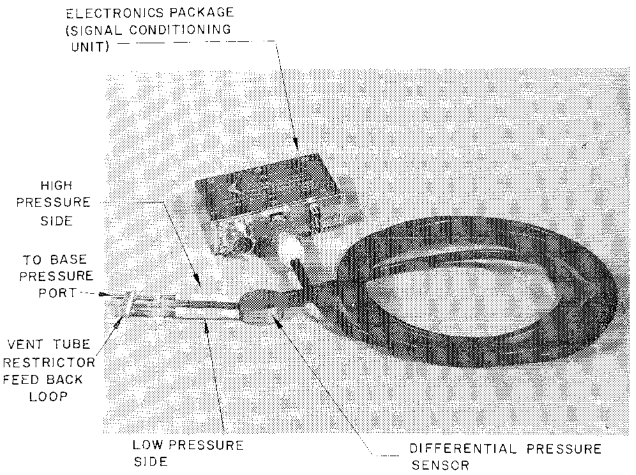


**Fig. 6 Commercial differential sensor retrofitted with vent tube restrictor time constant.**

ular axes. Calibration shifts were acceptably small (Fig. 4). Another test was made to simulate sustained deceleration of 220 $g$'s such as would be experienced during re-entry. Figure 5 shows results for three orthogonal axes. There is not appreciable change in output voltage for axes C and B, which represent planes parallel to the diaphragm of the transducer, but in the plane perpendicular to the diaphragm (axis A), the output voltage changed by 13%. Therefore, the unit should be mounted such that the maximum loads during re-entry will occur in the plane parallel to the diaphragm.

Finally, a commercial differential sensor was retrofitted with a vent tube restrictor (Fig. 6), and re-entry pressure simulation test results were compared with those from a commercial absolute sensor. The results were good (Fig. 7).

### Concluding Remarks

The concept of using a shock-tunnel-type differential sensor with a time constant to obtain low-level base-pressure measurements in re-entry vehicles has been demonstrated in ground tests with a flight prototype unit. This unit also successfully withstood the flight qualification environments of sustained acceleration, shock, and vibration with no degradation in calibration. A commercial differential sensor retrofitted with a vent tube restrictor agreed well with a commercial absolute sensor in other ground tests. Thus, a smaller and lighter flight package for base pressure measurements on re-entry test vehicles can be provided with no degradation in performance.

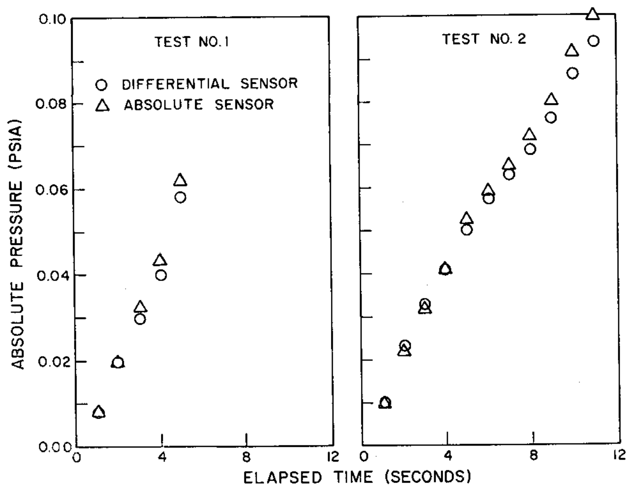


**Fig. 7 Comparison of retrofitted commercial differential sensor's readings with those of a commercial absolute pressure transducer during re-entry pressure simulation.**


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# Manned Maintenance and Refueling in Near and Deep Space Logistics

