration of the particular orbital operation or of the sequence of orbital operations, all assumed to be using the same OSE.

For the hourly orbital labor rate, in terms of dollars per labor hour based on the period of the particular orbital operation, T_{op}, the following equation was developed,

$$(C_{h,OL})_{T_{op}} = \text{f (cost of special job training)} + \text{f (cost of transportation to and from orbit)} + \text{f (cost of living)} + \text{f (cost of housing)} + \text{f (cost of operating and maintaining orbital housing for the work force)} \tag{11}$$

$$(C_{h,OL})_{T_{op}} = \frac{C_{T\,rng}}{24 N_D T_D f_w} + \frac{1}{24\, T_{op} f_w} \quad \frac{T_{op}}{T_D} C_{T_r} + C_L + \frac{C_{OH} + C_{OM}}{\overline{N}_P} \tag{12}$$

where (1 day = 24 hrs),

$C_{T\,rng}$ (\$) = cost of special training of person for his orbital job, as paid for by the Government

N_D = number of orbital duty periods, T_D, of a given person during the period of orbital operation, T_{op}

T_D (days) = orbital duty period (i.e. time between ascent into orbit and return)

f_w = fraction of 24-hr period spent working

T_{op} (days) = total period of the particular orbital operation

T_{op}/T_D = number of transportations to and from orbit per equivalent person (if the ratio is not a full number, the next high full number must be taken)

$C_{Tr,P}$(\$) = transportation cost per person to orbit and back

C_L (\$) = cost of living

C_{OH} (\$) = cost of orbital housing for the labor force (no development cost)

C_{OM} (\$) = cost of operation and maintenance of orbital housing for the labor force

$\overline{N_P}$ = average number of personnel in the particular orbital labor force

In particular, it is

$$C_{Trng} = Y\, C_y \tag{13}$$

Y (years) = number of years of special training for orbital work

C_y (\$/yr) = annual cost of special training

$$C_{Tr,P} = (C^{**}_{ETO} + C^{**}_{OTE})\, W_P \tag{14}$$

C^{**}_{ETO} (\$/lb) = Earth-to-orbit personnel transportation cost (\$/lb of person and personal equipment)

C^{**}_{OTE} (\$/lb) = Orbit-to-Earth personnel transportation cost (\$/lb of person and personal equipment)

W_P (lb) = weight of person and personal equipment

$$C_L = T_{op}\, C^{**}_{Tr} (\dot{w}_F + \dot{w}_W + \dot{w}_X) \tag{15}$$

C_{Tr}^{**} (\$/lb) = cost of cargo transportation into orbit per pound of cargo

$\dot{w}_F$ (lb/d) = daily consumption of food which has to be replaced by supply from Earth (mostly solid, since water is recycled)

$\dot{w}_W$ (lb/d) = water loss per person per day

$\dot{w}_X$ (lb/d) = expendables per person per day (e.g. tooth paste, tissues, etc.)

$$C_{OH} = C_{production} + C_{launch} = W_{OH}\,\overline{C}_{prod} + W_{OH}\,C_{Tr}^{**} \qquad (16)$$

W_{OH} (lb) = weight of orbital housing facility

$\overline{C}_{prod}$ (\$/lb) = mean production cost of facility

$$C_{OM} = 0.003\,\frac{T_{op}}{365}\,W_{OH}\,C_{Tr}^{**} + C_{GO} + C_{crew} \qquad (17)$$

assuming that the cost of maintenance corresponds in the average to transporting daily 0.3% of the weight of the orbital housing facility into orbit at \$150/lb transport cost.

$C_{GO}(\$) = C_{Daily} \cdot T_{op}$ = cost of ground operations, i.e. average daily cost times period of operation (tracking, etc.)

