Orbital Burden Rates for Manned Space Missions

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The present trend of making maximum use of available space flight hardware focuses the attention of the systems analyst on orbital operations, such as assembly, maintenance, fueling, checkout, and launch of deep-space ships. Such operations require skilled labor and additional masses to be available in earth orbit. The purpose of this paper is to derive the mass and cost burden rates associated with the orbital preparation of space vehicles for departure on specific missions. Major system parameters are defined and their sensitivities are determined. It is shown that the daily propellant consumption in orbit, the maximum launch-rate capability of the primary cargo transport, the assembly reliability, and the mass of orbital support equipment are the more influential parameters. Representative values for the burden rates are given in dimensionless graphs with orbital departure mass and number of ships leaving as parameters. It is shown that they can be of the same orders of magnitude as the minimum mass and cost required to place the space vehicle departure mass in orbit. It is clear that orbital burden rates can not be neglected in space mission evaluations, but that they would be much smaller (factors up to 10) if a large, post-Saturn cargo vehicle were available.

Nomenclature

C = cost, for particular mission, \$
c = specific cost per unit mass, \$/kg
c' = specific cost per man, \$/man
k = proration factor, fraction of Σm_{sv}
$\dot{k}$ = use rate factor, fraction of Σm_{sv}/day
k_1 = cargo packaging factor, fraction of payload delivered to orbit that is actually useful
k_c, k_p = loading efficiency factors (payload mass loaded over maximum vehicle payload capability) for cargo and passenger vehicles, respectively
m = mass, for particular mission, kg
m' = equivalent mass per man, kg/man
$\dot{m}$ = amortized use rate, kg/day
$\dot{m}'$ = personal use rate, kg/man-day
N = number of men in given crew or orbital activity, for particular mission, men
n = number of units, operations, or events of a given type, for particular mission
$\dot{n}$ = launch rate for critical earth-to-orbit vehicle, launches/month
R = reliability (probability of success) of given type of operation
t = time required (or available) for given operation, calendar days

Subscripts

com = tracking and communications
cv = cargo vehicle, earth-to-orbit
cvp = cargo vehicle payload capability
dc = duty cycle for trained orbital crewman (whole tour, not work/rest cycle)
fa = fuel for main assembly and docking operations
fo = fuel for all other orbital operations
in = indirect labor and services
k = countdown
l = launch-window waiting (readiness) time
ls = logistics supplies or support
met = survival of meteorite damage
oo = total orbital operations for particular mission
ose = prorated orbital support equipment (tugs, taxis, tankers, etc.); cost includes development
osf = orbital support fuel (includes fa and fo)
osh = prorated orbital support facility (housing, etc.)
pv = passenger vehicle, earth-to-orbit
pvp = passenger-vehicle payload capability
s = space vehicle to be launched from orbit
ss = space station
sao = in-orbit space-vehicle assembly operations
sco = in-orbit space-vehicle checkout operations
sfo = space-vehicle fueling operations
sp = space-vehicle personnel (crew for space mission)
ssr = space-vehicle spare parts or repairs
tc = transportation, cargo
tcf = transportation, propellants
tg = training of orbital crewman
tp = transportation, personnel

Received May 20, 1964; revision received May 31, 1964. The opinions expressed in this paper are those of the author and not necessarily those of NASA.

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Introduction

MANY manned deep-space missions require such large vehicle masses in Earth orbit that some degree of orbital support operations becomes mandatory. These orbital support operations, for the subject analysis, are defined as the sum of rendezvous, docking, fueling, maintenance, repair, checkout, and countdown operations required to ready and launch a particular space vehicle or a fleet of space vehicles from orbit. These operations require additional mass (m_{oo}) in orbit over and above the departure mass (m_s) of the space vehicle(s). This additional mass, if divided by the total departing space-vehicle mass, is defined as the "orbital mass burden rate," and similar definition is used for the cost burden, in dollars per kilogram, associated with the orbital support operations:

Mass Burden Rate

$$\beta_{m_o} \equiv m_{oo}/\Sigma m_s \tag{1}$$

Cost Burden Rate

$$\beta_{C_o} \equiv C_{oo}/\Sigma m_s \tag{2}$$

As will be shown in this discussion, β_{m_o} can be of order of unity, and β_{C_o} can represent several times the cost of the space expedition. The purpose of this paper is to derive relationships that approximate these burden rates in a generalized, relatively simple but satisfactory manner. A secondary objective is to determine the sensitivities of the major system parameters and estimate the constants involved. Finally, several missions were selected to calculate representative values for these orbital burden rates.