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### Nomenclature

$C$ = sum of annual logistic ($C_l$) and amortized (acquisition + deployment, $C_{a/d}$) cost per mission payload
$C_b$ = boost cost per pound of payload in orbit
$C_p$ = acquisition cost per pound for mission payload
$C_s$ = acquisition cost per pound for station and associated equipment
$g$ = gravitational acceleration, 32.2 ft/sec$^2$
$I$ = specific impulse, sec
$K$ = (stage gross wt/stage payload) ratio, $w_g/w_p = (r-1)/(1-\lambda r)$
$l$ = station crew duty cycle
$n_c$ = number of shuttle flights to rotate one station crew
$n_m$ = number of payloads serviced per earth-based flight
$n_s$ = number of payloads serviced from one station
$R$ = reliability for a launch-transit rendezvous
$r$ = vehicle gross weight/burnout weight
$T$ = time from initial system operation
$t$ = mean time between failures for unattended payload
$w$ = weight
$\alpha$ = large payload boost cost parameter [boost cost per pound in near orbit for large payload/boost cost per pound in near orbit for nominal (~25,000 lb) payload]
$\Delta v_1$ = ideal velocity gain required for launch-transit rendezvous between near-orbit injection and single refueling, or between first and second tankers
$\Delta v_2$ = ideal velocity gain required after final refueling, for mission maneuvers (e.g., altitude change from near to far orbit) and return to aerodynamic re-entry
$\Delta v_3$ = ideal velocity gain required after mission maneuvers to return truck and manned shuttle to near orbit
$\lambda$ = stage structure factor, $w_{str}/(w_{pr} + w_{str})$
$\tau$ = t/(service cycle maintained)

*Subscripts*

$DF$ = direct flight
$DR,SR$ = double refueling and single refueling, respectively
$EB,SB$ = earth-based and station-based, respectively
$MT$ = maneuvering truck
$TR$ = total replacement
$g$ = stage gross

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|---|---|---|
| $m$ | = | manned shuttle vehicle |
| $n$ | = | near orbit |
| $p,pr$ | = | payload and propellant, respectively |
| $s$ | = | station and associated equipment including tenders |
| $str$ | = | structure |
| $t$ | = | tanker or maneuvering truck |

## Introduction

THE exploration and use of space on a broad basis will be practical only when the cost effectiveness of space operations can be improved significantly. This study considers what cost benefits can be achieved by extending the useful life of space payloads through manned maintenance (either by flights from earth or from space stations) and increasing transportation economies through refueling and improved space propulsion. To facilitate analysis, maintenance modes and refueling modes are treated separately, although their coupling through boost cost ($C_b$) is indicated. Only the recurring costs of acquiring, deploying, operating, and maintaining spaceborne equipment are considered. (Research, development and ground facilities costs are not included because they generally can be amortized over many programs or missions.) The major results are presented in terms of breakeven conditions and parametric sensitivity curves, and separate and combined cost reduction effects are shown for a typical space system.

## Maintenance

Where continuous functioning of equipment in space is required, any of several maintanance modes may be employed. In the total replacement mode,† the entire payload is replaced by an unmanned launch; the payload is assumed to include the optimum degree of redundancy, so that any increase in redundancy increases the payload cost more than is compensated by increased useful life, and vice versa. The annual allocable acquisition-plus-deployment cost and logistic cost per payload can be written

$$C_{a/d} = (1/T)(C_p w_p/R + C_b w_p/R) \quad (1)$$

$$C_l = (1/t)(C_p w_p/R + C_b w_p/R) \quad (2)$$

For earth-based maintenance, a manned service vehicle from earth repairs the malfunctioned payload, then returns to earth. Proper design of the payload (e.g., by modules) to facilitate diagnosis and repair in an orbital environment, is critical. Moreover, preventive maintenance (to increase $t$) could prove sufficiently beneficial to warrant regularly scheduled servicing flights. These possibilities are represented by the parameter $\tau$. Also, depending on the number and deployment of payloads in the mission system, and on the maneuver capability of the manned vehicle, several ($n_m$) payloads may be serviced per flight. Unless such payloads are clustered, $n_m$ cannot be expected to be large for most near-orbit deployments because of the extensive $\Delta v$ requirements for near-orbit maneuvers. Equation (1) is used again for $C_{a/d}$, but we now have

$$C_l = (\tau/T)(C_b w_m/n_m R) \quad (3)$$

Equation (3) does not include costs of replacement parts or modules, which are assumed to be small relative to the other cost elements.