C_{crew} (\$) = cost of crew to run and maintain the orbital housing facility. This cost is assumed presently to be zero, since "facility duty" can be handled by the labor crew; however, if a special crew or a specialist were required, apart from the work force, the associated cost would be carried under C_{crew}

Based on values selected for the various parameters, listed in Tab. 3, the orbital labor cost has been computed for orbital operations lasting 360 days, 180 days and 720 days, respectively. The results are shown in Figs. 14 through 17. Fig. 15 shows a cost breakdown for a 360 day operational period. This cost breakdown is typical also for the two other operational periods shown. From this figure it is seen that the cost of special training of the orbital labor force represents the dominant cost item and that the period of orbital duty and the number of orbital duty periods are the most important variables. If the

Tab. 3 COMPUTATION OF ORBITAL LABOR COST

Period of given orb. operation, T_{op} (d)		180	360	720		
Orbital duty period, T_D (d)	30	60	90	180	270	360
Number of orbital duty periods per person, N_D						
for T_{op} = 180 d	1, 2, 3	1, 2	1			
360 d	1···6	1···4	1, 2, 3	1		
720 d	1···12	1···6	1···4	1, 2, 3	1, 2	1
Fraction of 24-hr period spent working, f_W			1/3			
Number of years of special training, Y (years)			2			
Annual cost of special training per person, C_Y (\$/a)[1]			400,000			
Average weight of person & personal equip., W_P (lb)			200			
Cost of personnel transp. to & from orbit, $C^{**}_{Tr,P}$ (\$/lb W_P)			100			
Daily consumption of expendable food, $\dot{w}_F$ (lb/d/person)			3.66			
Daily water loss (to be replaced), $\dot{w}_W$ (lb/d/person)			0.35			
Daily expendables (to be replaced), $\dot{w}_X$ (lb/d/person)			0.74			
Cost of cargo transportation to orbit, C^{**}_{Tr} (\$/lb cargo)			150			
Average number of personnel, $\overline{N_P}$ (persons)			50			
Weight of orbital housing, W_{OH} (lb)			200,000			
Mean production cost of orbital facility, $\overline{C}_{prod}$ (\$/lb)			80			
Average daily cost of ground operations, directly charged to the orbital operations budget, C_{daily} (\$/d)			10,000			

[1] Special training comprises all ground and orbital training required to render a person capable of handling expensive orbital payloads professionally and with high confidence level as a fully effective member of the orbital team.

orbital duty period is brief, the cost of special training remains the dominant factor even if the cost is one half or one third of the $400,000 value assumed in Tab. 3. The cost of personnel transportation is a comparatively small item in the framework of a 360 day orbital operation. However, Fig. 18 shows that its contribution increases with decreasing period of orbital operation and increasing number of personnel rotations, expressed by the ratio of period of orbital operation to period of duty of the individual.[1] The cost of living contribution nominally is not a function of T_{op}, since both, food requirement and number of labor hours vary in the same manner with T_{op}. The contribution of orbital housing to the hourly labor rate exceeds that of transportation by a factor of 4 and higher, as shown in Fig. 19 for various average numbers of personnel, $\overline{N}_P$, and on the basis of the specifications listed in Tab. 3 and in Fig. 9.

These data show:

1. For periods of orbital operations of 100 days or more, personnel transportation costs play a comparatively minor role in the overall hourly labor rate, provided 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 doubling the transportation cost of $100/lb assumed here (postulating an all-recoverable 2-stage personnel transport vehicle).

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[1] As far as transportation cost is concerned, it does not matter, whether or not 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.

2. The cost of supplying the orbital crew with expendable items, primarily (on a per person basis) food (3.66 lb/d/p), make-up water (0.35 lb/d/p) and miscellaneous, ranging from food containers, filters, sanitary supplies, etc. (0.74 lb/d/p) contributes approximately $89 to the hourly labor rate, based on a transportation cost of $150/lb.

3. The principal cost item, aside from the cost of special training, is orbital housing and its maintenance. Even for an operational period of one year, its contribution to the hourly labor rate is between $350 and $850 for crew sizes between 50 and 20 persons.

4. If the cost of ground and orbital training of the individual is taken into account, the hourly labor cost varies within wide limits, being now strongly dependent upon the individual's orbital duty periods during the total period of a given orbital operation.

5. Unless the cost of special training can be kept at a level of $50,000 to $60,000 per person per year (for a two-year period), it is of great economic importance to maintain long orbital periods of duty (at least 90 days): or, if this meets with difficulties from the standpoint of work efficiency, to assure at least three tours of duty ($N_D = 3$) of 30 days per individual for orbital projects ranging from 180 to 720 days.