Four steps are required in an investigation of this nature: 1) determination and definition of factors influencing the problem in a significant way; 2) description of the interrelationships between these factors in an approximate manner and structuring of the resulting equations in a suitable form; 3) choice of assumptions for the constants and variables entering the equations, and determination of the sensitivities of these assumptions; and 4) verification or qualification of the assumptions, by means of an error analysis, to increase the confidence level for the conclusions arrived at. The first three steps are accomplished to a satisfactory degree in this paper.

Mass Burden Rate for Orbital Operations

Mass Balance

The mass burden (m_{oo}) is the sum of the following six individual mass burdens:

Prorated Space Station Mass (assuming that no idle period will be charged to this particular operation)

$$m_{osh} = k_1 N_{oo} t_{oo} \dot{m}_{osh}' \tag{3}$$

Life Support Mass

$$m_{1s} = k_1 N_{oo} t_{oo} \dot{m}_{1s}' \tag{4}$$

Propellant Mass

$$m_{osf} = k_1(k_{fa}\Sigma m_s + \dot{k}_{fo} t_{oo} \Sigma m_s) \tag{5}$$

Prorated Orbital Support Equipment Mass

$$m_{ose} = k_1 t_{oo} \dot{m}_{ose} \equiv k_1 t_{oo} \sum_i \left(\frac{m_{ose,\,i}}{t_{ose,\,i}}\right) \tag{6}$$

Passenger Mass

$$m_{tp} = m_{tp}'[(N_{oo}t_{oo}/t_{dc}) + N_{sp}] \tag{7}$$

Mass for Fight Hardware Replacements

$$m_{ssr} = \Sigma m_s(k_1 k_{ssr} + 1 - R_{oo}) \tag{8}$$

The total mass burden is then

$$m_{oo} = k_1 t_{oo}[N_{oo}(\dot{m}_{osh} + \dot{m}_{1s}') + \dot{k}_{fo}\Sigma m_s + \dot{m}_{ose}] + \Sigma m_s(k_1 k_{fa} + k_1 k_{ssr} + 1 - R_{oo}) + m_{tp}'[(N_{oo}t_{oo}/t_{dc}) + N_{sp}] \tag{9}$$

where the terms t_{oo}, N_{oo}, and R_{oo} are further defined in the following subsections.

Duration of Orbital Operation (t_{oo})

The "duration" of orbital support operations is primarily a function of the launch rate capability (on the ground) of the most critical launch vehicle. Additional time is required for final checkout, repair, and the countdown; thus

$$t_{oo} = t_{sao} + t_{sfo} + t_{sco} + t_k + t_1 \tag{10}$$

where these times are in calendar days. The assembly time is governed by the launch rate capability and is expressed as

$$t_{sao} + t_{sfo} = 30 n_{cv}/\dot{n}_{cv} \tag{11}$$

where $n_{cv,i}$ and $\dot{n}_{cv,i}$ can be any of the launch vehicles participating in the operation. That launch vehicle that results in $t_{sao} + t_{sfo}$ maximum has to be used for determining t_{oo}. The checkout time is a function of the number of checkout events (n_{sco}), the rate at which these can be performed (k_{sco}), and the number of people in the checkout crew N_{sco}:

$$t_{sco} = n_{sco} k_{sco}/8N_{sco} \tag{12}$$

where 8 stands for an 8-man-hr duty time/man-day. The countdown time t_k is an absolute number of days. The launch-window waiting time includes that part of the launch-window cycle during which the vehicle has to remain in launch readiness.

Number of Orbital Operations Support Personnel Required (N_{oo})

A suitable relationship can be developed only from actual experience. At least two approaches are possible: one based on minimum skills to be available, the other on the basis of actual man-hours of labor required. The latter approach will eventually be the more accurate one, particularly in a major operation. At this time, however, it is easier to make an estimate of the minimum skills required, which is the more realistic approach for a smaller operation. There are four different activities to be performed, each requiring a minimum number of people. Also shift operation and redundancy for incapacitation (sickness) have to be taken into consideration. These requirements can then be broken down into minimum crews for operation of support equipment N_{ose}, assembly operations N_{sao}, fueling operations N_{sfo}, and checkout operations N_{sco}. A special allowance is made for jobs that result from the unreliability of the entire operation, i.e., for backup personnel with special skills and/or more available manpower for peak workloads. Finally, a share of the housekeeping functions of the support facility (such as a space station) has to be taken into consideration, and a typical relation for the number of people required in orbit can have the form

$$N_{oo} = N_{in} + k_{in}(1 - R_{oo}^{1/2})(N_{ose} + N_{sao} + N_{sfo} + N_{sco}) \tag{13}$$