For station-based maintenance, manned tender vehicles from a space station repair and service failed payloads in orbit or return them to the station for maintenance. The station itself may serve as a common deployment point for one or more ($n_s$) mission payloads, which would then be accessible for maintenance at all times. In certain applications this may be a requirement (to permit frequent servicing and adjustments of experiments, or for military security and control). In this case, the frequency of costly logistic flights is decoupled from equipment $t$'s and depends instead on the crew duty cycle $l$. For $n_s \leq 3$, the station is assumed to be colocated with the payloads and to weigh 20,000 lb, exclusive of payload weight. For $n_s > 3$, the station is assumed to weight 40,000 lb and to require two manned space tenders weighing 10,000 lb each, including propulsion. (These weights include solar-flare shielding required for extended crew duty cycles.) For simplicity, it is assumed that either the maneuvering $\Delta v$ required of the tenders is small (typical of many far-orbit deployments), or that they have high-performance propulsion (e.g., nuclear or electric), and that they may refuel from a low-cost tanker arrangement such as described later. Thus, the tender propellant requirement is negligible compared to the primary station logistic requirements. Then

$$C_{a/d} = (1/T)[(C_b + C_s)w_s/n_s R + (C_p + C_b)w_p/R] \quad (4)$$

$$C_l = (1/l)C_b n_c w_m/n_s R \quad (5)$$

The sums of the equations for $C_{a/d}$ and $C_l$ for the foregoing three maintenance modes can be combined to form the following set of breakeven equations, which define the conditions producing equal costs for the different operational modes:

$$C_{TR} = C_{EB} \text{ at } w_p = w_m \tau / n_m C_p' \quad (6)$$

$$C_{TR} = C_{SB} \text{ at } w_p = (T/C_p')/(n_c w_m/n_s l + C_s' w_s/n_s t) \quad (7)$$

$$C_{SB} = C_{EB} \text{ at } t = n_s \tau / n_m (n_c/l + C_s' w_s/w_m T) \quad (8)$$

where $C_p' \equiv 1 + C_p/C_b$, and $C_s' \equiv 1 + C_s/C_b$.

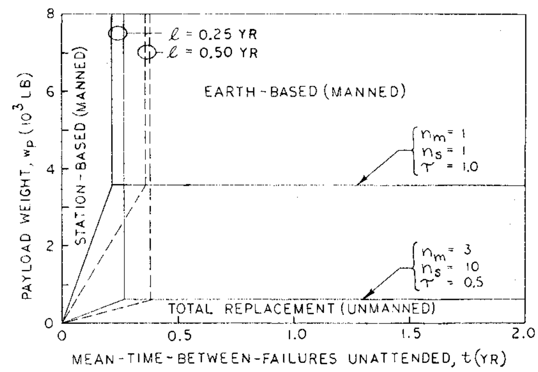


**Fig. 1 Regions of cost preference for manned and unmanned maintenance (typical near-orbit conditions: $C_{bn}$ = \$500/lb).**

Quantitative evaluations of Eqs. (6–8) are shown in the breakeven diagram in Fig. 1, and parametric sensitivities of ($C_{a/d} + C_l$) are shown in Fig. 2. Results are based on the assumptions noted in each figure, plus the following assumed parameter values: $C_p$ = \$3000/lb; $C_s$ = \$2000/lb; $n_c = 1$; $R = 0.98$; $T = 5$ yr, and $w_m$ = 25,000 lb. Where applicable, $C_b$ = \$500/lb is taken as typical of current boost costs to near orbit. Essentially two sets of conditions are

† A partial replacement mode also was considered but was judged to be impractical from design and operational viewpoints and of questionable economic value because of the inevitable increase in boost cost per pound of payload with decrease in payload weight. Another mode, self-repair by remotely operated devices, is essentially a special case of the total replacement mode in which the optimized redundancy includes provisions for remote operation of switches, and other devices. In addition, a recovery-repair-relaunch mode was considered, but its costs would be similar to total replacement as given in Eqs. (1) and (2), with two essential differences: 1) the first term of Eq. (2) is replaced by a term representing recovery costs, and 2) because of the weight of re-entry subsystems and deorbit propulsion (especially important for far-orbit payloads), the second term of Eqs. (1) and (2) must be increased by a factor of 2 or 3, even for ballistic recovery. When recovery reliability and time penalties are included, it becomes clear that this mode offers no cost advantage over total replacement.