The overall orbital labor cost is a function of the various items discussed above and of the period of the orbital operation. Assume, for instance, that a 100 day orbital operation is planned, involving a crew of 30 persons, which is not rotated, but stays up for 100 days. Then the hourly labor rate becomes, not counting special training,

Cost of living (Fig. 18)	89 \$/hr
Personnel transportation (Fig. 18, $T_{op}/T_D = 1$)	24.5 \$/hr
Housing (Fig. 19, $\overline{N_P} = 30$)	2000 \$/hr
Hourly labor rate without special training	2113.5 \$/hr

resulting in a cost of $2113.5 \cdot 800 \cdot 30 = \$50,724,000$. At the cost of special training specified in Tab. 3, the amount of $30 \cdot 2 \cdot 400,000 = \$24,000,000$ must be added, yielding a total of \$74,724,000, or an overall hourly labor rate of \$3110.

5. Operational Considerations and Probability of Success of Orbital Delivery and Establishing Orbital Installations

5.1 Criteria

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:

(1-a) number of deliveries required,

(1-b) probability of successful delivery,

(1-c) probability of successful orbital mating and/or fueling.

Tab. 4 relates these parameters to six criteria, grouped in three categories. The number of launchings affects ground operation and ELV procurement cost, especially if the vehicles are expendable. The reliability of the overall 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.

Tab. 4 **CRITERIA AFFECTING THE COST OF ESTABLISHING AN ORBITAL INSTALLATION**

Parameter	Criterion					
	No. of launchings	Procurement Volume		Orbital Operation		
		ELV	Modules	Level	Duration	Labor Cost
Number of orbit deliveries	*	*		*	*	*
Probability of successful delivery	*	*	*		*	*
Probability of successful orbital mating and/or fueling	*	*	*	*	*	*

5.2 Probability of Successful Establishment of Orbital Installations

The total requirement on the transportation system is determined by the probability of success desired for the delivery operation in addition, by the orbital operation associated with the payload weight delivered and the desired level of its probability of success.

First, it is assumed that the payload packages are modules of a larger system which is assembled in orbit by mating these modules. We consider two cases:

Case A: All modules delivered are mated. Failure to mate one module to several modules already mated is assumed to lead to the loss of the two modules concerned, but not of the other modules. Thus, if module II of a I-II complex fails to be mated with module III, both modules II and III are assumed to be made unsuitable, but not module I. Module II must be separated from I and two new modules II and III delivered and mated with each other and with I.

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

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

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

$$P_D^* = \sum_{n_D = n}^{n+j} A_j \, P_D^{\,n} (1 - P_D)^j \tag{18}$$

where P_D is given by Eq. (1a) and A_j follows from Tab. 5. Thus, for 3 or more

Tab. 5 COEFFICIENT A_j IN EQ. (18)

	A_j														
j	n=1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2	1	3	6	10	15	21	28	36	45	55	66	78	91	105	120
3	1	4	10	20	35	56	84	120	165	220	286	364	455	560	680
4	1	5	15	35	70	126	210	330	495	715	1001	1365	1820	2380	3060
5	1	6	21	56	126	252	462	792	1287	2002	3003	4368	6188	8568	11, 628

successful deliveries out of 5 attempts, i. e. $n_D = 3 + 2$, it is

$$P_D^* = P_D^3 + 3\, P_D^3 (1 - P_D) + 6\, P_D^3 (1 - P_D)^2 \tag{19}$$

and so forth.

The probability of m or more successful matings of m + 1 modules in m to m + k attempts under the ground rules specified for case A above is given by the following equations.

$$k = 0 \quad P_{M,m}^* = P_M^m$$

$$k = 1 \qquad = P_M^m \left[1 + (1 - P_M)\right] \tag{20}$$

$$k = 2 \qquad = P_M^m \left[1 + \sum_{k=1}^{2} (1 - P_M)^k\right] + (m-1)\, P_M^m\, P_M P_d (1 - P_M) \tag{21}$$

$$\begin{aligned} k = 3 \qquad &= P_M^m \left[1 + \sum_{k=1}^{3} (1 - P_M)^k\right] + (m-1)\, P_M^m P_M P_d \\ &(1 - P_M) \left[1 + (1 - P_M)\right] + (m-1)\, P_M^m P_M P_d (1 - P_M)^2 \end{aligned} \tag{22}$$