It should be noticed that this is not necessarily a function of the mass in orbit, since such a crew can serve the same function on a number of vehicles in a sequential manner. On the other hand, the complexity of the operation is included by the factor $k_{in}(1 - R_{oo}^{1/2})$, and this will result in a requirement for more people, if the expedition is built up with the support of a small launch vehicle. The number N_{oo} does not include the crew (N_{sp}) finally departing with the ship or convoy, which arrives only shortly before the final countdown. This is, however, considered in the transportation requirements.

The assembly reliability appearing in Eq. (14) can be written as follows:

$$R_{oo} = R_{sao}^{n_{sao}} R_{sfo}^{n_{sfo}} R_{\text{met}} \tag{14}$$

This equation applies to the assembly of one ship, or a convoy, provided the operation is done parallel. This reliability, however, has nothing to do with the probability that the expedition will leave on time, which has to be determined separately.

Launch Rates (n_{cv})

In a standard operation, several launch vehicles will be used to support the preparation of a mission leaving from earth orbit. A typical case would be a passenger transport which also can carry spare parts and life support, a medium-size cargo vehicle, and a large cargo vehicle. Two important figures enter the calculation here: $n_{cv,i}$, the total number of launches for each vehicle; and $\dot{n}_{cv,i}$, the maximum launch rate for each vehicle. In general, if only one launch vehicle participates in the operation, one can write for the total number of launches required:

$$n_{cv} = (\Sigma m_s + m_{oo})/m_{cv} k_c R_{cv} \tag{15}$$

Or, if one cargo vehicle and one passenger vehicle participate we can use (with proper payload distribution) for the cargo vehicle, which transports the stages, all propellants and support equipment, and the space station:

$$n_{cv} = [\Sigma m_s(2 - R_{oo}) + m_{ose} + m_{osf} + m_{osh}]/m_{cvp} k_c R_{cv} \tag{16}$$

For the passenger transport, which carries people, life support cargo, and spare parts, we can use

$$n_{pv} = (m_{1s} + m_{tp} + k_1 k_{ssr} \Sigma m_s)/m_{pvp} k_p R_{pv} R_{sao} \tag{17}$$

If more than one cargo vehicle participates in the operation, Eq. (16) has to be split accordingly. It generally helps to use two different cargo vehicles in order to reduce stay time in orbit if the launch rate from orbit is restricted. Use of the launch vehicle mission reliability R_{cv} and R_{pv} in the denominators of Eqs. (16) and (17) results in the number of launch attempts to be programed, rather than the number of successful launches required. Another correction factor (k_c, k_p) is entered to consider the payload degradation, which results from the inability to match all spacecraft and fuel packages (as well as number of passengers flown) with the maximum capacity of the vehicles theoretically available.

Numerical Assumptions for the Mass Burden Rate

Orbital operation constants

Most of these assumptions represent "typical" values or "educated guesses" based on studies[1–6] on the subject proper. One of the more critical assumptions is the one on propellant consumption in earth orbit, as will be shown later. This parameter includes the following: 1) vaporization losses, 2) propellants required for the transportation of personnel and spare parts between orbital launch facility and space vehicles, 3) leakage losses through valves and airlocks, 4) propellants for attitude control of all vehicles in orbit, and 5) propellant requirements for maneuvering and orbit control of all vehicles in orbit. These are not easy to estimate as they are very vehicle-dependent. Reference 2 gives, for one typical design, vaporization losses from orbital boosters (item 1) in the order of 12 kg/m²-day. This would be approximately 0.13% of the vehicle weight per day. Liquefaction systems could probably reduce this amount, but they tend to increase hardware weight and maintenance work in orbit and to decrease reliability. All of these losses are estimated to be in the order of $\dot{k}_{fo} = 0.005\Sigma m_s$/day, with a variance of probably ± 50%. Other assumptions are less critical and are, for a typical operation, selected as follows:

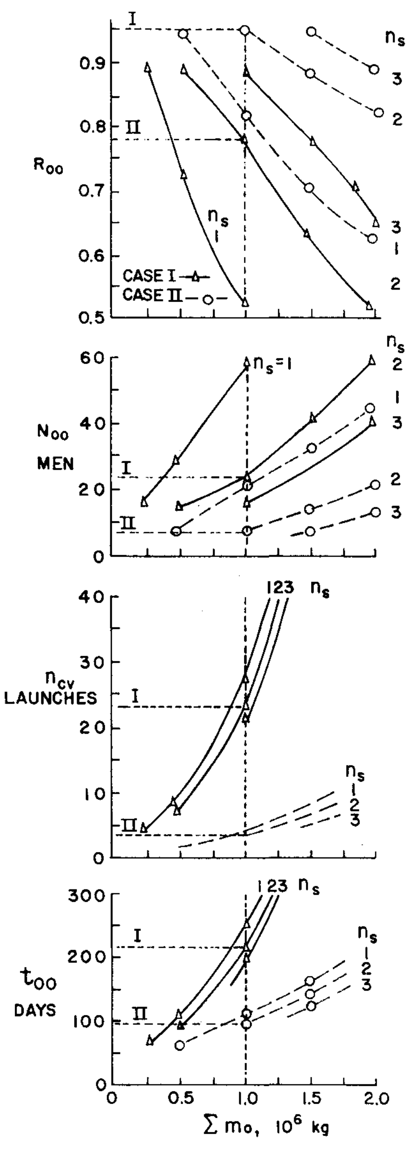

Fig. 1 Comparison of operating parameters for case I (solid curves; Saturn V is largest cargo vehicle) and case II (dashed curves; post-Saturn-size vehicle permitted for large units).

Crews, men:

$$\left\{\frac{N_{in}}{3} \quad \frac{N_{ose}}{6} \quad \frac{N_{sao}}{3} \quad \frac{N_{sfo}}{2} \quad \frac{N_{sco}}{2} \quad \frac{N_{sp}}{8}\right\}$$

Times, day:

$$\left\{\frac{t_k}{3} \quad \frac{t_1}{30} \quad \frac{t_{dc}}{60}\right\}$$

Other constants (see Nomenclature):

$$\left\{\frac{k_1}{1.2} \quad \frac{k_{ssr}}{0.01} \quad \frac{k_{fa}}{0.01} \quad \frac{k_{fo}}{0.005} \quad \frac{k_{in}}{15} \quad \frac{k_{sco}}{0.2} \quad \frac{n_{dc}}{10} \quad \frac{n_{sco}}{1200}\right\}$$

and

$$m_{tp}' = 120 \text{ kg/man} \qquad \dot{m}_{ose} = 1000 \text{ kg/day}$$

$$\dot{m}_{osh} = 3.33 \text{ kg/man-day} \qquad \dot{m}_{1s} = 5 \text{ kg/man-day}$$

Space Vehicle Data

all vehicles: $R_{\text{met}} = 0.99$

Reusable Orbital Transport (Hypothetical)

12 passengers	1440 kg
Cargo	2800 kg
Total useful payload, m_{pvp}	4240 kg

$$\left\{\frac{R_{pv}}{0.98} \quad \frac{R_{sao}}{0.98} \quad \frac{k_p}{0.90}\right\}$$

Medium Sized Cargo Carrier (Saturn V Class)

Total useful payload $m_{cvp} = 150{,}000$ kg

R_{cv}	R_{sao}	R_{sfo}	k_c	$\dot{n}_{vc}$
0.90, case I 0.88, case II	0.90	0.95	0.90	4/mo

Large Cargo Carrier (Post-Saturn Class)

$m_{cvp} = 500{,}000$ kg

$$\left\{\frac{R_{cv}}{0.88} \quad \frac{R_{sao}}{0.90} \quad \frac{R_{sfo}}{0.96} \quad \frac{k_c}{0.85} \quad \frac{\dot{n}_{vc}}{2/\text{mo}}\right\}$$

Using these assumptions and the preceding equations, one obtains as a first approximation for the orbital mass burden rate

$$\frac{m_{oo}}{\Sigma m_s} = 9.33\,\frac{t_{oo}N_{oo}}{\Sigma m_s} + 1.024 - R_{oo} + 0.006\,t_{oo} + \frac{120}{\Sigma m_s}\left(10\,t_{oo} + \frac{t_{oo}N_{oo}}{60} + 8\right) \quad (18)$$