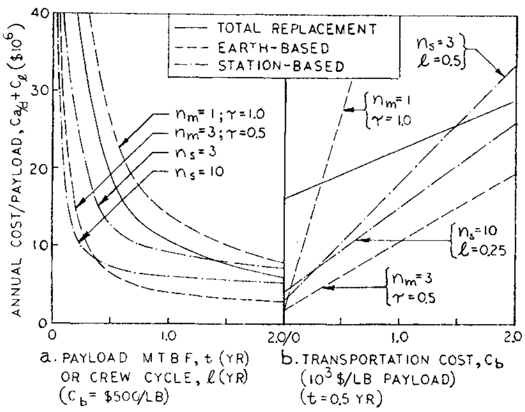


**Fig. 2 Annual cost per mission payload vs MTBF or station crew duty cycle, and transportation cost (payload weight = 2500 lb).**

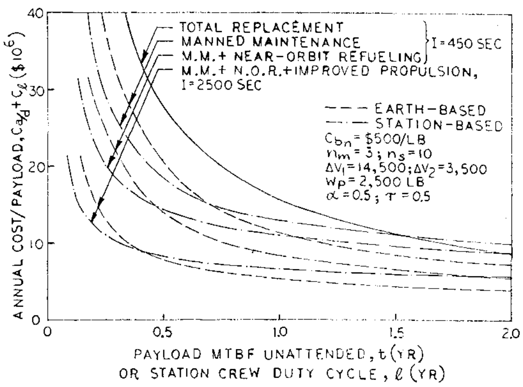


**Fig. 4 Annual cost per mission payload in far orbit (separate and combined cost benefits of manned maintenance, refueling and improved propulsion).**

considered. The first, corresponding to early capability, assumes one payload serviced per earth-based flight ($n_m = 1$) or per station ($n_s = 1$), and no benefits from preventive maintenance. The second, corresponding to more advanced capability, assumes $n_m = 3$, or $n_s = 10$, and a doubling of useful life through preventive maintenance ($\tau = 0.5$).

### Refueling and Space Propulsion

To perform orbital transfers or special maneuvers requiring velocity gains beyond that needed for boost to near orbit, any of several operating modes may be employed. Three primary examples are direct flight, refueling (single or double), and a "truck" that carries the payload between orbital levels. Refueling is considered using earth propellants only, although lunar propellants may be preferable for deployment in far orbit and beyond.[1] This analysis will consider expendable tanker vehicles only, because for earth propellants, reusable tankers are not cost competitive because of heavy propulsion and cost penalties associated with returning the tankers to near orbit for turnaround.[1]

In the direct flight mode, no refueling or other propulsive aid is used, and the mission vehicle is accelerated through the required $\Delta v_1 + \Delta v_2$ by its own propulsive stage or stages. The cost per pound of payload for the flight can be expressed as the sum of the cost per pound to boost the mission vehicle to near-orbit equivalent ($C_{b_n}/R$), plus a proportionate cost to boost the required space propulsion to near-orbit equivalent; thus

$$C_{bDF} = (C_{b_n}/R)(1 + K_{\Delta v_1 + \Delta v_2}) \qquad (9)$$

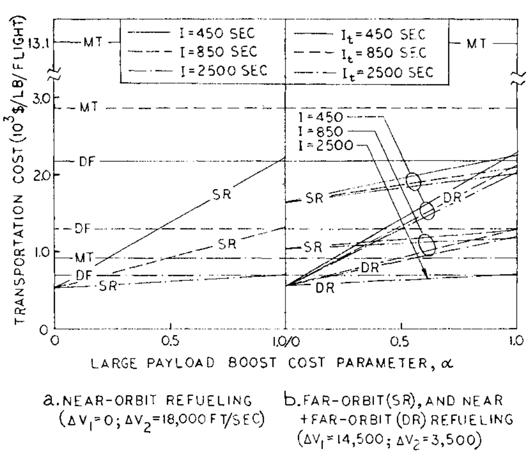


**Fig. 3 Transportation cost vs large-payload boost-cost parameter for round trip flights to far or lunar orbit ($C_{bn}$ = \$500/lb).**

This expression is derived and discussed in more detail in Eqs. (1–6) of Ref. 1.