$$\begin{aligned} k = 4 \qquad &= P_M^m \left[1 + \sum_{k=1}^{4} (1 - P_M)^k\right] + (m-1)\, P_M^m\, P_M P_d (1 - P_M) \\ &\left[1 + \sum_{a=1}^{2} (1 - P_M)^a\right] + (m-1)\, P_M^m\, P_M P_d (1 - P_M)^2 \\ &\left[1 + (1 - P_M)\right] + (m-1)\, P_M^m P_M P_d (1 - P_M)^3 \\ &+ 2\,(m-1)\, P_M^m\, P_M^2\, P_d^2 (1 - P_M)^2 \end{aligned} \tag{23}$$

$$k = 5 \qquad = P_M{}^m \left[1 + \sum_{k=1}^{5} (1 - P_M)^k \right] + (m - 1) P_M{}^m P_M P_d (1 - P_M)$$

$$\left[1 + \sum_{a=1}^{3} (1 - P_M)^a \right] + (m - 1) P_M{}^m P_M P_d (1 - P_M)^2$$

$$\left[1 + \sum_{a=1}^{2} (1 - P_M)^a \right] + (m - 1) P_M{}^m P_M P_d (1 - P_M)^3$$

$$\left[1 + (1 - P_M) \right] + (m - 1) P_M{}^m P_M P_d (1 - P_M)^4$$

$$+ 2(m - 1) P_M{}^m P_M{}^2 P_d{}^2 (1 - P_M)^2 \left[1 + (1 - P_M) \right]$$

$$+ 2 (m - 1) P_M{}^m P_M{}^2 P_d{}^2 (1 - P_M)^3 \qquad (24)$$

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 above 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 $(m + 1) + (k + 2)$. This number, then, determines the possible number of successful launches required. Thus, if $m = 3$, $k = 2$, 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 non-reusable) and of nine modules (if interchangeable) would have to be procured to attain the associated overall success probability.

$$P^* = P_D^* P_M^* = \sum_{8}^{9} A_1 P_D^8 (1 - P_D) \left\{ P_M^3 \left[1 + \sum_{k=1}^{2} (1 - P_M)^k \right] + 2 P_M^2 P_M P_d (1 - P_M) \right\} \tag{25}$$

In case B, Eqs. (18)through(24) 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. Thus, in the example leading to Eq. (26), assume that p = 3 orbital installations of m + 1 = 4 modules each would have to be established. Then the overall success probability is

$$P_p^* = (P_D^* P_M)^p \tag{26}$$

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

A third case is also considered:

Case C: 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 A and B.

For case C, Eq. (18) applies also to the orbital operation. The probability of s or more successes in p = s + q attempts to fuel or service the installation in any other manner is

$$P_S^* = \sum_{p=s}^{s+q} A_q P_S^s (1 - P_S)^q \tag{27}$$

where A is found from Tab. 5 for q = j and n = s. The probability of success of the entire operation is then in case C

$$P^* = P_D^* P_S^* \tag{28}$$

Probabilities P_D^*, P_S^* and P_M^* are shown in Figs. 20 through 23 for relevant ranges of individual probabilities P_D, P_S and P_M.

6. Comparison of Operational and Economic Aspects of Establishing Orbital Installations with a Large Number of Saturn V ELV Versus a Smaller Number of Post-Saturn ELV

6.1 Approach

The preceding Sections have laid the foundation for a comparison of the alternatives (1) and (2) presented at the end of Sect. 1. A comparison of two vehicles which do not exist, under operational conditions which have not yet been experienced, performing loosely defined tasks under economic conditions 12 years in the future is necessarily uncertain. Moreover, no exhaustive treatment of the subject is claimed in the framework of this paper. However, if the two cases are treated consistently, the resulting trends should nevertheless be of significance for future planning.

It is attempted to show that not only transport cost effectiveness is involved; but that the associated cost of payload procurement and of orbital operations also plays an important role.

