ϕ as shown in Fig. 3, which has been obtained for λ_∞ = 2.5 and 5.0, which cover many expected jet parameters.

In the case of trajectories nearly parallel to the jet axis ($\phi \simeq \pi/2$) the lateral velocity impulse of the jet plume can be approximated using Eqs. (10) and (11) and noting that ordinarily $\lambda > 2$ (Fig. 2):

$$\Delta V_y' \approx \pi^{1/2}/2\lambda r_c V_0 \tag{12}$$

This impulse turns the original trajectory outward from the jet axis by the small angle δ,

$$\delta \approx \Delta V_y/V_0 = (T/r_c V_0^2)(C_{F_{\max}}/C_F)(1/4\pi\beta) \tag{13}$$

For fixed λ the body passes through a relatively sharp dynamic pressure peak $q_{\max}$ at a fixed angle θ_m which can be obtained from the equation

$$\cot\theta_m/(1 - \cos\theta_m) = \lambda^2 \tag{14}$$

Then displacing the body trajectory by δ at the intersection of the original trajectory with θ_m will approximate the new body path through the jet plume.

Reference

[1] Hill, J. A. F. and Draper, J. S., "Analytical Approximation for the Flow from a Nozzle into a Vacuum," *Journal of Spacecraft and Rockets*, Vol. 3, No. 10, Oct. 1966, pp. 1552–1554.

Is Booster Recovery and Re-Use Practical?

John S. Knaur*
The Boeing Company, Huntsville, Ala.

STUDIES conducted by government and industry since 1958 have defined two fundamental groups of re-usable systems. The first group, which has received the most attention, is the sophisticated, manned flyback system. The second group is the simple systems that fly ballistic recovery trajectories and use aerodynamic and impact deceleration systems to absorb the kinetic energy of the returning vehicle. The purpose of this Note is not to evaluate the detailed differences between these groups, but to determine whether booster recovery is practical in terms of the relative costs of three typical launch systems studied to date. The first two are modifications of a Saturn-size booster for simple ballistic and sophisticated flyback recovery. The third is a new, two-stage, fully re-usable, flyback recovery system.

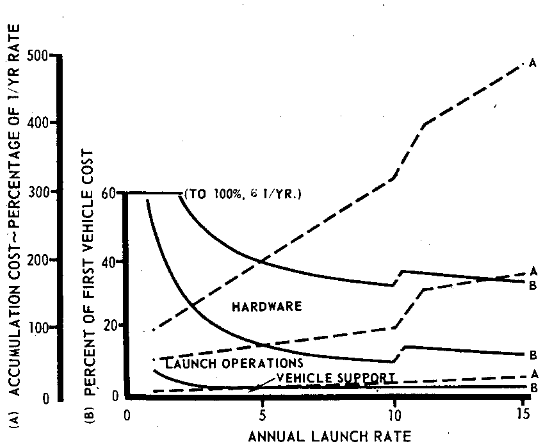


Fig. 1 Operating costs.

Table 1 Development and hardware costs of re-usable vehicles in multiples of expendable vehicle cost

Type recovery	Ballistic Dev.	Ballistic Hdw.	Flyback Dev.	Flyback Hdw.	New flyback Dev.	New flyback Hdw.
Stage	0.9	1.29	5.8	2.2 (2 req'd/wing)	47.2	4.9 (2 stages)
Recovery system	0.1	0.02	22.6	4.4	...	...
Flight test	0.2	0	1.2	0	3.0	0
Facilities and GSE	0.6	0	6.2	0	8.9	0
Total	1.7	1.3	35.8	4.4	59.1	4.9

Cost Elements

There are two categories of cost associated with any space launch system. The first, development costs, includes design, test, production facilities, and qualification of the system. The second, operational costs, includes hardware productions, vehicle support, and launch preparation and launch. Table 1 shows the development and operational costs for the hardware portion for each of the re-usable systems.

Savings in a re-usable system are directly proportional to the reduction in operational cost obtained by hardware re-use, hence the porportion of re-usable hardware to total operating costs. Figure 1 shows over-all operational costs for a liquid-fueled expendable launch vehicle in terms of the cumulative recurring costs (curve A) and average cost per flight (curve B) vs number of launches per year. With increased use, the percentage of cost represented by hardware increases significantly even though the over-all cost per launch is reduced.

For re-usable systems, use of a liquid first stage is indicated because only the propellants, representing less than 1% of the stage costs, are expended during flight. In contrast, a large solid, having the same performance potential as the Saturn-size liquid rocket, expends the solid propellant (19% of stage cost) and the ablative nozzle (35% of stage cost), leaving only 46% potentially re-usable.