In the single refueling mode, the propulsive stage or stages of the mission vehicle are refueled after executing $\Delta v_1$, from a prepositioned propellant supply tanker, after which $\Delta v_2$ is executed with no further refueling. Here, not only the mission vehicle and its propulsion for $\Delta v_1$ must be boosted into orbit at a cost per pound of $(C_{b_n}/R^2)(K_{\Delta v_1} + 1)$, but, in addition, the refueling propellant and the propulsion to accelerate it through $\Delta v_1$ to the prepositioning or deployment location must also be boosted to near-orbit equivalent. Thus

$$C_{bSR} = (C_{b_n}/R^2)[1 + K_{\Delta v_1} + \alpha K_{\Delta v_2}(K_{t\Delta v_1} + 1)] \qquad (10)$$

where the $R^2$ factor allows for unreliabilities associated with the added rendezvous docking, refueling and restart required by this mode.

In the double refueling mode, the propulsive stage or stages of the mission vehicle are refueled both in near orbit before executing $\Delta v_1$, and between the executions of $\Delta v_1$ and $\Delta v_2$. In this case, not only the mission vehicle itself must be boosted to near orbit, at a cost per pound of $C_{b_n}/R^3$, but propellants for the first and second refuelings must also be placed in near orbit at proportionate costs, so the total boost cost is

$$C_{bDR} = (C_{b_n}/R^3)[1 + \alpha K_{\Delta v_1} + \alpha K_{\Delta v_2}(K_{t\Delta v_1} + 1)] \qquad (11)$$

where $R^3$ allows for the unreliabilities of the two additional refueling stops characterizing this mode.

When a "maneuvering truck" is used, the mission vehicle is boosted to near orbit, where it is coupled to the truck, which uses, perhaps, some form of advanced propulsion applicable only in space and requiring recovery and reuse because of high hardware cost and complexity. The truck provides $\Delta v_1$, $\Delta v_2$, and the $\Delta v_3$ required to return to near-orbit where the mission vehicle is released for return to earth, and the truck is prepared for its next flight. In this case, the cost per flight of the truck and its initial launch is neglected since it can be spread over an arbitrarily large number of flights, leaving only the cost of the propellants used each flight, so that

$$C_{bMT} = (C_{b_n}/R^2)(1 + K_{t_{\Delta v_1 + \Delta v_2 + \Delta v_3}}) \qquad (12)$$

It is evident from Eqs. (9–12) that the benefit of refueling depends strongly on $\alpha$, which represents the potential reduction of boost cost for payloads (in this case, refueling propellants) launched in large quanta. Referred to $C_{b_n}$ = \$500/lb (a nominal current value for the Titan III), various studies have projected a range for $\alpha$ of $0.2 < \alpha < 1.0$. The equivalent transportation costs for the various modes and propulsion methods are shown by plotting Eqs. (9–12) in Fig. 3.‡

To illustrate combined effects on the cost of a specific far-orbit space operation, Fig. 4 shows annual cost vs $t$ or $l$ using total replacement, manned maintenance, manned maintenance plus refueling, and manned maintenance plus refueling plus improved propulsion.

### Observations

Earth-based manned maintenance (EBM) is economically preferable to total replacement for payloads weighing more than 500 to 3000 lb (depending on $\tau$, $n_m$, etc.), essentially independent of $t$. Station-based manned maintenance (SBM) is preferable to EBM for $t < 0.2$ to 0.4 yr (depending on $n_s$, $l$, etc.), essentially independent of payload weight, and SBM may also be preferable to total replacement (TR) for $w_p < 500$ to 3000 lb and $t < 0.2$ to 0.4 yr. These results refer to typical near-orbit conditions, but are not much different for far-orbit cases. If payload useful life is increased without manned maintenance by improved electronic technology, the breakeven condition between TR and EBM will not change appreciably, but the preferability of EBM vs SBM will then depend on whether $t$ or $l$ could be extended most.