where

$$N_{oo} = 3 + 205(1 - R_{oo}^{1/2}) \quad (19)$$

$$t_{oo} = 30(n_{cv}/\dot{n}_{cv}) + (n_{sco}/240) + 33 \quad (20)$$

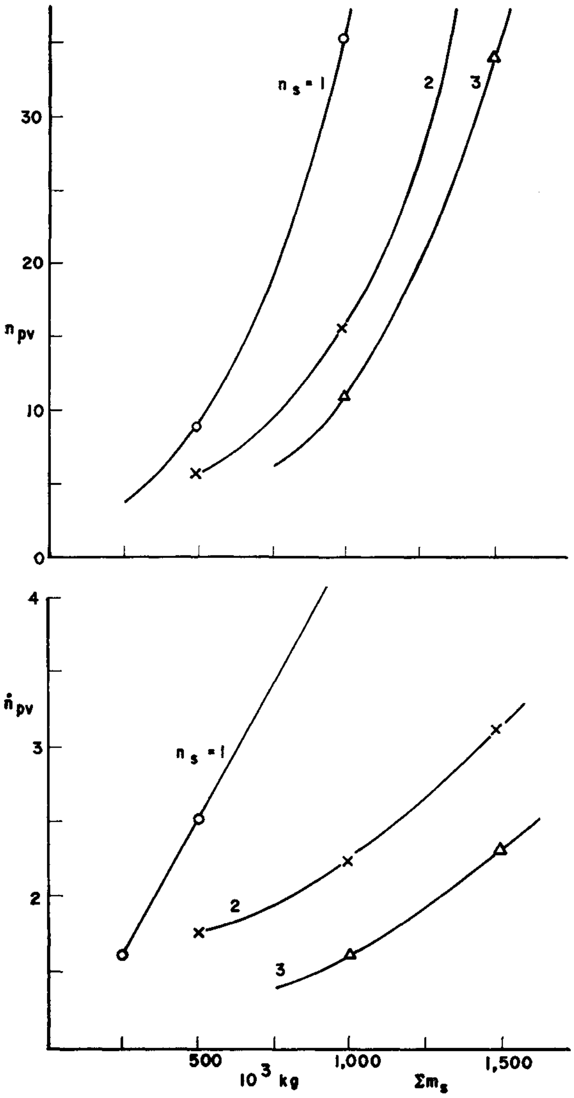

Fig. 2 Number of total launches and monthly launch rates required for reusable orbital transport (case I).

We are now ready to evaluate some trends with the numerical example chosen which might, or might not, be representative of the state of the art in the late 1970's. Two cases are considered, namely:

Case I: A reusable transport is used for the transportation of personnel and small cargo items, and a medium-sized cargo carrier of the Saturn V class is used to handle all orbital transportation jobs.

Case II: A large cargo vehicle of the post-Saturn size is used for very large pieces and units to be hauled into orbit.

Figure 1 shows R_{oo}, N_{oo}, n_{cv}, and t_{oo} as functions of total departure mass for both cases. In each case, the number of space vehicles (n_s) leaving earth orbit is varied between 1 and 3. Let us examine, as a typical mission, an expedition consisting of two ships with 1×10^6 kg mass total (2,200,000 lb):

1) R_{oo}: The reliability of the assembly and fueling operation to be expected is about 0.78 for case I and 0.95 for case II.

2) N_{oo}: In case I, we need 25 people, in case II, only 9.

3) n_{cv}: The total number of launch attempts required will be 23 for case I, and five launches of the large cargo vehicle (plus about an equal number of the medium-size cargo vehicle) for case II. Total departure weights larger than 1×10^6 kg do not look feasible for case I.

4) t_{oo}: Case I requires 210 days of preparation time in earth orbit, and case II, only about 100. This difference alone will produce a sizeable increase in the mass burden rate for case I. A six-month preparation time is considered a practical upper limit, and even this might be too high.

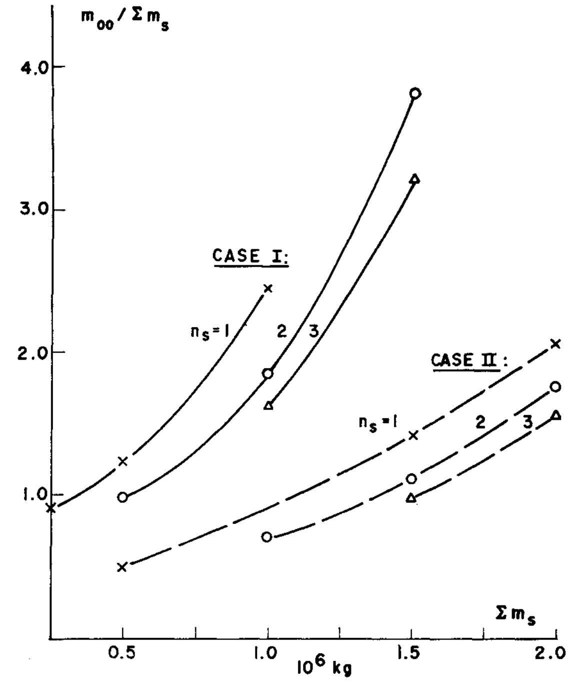

Fig. 3 Total mass burden rates for cases I and II plotted vs departure mass with number of departing ships as a parameter.