The technique of comparison is illustrated in an example, listed in some detail in Tab. 6. The task is to establish an orbital installation which consists of four complexes of 10^6 lb each. Saturn V, given a useful payload of 250,000 lb, is compared with a chemical Post-Saturn vehicle of 10^6 lb useful payload. The year selected is 1975, assumed in this paper (as an example, not a prediction) to be the first operational year of "the" Post-Saturn vehicle. This year puts the Post-Saturn, therefore, in a particularly unfavorable position reliability wise. The nevertheless comparatively high reliability resulting in a probability of successful delivery of $P_D = 0.75$ is justified on the basis that a 1-stage-to-orbit vehicle (no auxiliary systems jettisoned), a 10-vehicle test

Tab. 6 COMPARISON OF ECONOMIC AND OPERATIONAL ASPECTS OF ESTABLISHING FOUR COMPLEXES @ 10^6 lb WEIGHT IN ORBIT IN 1975 WITH SATURN V AND POST-SATURN

		Saturn V									Post-Saturn ELV		
Line	Col.	1	2	3	4	5	6	7	8	9	10	11	12
1	n	4	4	4	6	6	6	8	8	8	4	4	4
2	j	0	1	2	0	1	2	0	1	2	0	1	2
3	m = 3: k	0	0	0	1	1	1	2	2	2	No mating req'd		
4	N_L	4	5	6	7	8	9	8	9	10	4	5	6
5	N_{Mod}	4	5	6	7	8	9	8	9	10	4	5	6
6	P_D^*	.498	.417	.9445	.351	.688	.877	.295	.493	.765	.316	.632	.829
7	P_M^* (P_M=.95; P_d=.99)	.855	.855	.855	.90	.90	.90	.983	.983	.983	--	--	--
8	$P^* = P_D^* \cdot P_M^*$	.425	.699	.806	.316	.619	.79	.29	.484	.751	.316	.632	.829
9	h	0	0	0	0	0	0	0	0	0	--	--	--
10	$N_L^* = 4\ N_L$	16	20	24	28	32	36	40	44	48	--	--	--
11	$N_{Mod}^* = 4\ N_{Mod}$	16	20	24	28	32	36	40	44	48	--	--	--
12	$P_p^* = (P^*)^4$	.033	.239	.422	.01	.147	.389	.007	.055	.318	--	--	--
13	h	1	1	1	1	1	1	1	1	1	--	--	--
14	$N_L^* = 5\ N_L$	20	24	28	32	36	40	41	48	52	--	--	--
15	$N_{Mod}^* = 5\ N_{Mod}$	20	24	28	32	36	40	44	48	52	--	--	--
16	P_p^* (h = 1)	.109	.527	.75	.037	.371	.716	.027	.168	.635			
17	Launch rate	1 per week (7 days) per launch pad									1/30d/launch pad		
18	Launch pads	4 + 1 spare = 5									3 + 1 spare (off-shore pltfms)		
19	Orbit. crew size (p)	$\overline{N}_P$ = 40									$\overline{N}_P$ = 20		
20	Launch period (d)	28	35	42	49	56	63	70	77	84	30	40	50
21	T_{op} (d)	38	45	52	59	66	73	80	87	94	40	50	60
22	Nomin. labor hrs.	11,800	14,400	16,600	18,900	21,100	23,400	25,600	27,800	30,100	6400	8000	9600
23	Cost of living (Fig. 18)	$89/hr	89	89	89	89	89	89	89	89	89	89	89
24	Housing ($\overline{N}_P$ = 40)	$4200/hr	3450	3000	2630	2350	2140	1940	1790	1650	No housing req'd		
25	Personnel Transp.	40 (persons) · 200 (lb/p) · 100 ($/lb) = $800,000									$61/hr	49	41
26	Total Orb. Labor	$51.3M	51.7	52.2	52.1	52.4	52.9	52.8	53	53.2	$.96M	1.1	1.25
27	Total hourly rate	$4350	3590	3140	2760	2480	2260	2070	1908	1770	$150/hr	138	130
28	C**	$160/lb Pld (Fig. 9, 1975); 160 · 250,000 = $40 M per ELV									$120/lb Pld; $120M/ELV		
29	Max. # ELV procured	16	20	24	28	32	36	40	44	48	4	5	6
30	Max. launch cost	$640M	800	960	1120	1280	1440	1600	1760	1920	$480M	600	720
31	Total cost w/o Pld.	$691.3M	851.7	1012.2	1064.3	1332.4	1492.9	1652.8	1813	1973.2	$481M	601.1	721.25
32	Max. payload wt. procured (10^6 lb)	4	5	6	7	8	9	10	11	12	4	5	6