If crew duty cycle ($l$) can be extended to 3 to 6 months, and multiple payload servicing is done, SBM appears attractive economically (Fig. 2a), and has several inherent advantages over both TR and EBM. First, the continuous presence of man can reduce the requirements for equipment that is redundant or could be replaced by man. Second the system cost for SBM is far less sensitive to uncertainties in $w_p$ and $C_p$ and is essentially independent of $t$, whereas both TR and EBM are very sensitive to these parameters. Third, more payloads can be serviced readily by a single station equipped with maneuvering tenders, than by a single earth-based flight; in certain applications (e.g., missile launching platforms) hundreds of payloads may be serviced from each station.

For a large-payload-boost-cost reduction of 50%, refueling in near orbit can reduce the near-orbit/far-orbit/earth round trip ($\Delta v$ = 18,000 fps) cost by about \$800/lb for $O_2$-$H_2$ chemical propulsion (Fig. 3a); for a 10,000+ lb. payload such as the Apollo command module, this is equivalent to a savings of nearly 10 million dollars per deep space or lunar flight. Greater savings can be obtained if nuclear propulsion is used, or if refueling is done in both near and far orbit. All such reductions in transportation cost increase the economic attractiveness of manned maintenance (Fig. 2b).

The maneuvering truck appears economically preferable only if it utilizes gas-core nuclear propulsion and for large-payload boost-cost reductions up to about 75% when compared to near-orbit refueling using $O_2$-$H_2$ chemical propulsion, and up to about 50% when compared to near-orbit refueling using gas core nuclear propulsion (Fig. 3b). Since it operates only in space, the truck might be able to utilize higher performance space propulsion such as nuclear explosion (or electric, if the increased maneuver times resulting from low thrust-to-weight ratios could be tolerated) to improve its economy. This mode, of course, would be required by definition if some need developed for the mission vehicle to return to near orbit after each trip.

For a typical far-orbit or deep space system utilizing 2500-lb payloads, if $t$ = 0.5 yr and $l$ = 0.5 yr, the combined use of manned maintenance, refueling and improved propulsion is shown (Fig. 4) to produce a 71% (or 20 million dollars) reduction in annual cost per payload, with each contributing about equally to the savings. Further savings could be achieved, especially in deep space operations, if lunar propellants become available, as described in Ref. 1.

‡ In all cases except the maneuvering tanker which is single-stage by definition, two-stage $K$ values have been used where $\Delta v > 15{,}000$ for $I$ = 450 sec and $I$ = 850 sec cases. [For a total $\Delta v$, it can be shown that $K_{(2\text{-stage})} = K_{\Delta v/2}(K_{\Delta v/2} + 2)$.]

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# Analysis of Two-Phase Impingement from a Cryogen Vented in Orbit

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### Nomenclature

$A$ = area
$D$ = drag force
$d_s$ = particle diameter
$h_{fg}$ = latent heat of vaporization
$j_{m_0}$ = interphase mass transport flux
$k$ = slip ratio
$M$ = local Mach number
$\dot{M}$ = total mass flow rate
$\dot{m}$ = mass flux
$P,P_t$ = pressure and total pressure, respectively
$\dot{q}$ = heat flux
$r,\theta$ = radial and angular coordinates (Fig. 1)
$R$ = gas constant
$T$ = temperature
$v$ = velocity; $v_g* = (\gamma RT_*)^{1/2}$
$V$ = volume
$x$ = quality
$\alpha$ = void fraction
$\delta_m$ = percentage of second phase reduction
$\gamma$ = ratio of specific heats
$\phi$ = angle between inward normal to impingement surface and radial vector
$\rho$ = density
$\tilde{\lambda}$ = interphase mass transport relaxation constant
$\theta_{\max}$ = maximum flow angle
$\tau$ = tangential surface traction

***Subscripts***

$A,N$ = actual and Newtonian, respectively
$0,f$ = initial and final conditions, respectively
$g,s$ = gas phase and second phase, respectively
$n$ = normal
$p$ = particle
$r,\theta$ = properties at $r$ and $\theta$, respectively
$*$ = choked flow property at orifice

### Introduction

THIS Note addresses the problem of impingement forces on surfaces in the vicinity of a cryogen that is being vented. This problem necessitates an investigation of the local multiphase momentum flux. Using the assumption of steady flow, the problem is reduced to considering a spatially

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