Figure 2 shows the number of flights to be made n_{pv} and the launch rate $\dot{n}_{pv}$ for the small passenger carrying vehicle (reusable orbital transport), case I. For $\Sigma m_o = 10^6$ kg, $n_{pv} \approx 15$, it will be less for case II. This number does not appear to be critical. The launch rate $\dot{n}_{pv} < 3$ per month should not present a problem at all if a reusable vehicle is available.

Figure 3 presents the total mass burden rates for the two cases. Our two-vehicle, $n_s = 2$, 10^6-kg expedition must be charged with a burden rate of about 180% in case I and with only about 75% in case II. This is quite a remarkable difference. It is noted that, for case I, departure masses below 0.75×10^6 and one or two ships result in acceptable burden rates.

Finally, Fig. 4 shows the sensitivity of the mass burden rate to the individual parameters. The nominal assumptions leading to the results shown in Fig. 3 are used as unity, and changes up to $\pm 50\%$ in some of the more imported parameters are investigated. The steeper the gradient, the more sensitive is the parameter. The two outstanding parameters to watch (and to investigate further with great care) are the maximum launch rate possible ($\dot{n}_{cv}$) and the daily fuel consumption in orbit ($\dot{k}_{fo}$). Next in line is the over-all unreliability of the assembly operation ($1 - R_{oo}$) and the requirement for orbital support equipment prorated over this mission. Other parameters (not shown) are less important.

Another interesting presentation of the mass burden rate results is obtained by calculating, for each of the eight examples (data points on figures), the mass percentage for each of the elements contributing to the total departure masses. Listed in Table 1 are only the maximum and minimum values, pointing out that case II has a smaller spread than case I.

Cost Burden Rate for Orbital Operations

The cost burden is derived in a similar manner as the mass burden, and is based on the masses calculated for the mass burden rate. The cost burden is the sum of the following

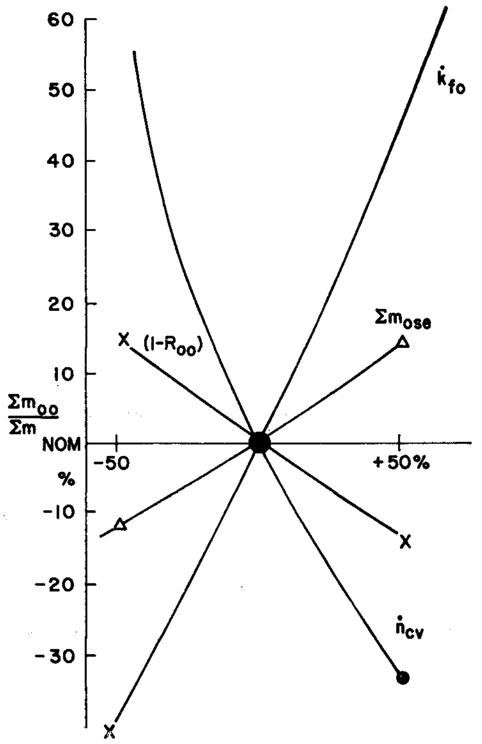

Fig. 4 Sensitivity of mass burden rate with change of major influence factors (case I).

subtotals, wherein the weight definitions and relations of the previous section apply:

Housing

$$C_{osh} = m_{osh}(c_{tc} + c_{osh}) \tag{21}$$

Training

$$C_{tg} = N_{oo}T_{oo}c_{tg}'/T_{dc}n_{dc} \tag{22}$$

Life Support

$$C_{ls} = m_{ls}c_{tp} \tag{23}$$

Personnel Transportation

$$C_{tp} = m_{tp}c_{tp} \tag{24}$$

Propellant Transportation

$$C_{osf} = m_{osf}c_{tcf} \tag{25}$$

Orbital Support Equipment

$$C_{ose} = m_{ose}(c_{tc} + c_{ose}) \tag{26}$$

Spare Parts

$$C_{ssr} = \Sigma m_s\, k_1\, k_{ssr}\, C_{tp} + \Sigma m_s(1 - R_{oo})C_{tc} \tag{27}$$

with

$$c_{ssr} \ll c_{tc}$$

Communications

$$C_{com} = T_{oo}c_{com} \tag{28}$$

Lost Payloads

$$C_{losses} = n_{cv}k_{cv}m_{cvp}(1 - R_{cv})c_{tc} + n_{pv}k_{pv}m_{pvp}(1 - R_{pv})c_{tp} \tag{29}$$

