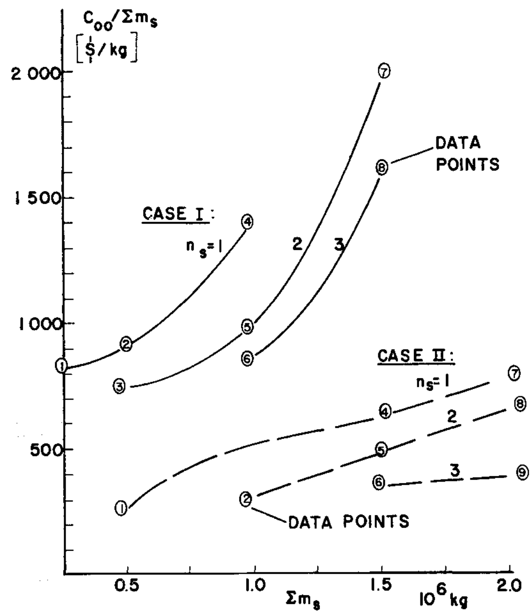

Fig. 5 Total cost burden rates for cases I and II plotted vs departure mass with number of departing ships as a parameter.

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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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 probabilty 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, $\dot{k}_6$ becomes large and time sensitive. But many ISV's require complete checkout and diagnostic provisions built into the mission modules to maintain high probability of crew survival and mission success, especially in heliocentric flights. It can be assumed that an orbital assembly operation would use the ISV mission module as a principal OLF center and for housing the orbital crew. Thereby the daily propellant consumption can be reduced substantially.

2.2) The daily propellant consumption has been put equal to the daily propellant supply requirement. This is not necessarily the case, because, due to limitations in the mating reliability of fueled ISV modules, some modules are expected to be damaged during mating attempts. In most cases, this damage will disqualify the module for mission considerations while the module will continue to hold its propellants. Such modules represent a potential propellant source for the auxiliary vehicles of the orbital crew.

For these reasons, an over-all treatment of all aspects of orbital burden rate is necessarily a bit more indeterminate than perhaps a discussion of the orbital labor cost alone where fewer alternatives seem to exist. H. H. Koelle's paper, aside from its professional excellence, is a thought provoking contribution to a critically important aspect of space operations and will no doubt be the starting point of many investigations to economize orbital operations.

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Preliminary Study of Air Augmentation of Rocket Thrust

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A one-dimensional-flow analysis of an air-augmented solid rocket using supersonic afterburning indicates that significant gains in I_{sp} should be possible. Various hypothetical fuel-rich propellants are compared at a Mach 3, 40,000-ft flight condition. Net I_{sp} near 400 sec is typical for all propellants at $\dot{w}_a/\dot{w}_p$ between 1.0 and 1.5; I_{sp} increases with $\dot{w}_a/\dot{w}_p$. Density impulses are even higher for grains with high Al or Zr content; however the Zr grains require high temperatures to keep the unburned fuel species volatile for afterburning, and both Al and Zr lead to high condensed phase contents in the nozzle flow. Effects of air injection and mixing parameters are examined for a 45% Al propellant. Results at $\dot{w}_a/\dot{w}_p = 1.3$ are as follows: 1) complete mixing is not necessary, because if half of the rocket flow remains unmixed, the I_{sp} gain (120 sec) is reduced by only 10 sec; 2) for sonic air injection, there is a 1% loss in net I_{sp} for each 1% loss in diffuser kinetic energy efficiency; 3) near-sonic air injection is better than supersonic air injection; and 4) weak oblique shocks in the rocket gas due to moderate pressure mismatch hardly affect performance. Analytical and experimental studies of nonequilibrium flow effects, inlet-afterburner matching problems, and effects of mission and trajectory constraints are needed.

Nomenclature

c_p = specific heat, Btu/lb°R
F_{aug} = effective thrust of augmented rocket [Eq. (8)], lb
g = gravitational acceleration, 32.17 ft/sec²
h = enthalpy, Btu/lb
Δh_f^{298} = heat of formation at 298°K, Btu/lb
I_{sp} = propellant specific impulse; generally means value for augmented rocket, lb thrust/(lb propellant/sec)
$I_{sp}°$ = specific impulse for nonparticipating rocket core flow [Eq. (11)]
I_{sp}' = specific impulse for participating rocket propellants in partial mixing case [Eq. (11) and Fig. 1a]
I_Ω = density specific impulse [Eq. (10)]
J = mechanical equivalent of heat, 778 ft-lb/Btu
M = Mach number
$\mathfrak{M}$ = molecular weight, lb/mole
P = pressure, psia
r = weight fraction of rocket exhaust (central core) that does not mix or burn in partial mixing example (Fig. 1c)
T = temperature, °R
V = velocity, fps
$\dot{w}$ = weight flow rate, lb/sec
x = weight fraction
Z = altitude, ft
α = exponent on density ratio for I_Ω [Eq. (10)]
γ = effective specific heat ratio
ρ = propellant density, g/cm³
θ = local flow angle with respect to model axis, deg
φ = over-all air/rocket products equivalence ratio
φ' = $\varphi/(1-r)$
η_{KE} = diffuser kinetic energy efficiency, $P_{t_j}/P_{t_\infty} = [1 + (1 - \eta_{KE})(\gamma - 1)M^2/2]^{\gamma/(1-\gamma)}$

Subscripts

∞ = freestream conditions
a = air
aug = augmented
c = conditions after mixing and afterburning phase
e = nozzle exit conditions
i = ith product species
j = air jet at injection static conditions
k = kth reactant species
m = mixed, burned gas
p = propellant (generally the rocket gas entering the mixing zone)
t = stagnation condition

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Introduction

FUTURE gains in specific impulse for chemical rockets appear limited. Dobbins[1] has examined several fuel-oxidizer combinations with the following results: The highest performing liquid bipropellant systems, H_2-OF_2, H_2-F_2,