NOTES FOR TAB. 6

1. See text for discussion of Table and explanations beyond those given below.

2. Line 6: P_D = 0.84 for Saturn V; P_D = 0.75 for Post-Saturn

3. Line 9: Process of mating 4 modules to obtain a 10^6 lb complex has to be repeated 4 times to obtain the required 4 complexes @ 10^6 lb; h = 0 means that no additional attempt to mate one more 10^6 lb complex is planned. This results in the overall number of launches, modules to be procured and probability of success, indicated in lines 10, 11, 12, respectively.

4. Line 13: One additional attempt to assemble a 10^6 lb complex is planned (h = 1), resulting in improved probability of success (line 16) of obtaining the required 4 complexes @ 10^6 lb, but at correspondingly higher procurement and launch cost.

5. Line 20: Designates the period within which all launches take place.

6. Line 21: The orbital operation is 10 days longer than the launch period to account for mating and/or checkout of the last module (Saturn V) or complex (Post-Saturn) which may arrive at the last day of the launch period.

7. Line 22: Based on 8 labor hours per day of T_{op} on the number of days of T_{op} and $\overline{N}_P$ (line 19).

8. Line 24: In the case of Post-Saturn, the orbital crew is expected to live in the complex for the duration of the period T_{op} of orbital operation

9. Lines 26, 27, 30: The cost of special training of the orbital crew (cf. Sect. 4.3) is <u>not</u> included.
(M = million dollars)

10. Line 28: Cost effectiveness for Post-Saturn is derived from 160 · 0.75 = 120; where \$160/lb is given in Fig. 13 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 6 & 8), the cost effectiveness figure has been reduced to a value corresponding to 100% reliability. The cost figures in Fig. 13 account for the effect of reliability statistically over large numbers of launchings, whereas the values in lines 6 and 8 refer to success probability for the given, limited, number of delivery attempts.

11. Line 29: The procurement figures for Post-Saturn refer to expendable version, but are unlikely to be lower for the expendable version, in view of the short launch period (for which the vehicles have to be readied in advance) and in view of the low reliability (1975 being postulated as the first operational year in this example).

program, and careful, advanced quality control and checkout methods have been assumed. .

For Saturn V the task amounts to transporting 16 modules into orbit and mating them to 4 10^6 lb-complexes. Lines 1 through 8 determine, for the assembly of one 10^6 lb complex, the overall 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 $P_M = 0.95$, $P_d = 0.99$ (Sec. 5.2); and the overall probability of success P^*. The assumptions specified for orbital mating (rather than fueling) in Sect. 5.2 are used. Three alternatives are considered. First, in columns 1 through 3, no extra mating attempt beyond the minimum of 3 matings is planned (k = 0); whereas the number of extra delivery attempts is increased from zero (j = 0) to two (j = 2). The delivery probability grows, therefore, according to Eq. (18), for n = 4 and j = 0, 1, 2, i.e. 4 successful deliveries in 4, 5 and 6 delivery attempts. In practice, when 6 deliveries are planned, the first four deliveries may be successful; in which case the fifth and sixth ELV and payload 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 col. 1 through 3, which merely aims at maximizing the probability that the four required modules will actually be delivered. In col. 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 made in Par. 5.3 that 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 6 modules.

In col. 7 through 9, finally, k = 2 and j = 0, 1, 2. 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 (col. 3). Trying to accumulate excess modules in orbit (k = 0) in case they are needed there degrades the overall probability of success unless P_D is higher.