Note that, in Eqs. (23) and (25), the actual costs of life support items (food, etc.) and propellants are considered negligible in comparison to their transportation costs and are neglected. In Eq. (29), if men are lost, c_{tp}' is the adjusted value c_{tp} to include training cost of men on equivalent basis.

The total orbital cost burden for the mission C_{oo} is found by adding Eqs. (21–29). The "orbital cost burden rate" is then found by dividing this cost by the total mass of all space vehicles (Σm_s) readied for departure to a specified mission [Eq. (2)]. The descriptions of the space vehicle(s) required to accomplish the desired missions are obtained from Refs. 1–6.

In order to obtain a better feeling for the order of magnitude of the cost burden rate, as well as the relative importance of the contributing factors, the same numerical examples (based on N_{ss} = 30 and Σm_s = 10^6 kg) will be exercised as for the mass burden rate. The following assumptions are needed to proceed with the examples:

Cost Assumptions

c_{osh} = 2000 $/kg
c_{tg}' = 2×10^6 $/man
c_{ose} = 1000 $/kg (average)
c_{com} = 0.1×10^6 $/day
c_{tp} = 50 $/kg
c_{tc} = transportation cost for cargo, variable:

Data Points (Fig. 5), Ref. 7

Case I:	Saturn V only	= 440 $/kg for 1 to 3
		330 $/kg for 4 to 9
Case II:	(average)	= 330 $/kg for 1 to 3
		300 $/kg for 4 to 6
		265 $/kg for 7 to 9
	(Saturn V)	= 550 $/kg for 1 to 3
		440 $/kg for 4 to 6
		330 $/kg for 7 to 9
	(post-Saturn)	= 220 $/kg for 1 to 3
		178 $/kg for 4 to 6
		132 $/kg for 7 to 9

Figure 5 shows the results obtained in the numerical evaluation, where the cost burden rate is plotted vs the departure weight of the total expedition with the number of ships used as the parameter. Case I, using only the Saturn V as the primary cargo vehicle, appears to be practical only for departure weights below 1.5×10^6 kg. The burden rates approach 2000 $/kg, which indicates an extra charge of $$3 \times 10^9$ for a 1.5×10^6-kg expedition. Case II shows orbital burden rates much lower, in the order of about $\frac{1}{3}$ of case I. Also the sensitivity is much less. Departure weights up to 2.5×10^6 kg should result in cost burden rates not much more than 1000 $/kg. In the range of practical interest, 2 ships with a total of 1 to 1.5×10^6 kg, the cost burden rate is less than 500 $/kg.

The relative importance of the individual cost elements can easily be determined by calculating their share of the total cost burden rate. This has been done for all nine data points. The minimum and maximum values obtained for both cases are listed in Table 2. With the assumptions used, the greatest contributor is the propellant transportation cost, which can amount to as much as 55% of the total for case I, or 75% for case II. However, this is probably also the factor in greatest doubt. It could conceivably be 50% smaller with very careful propellant management techniques. It could also be 50% larger if operations are sloppy. The second most important element is the research, develop-

Table 1 Distributions of mass burden rate, %

Factors	Case I Min	Case I Max	Case II Min	Case II Max
Prorated space station	0.9	1.9	0.3	0.9
Life support	1.3	3.6	0.4	1.6
Propellants	45	82	66	84
Support equipment	10	35	3.4	14.2
Orbital crew	0.4	1.4	0.2	1.0
Spare parts	4	20	6.2	21.3

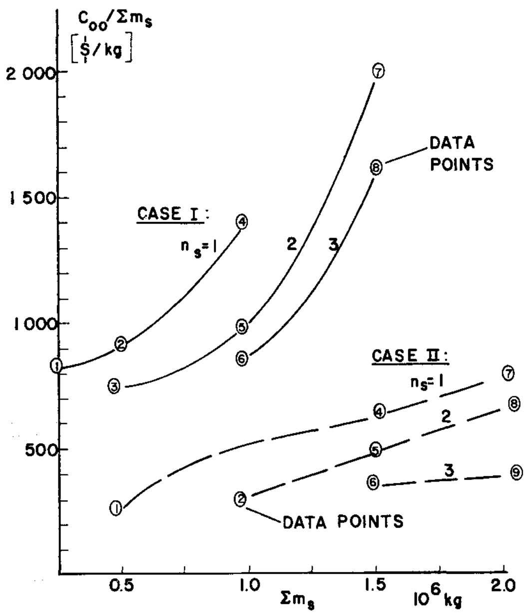

Fig. 5 Total cost burden rates for cases I and II plotted vs departure mass with number of departing ships as a parameter.

ment, and manufacturing cost of the orbital support equipment. The third is the transportation cost for this equipment, and the fourth place is taken by the transportation cost for the spares. All other elements contribute less than 10% each to the total. This information allows for further insight as to where to look for reductions first. Such savings can be obtained by proper design features and have to be studied individually.

Conclusions

The following conclusions seem to be justified at this early stage of the investigation on this subject.

1) Mass and cost burden rates for orbital operations are quite large, and probably more pronounced than those previously anticipated. They can be multiples of the mass and cost associated with transporting the space vehicles departing from orbit into earth orbit.

2) Critical parameters found were: a) daily propellant consumption in orbit; b) maximum launch rate capability of primary cargo transport; c) assembly reliability; and d) mass and utilization of orbital support equipment.

Table 2 Distribution of cost burden rate, %

Factors	Case I Min	Case I Max	Case II Min	Case II Max
Use of space station	3.4	8.8	1.8	5.9
Personnel training	1.3	3.5	0.7	2.3
Life support	1.3	3.4	0.9	2.3
Personnel transport	0.4	1.2	0.3	0.9
Propellant transport	22	55	42	75
Support equipment transport	6.5	17	6.1	14
Spare part transport	2.8	12	3.1	9.1
Support equipment R & D, manufacturing	21	40	9.4	22
Tracking and communication	1.6	3.3	1.6	3.2
Payload and spares	1.6	6.3	1.4	6.8

3) The transportation of support personnel to and from orbit was found not to be critical because a reusable orbital transport vehicle was assumed to be available. In case such a vehicle is not available and a Saturn IB and Apollo-type spacecraft must be used, this cost element can increase by a factor of 20 and thus would become a critical parameter.

4) It is very important to keep the stay time in orbit small, because many of the mass and cost elements are functions of this stay time. The most effective way to decrease this stay time is to increase the launch rate capability, or as an alternative attempt to send a larger number of smaller ships at a higher frequency when a mission opportunity becomes available in order to keep over-all cost low.

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[7] Koelle, H. H. and Voss, R. G., "The effects of new large launch vehicles on the cost effectiveness of the national booster program," AIAA Preprint 64-278 (June 1964).

Discussion by K. A. Ehricke (see also accompanying paper by Ehricke, p. 611)

The paper by H. H. Koelle is an excellent treatment of the over-all aspect of orbital burden rates for future manned space operations. The analysis is precise and sufficiently general to cover all aspects of orbital operations foreseeable at this time. The paper offers a clear insight into the potential economical problems associated with orbital operations and thereby furnishes an additional incentive to reduce as much as practical the use of orbital operations in the planning of future space operational models. It provides additional arguments in favor of a large reusable earth launch vehicle.

This author agrees fully with Koelle's conclusions in general and with his specific conclusions regarding the criticality of certain parameters, especially the daily propellant consumption in orbit. The examples given indicate the probability of considerable economical burden. At this point, however, this author would like to discuss two exceptions: the first pertains to reliability, the second to the inevitability of fuel consumption as the dominant critical parameter.

1) The reliability treatment presented does not bring out the effect of the issue of the differences in module mating vs fueling and the issue of module interchangeability. This is indeed difficult to do in the framework of the present analysis; but a reliability analysis along these lines done by this reviewer and his associates showed that the effect of the preceding factors is larger than perhaps was recognized previously. Thus, assembly reliability can move to the second or perhaps even the first place among critical parameters.

2.1) The daily propellant consumption depends on the orbital modulus operandi. If one envisions a separate system of orbital launch facility (OLF) and interorbital space vehicles (ISV's), much traffic between OLF and ISV's is required; hence, k_6 becomes large and time sensitive. But many ISV's require complete checkout and diagnostic pro-