In lines 9 through 12 the effect is shown of carrying out 4 times each of the 9 alternatives for establishing one 10^6 lb complex (lines 1 through 8), on the procurement requirements and on the overall probability, under the assumption that no additional attempt to assemble a 10^6 lb-complex is planned (h = 0). If one attempt is planned (h = 1), the figures in lines 13 through 16 are obtained. Lines 17 through 30 estimate the cost of delivery and of orbital labor. The procurement requirements for h = 0 are used. Instead of attaching a dollar figure to the payload modules, they are compared on a weight basis, since it is plausible that their specific cost ($/lb) is comparable for Saturn V and Post-Saturn. In regard to this weight and the associated number of Saturn V payloads it should be pointed out that this number represents the maximum number of interchangeable modules which could possibly be used. Actually, to procure one module for each delivery failure which could possibly occur and two modules for each mating failure which could possibly occur is excessively cautious and might be justified only if the procurement lead times for the modules is much longer than the launch period and if the importance of timely execution of this operation is so crucial that it must not be endangered by lack of an adequate module supply, however remote the probability. Since the probability of occurrence of every conceivable module-damaging failure which could possibly occur, is almost zero, the probability that these many modules will be needed is likewise zero; in other words, the risk to the success of the overall operation, entertained by reducing the procurement of modules by some 10 to 20 percent is very small. The same applies to the procurement of Saturn V vehicles, since it is most unlikely that the maximum number of launch failures (one or two, respectively, during the assembly of each 10^6 lb complex) actually will occur. Again this statement is based on the assumption that all Saturn V vehicles and their payload interfaces are alike and, therefore, freely interchangeable. If all 16 modules are significantly different (in the sense that a change to convert one module into another (given this is feasible) would require significantly more time than the planned launch period), then a significantly larger number of modules than indicated in line 31 must be procured to be consistent with the overall 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. Therefore, 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, compared to all-out interchangeability, the numbers given in line 31 could possibly have to be met.

In any case, for comparable success probability the procurement cost when using Saturn V is considerably higher than for Post-Saturn. Although the individual delivery reliability of the latter is a good deal inferior than that of Saturn V, the confidence level (.829) attained with $6 \cdot 10^6$ lb payload procurement (j = 2, k = 0) is significantly higher than that attainable with Saturn V for the same condition (.422, line 12, col. 3). Conversely, for a success probability of at least .75 (line 16, col. 3), $7 \cdot 10^6$ lb of payload would have to be procured. The reason for this is, of course, that no orbital mating is required. A maximum amount of preparation is done on the ground where it can be done more efficiently and far less expensively. The launch costs are likewise higher for Saturn V, since for each Post-Saturn launch at least 4 Saturn V launches are required, whereas the launch cost of an O_2/H_2 Post-Saturn ELV of the payload capability envisioned here appears to be only about 3 times as high as that of a Saturn V.

The example indicates the following:

1. The best alternative available to Saturn V, in terms of competitiveness with Post-Saturn would be n = 4, j = 2, k = 0, h = 1 (col. 3, lines 14 through 16).
2. This case compares with Post-Saturn, n = 4, j = 2 as follows:

   overall success probability: .75 vs. .829

   max. number of launches: 28 vs. 6

   max. launch cost (expendable ELV): \$1120M vs. \$720M

   max. payload wt. procurement: 10^7 lb vs. 10^6 lb.
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 Post-Saturn, 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 order of \$400M for the entire operation. The economic superiority of Post-Saturn is not raised significantly if the cost of special training of the orbital crew is taken into consideration. At the level specified in Tab. 3, this cost is \$16M higher for Saturn V, based on line 19 of Tab. 6.

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, 10^6 lb more payload weight must be procured, adding \$300M to the \$400M 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 for Post-Saturn, adding another \$50 to 65 million and bringing the total cost difference for this comparatively small orbital operation to the order of \$750 million in favor of Post-Saturn V. It is important to note that this advantage is due to about 50 percent to lower transportation cost, the other half being derived from lower payload weight procurement and simplification of the asso-

ciated orbital operations. Even if the savings were only half as large, they would still be very significant.

In conclusion, it should be pointed out that 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 be attached (so as to eliminate the need for demating a module). In that case, a mating failure results in a requirement for one, rather than two additional deliveries. This raises the overall probability of success significantly, even if the probability of mating success proper (P_M) is not raised.

This condition can certainly be assumed to exist in the case of fueling rather than mating. This case is, of course, predicated on the specification, not made previously, that the 10^6 lb complex is a vehicle. It must further be assumed that the vehicle uses chemical propellants (O_2/H_2 or denser), since the size of a 10^6 lb nuclear-powered hydrogen carrying vehicle is too big for the presently specified payload volume of Saturn V (about 52,000 ft^3) limited by facility limitations and design criteria. However, O_2/H_2, assuming a mean density of 24 lb/ft^3, requires only about 38,000 ft^3 for a propellant load of 900,000 lb. Thus, the complete vehicle can be carried aloft, partly fueled and subsequently fueled by tankers. To account for problems connected with mounting the entire vehicle in the nose section, and taking into consideration insulation weights for the tanker atop Saturn V, it is assumed that in this case, a minimum of 5 launches is required, 1 for the vehicle and 4 tankers.

6.2 Long Range Transportation Requirements

Although the example in Sect. 6.1 indicates an impressive potential cost superiority of Post-Saturn, the difference nevertheless is small compared to the development cost of such a vehicle which is expected to lie between 5 and 10 billion dollars. It is, therefore, necessary to establish a justification on the basis of sustained long-range transportation requirements.

As basis for this comparison has been selected the Case A transportation level (Fig. 7) which calls for an average successful orbital delivery of 6 million lb in 1975/79 and of 12 million lb in 1980/84. The delivery costs are based on the cost effectiveness values and associated varying success probabilities shown in Figs. 9 and 13. The orbital labor cost data are based on the cost analysis presented above and specifically on the resulting hourly rates, plotted in Fig. 24 for the conditions noted on the graph. For Saturn V a net payload of 250,000 lb is assumed. In computing the orbital labor cost, the orbital personnel required in the second 5-year period has been increased by 50% for Saturn V (corresponding to a reduction of the nominal period of duty by 50%) and by 33 percent for Post-Saturn. The results are shown in Fig. 25 for the expendable and the recoverable version of the Post-Saturn ELV. The cost figures shown are cumulative with progressing time. The upper three curves show both, delivery and orbital labor cost. The lower two curves show the orbital labor

Tab. 7 RELIABILITIES OBTAINED WITH SATURN V FOR THE SAME TASK AS IN TAB. 6, EXCEPT THAT MATING IS REPLACED BY LAUNCHING COMPLETE VEHICLE IN ORBIT AND FUELING

		Saturn V			
Line	Col.	1	2	3	4
1	n	1	1	1	1
2	j	0	0	1	1
3	N_L	1	1	2	2
4	N_V	1	1	2	2
5	$(P_D = .84) P_D^*$	.84	.84	.9745	.9745
6	Tankers s	4	4	4	4
7	q	0	1	0	1
8	N_L	4	5	4	5
9	N_T	4	5	4	5
10	$(P_s = .95)\ P_S^*$	.814	.977	.814	.977
11	N_L for 1 compl. veh.	5	6	6	7
12	$P^* = P_D^*\ P_S^*$	.684	.82	.792	.952
13	h	0	0	0	0
14	$P_p^* = (P^*)^4$	.219	.452	.393	.835
15	N_L^*	20	24	24	28

cost. The cost effect of the two approaches on payload is not included, since it cannot be assessed in this general form. However, the qualitative trend established in this respect by the example in Sect. 6.1 should apply also to the general case. Fig. 25 shows:

1. The cost superiority of the Post-Saturn appears to be based in the first place on size, in the second place on the more gradually developing effect of reusability, thirdly on savings in orbital labor cost which are the least certain factor, but are believed to be treated here conservatively, i.e. reducing the difference between Saturn V and Post-Saturn more than might be the case in a more specific 10-year orbital delivery program.
2. It is, therefore, not necessary that Post-Nova attains reusability from the start. It is more significant that its design and configurational characteristics permit the development to a reusable mode of operation in the course of approximately the first five years of its operational life.
3. If the cost of developing Post-Saturn is taken as 6 billion dollars, then this investment should be amortized during the first ten years of its operational life, if the transport requirements develop as assumed in Fig. 25, even if no reusability is attained during this period. In case of reusability, amortization is indicated after about 8 years of operational life.
4. It is, therefore, important that the Post-Saturn configuration selected, has a low rate of obsolescence. This is assured if

the vehicle is characterized by:

(a) a shape which offers as few volume restrictions as possible to a payload weight of this magnitude

(b) highest possible operational simplicity and reliability

(c) advanced chemical engines (high-pressure O_2/H_2) and a design which permits the vehicle to be adapted to more advanced propulsion systems, as the state-of-the-art advances, specifically to the use of nuclear and airbreathing engines.