The initial operational hardware cost or number of re-usable vehicles procured for a space program must equal the number of boosters expected to be lost plus the number required to meet the desired launch rate. Figure 2 shows a parametric plot of average number of vehicle uses vs turn-around-time for a launch rate of 6/yr and varying mission reliabilities. As turn-around-time decreases or reliability increases the average number of uses per vehicle rapidly increases. This plot, using 8-month turn-around-time and 90% reliability, which analyses have shown to be typical for ballistic-type recovery systems, indicates that an average of 6.7 uses per vehicle can be obtained. A similar analysis for a 24/yr launch rate indicates that a 99% reliability and 1-month turn-around will be re-

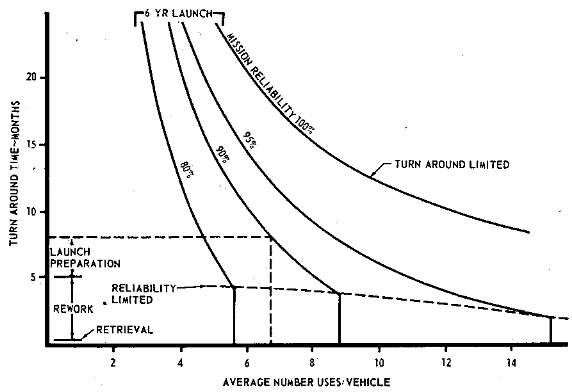


Fig. 2 New vehicle requirements.

Presented as Paper 67-909 at the AIAA 4th Annual Meeting and Technical Display, Anaheim, Calif., October 23–27, 1967; submitted October 20, 1967; revision received January 31, 1968.

* Reusable Systems Group Engineer, Launch Systems Branch, Space Division. Associate Fellow AIAA.

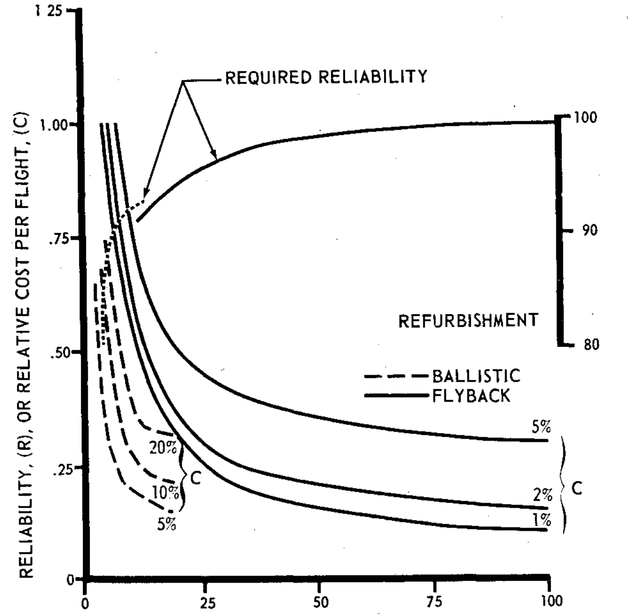


Fig. 3 Relative refurbishment costs.

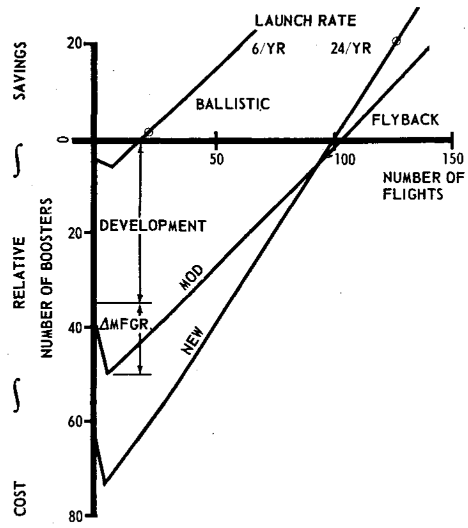


Fig. 4 Potential savings/launch.

quired to achieve the 100 uses per vehicle postulated for the sophisticated new flyback systems.

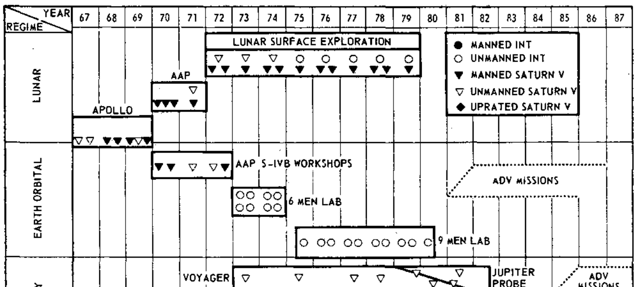
Refurbishment, the second part of operational hardware costs, includes retrieval, repair, and in-plant test and checkout.† Figure 3 shows the relative cost per flight vs number of uses for varying levels of refurbishment. The analysis of several ballistic recovery systems indicates possible refurbishment levels of 8–20% with 13% most probable. With this refurbishment level and 6.7 uses per vehicle, the re-usable ballistic system will cost approximately one-third as much as per flight an expendable system. Similarly, a flyback system used 100 times and having a postulated refurbishment level of 2% will have a cost per flight of about one-seventh that of an expendable system.

Potential Savings

Figure 4 combines the effects of the cost elements to indicate the potential effect of re-usability on launch costs. The ordinate indicates the costs in excess of the costs of a comparable-size expendable system below the abscissa, and savings above, and the abscissa indicates number of launches. Typical launch rates of 6/yr for the ballistic and 24/yr for the flyback system are shown. Development and increased manufacturing cost cause an initial program deficit which is recovered over the same time period by the much lower operational cost of the re-usable system. The ballistic system is obviously the best for small, low-launch-rate programs. The new flyback system becomes most attractive for large (minimum 200 launches), high-launch-rate programs.

Incorporating recovery on an existing or new launch vehicle will reduce payload from 3% for a minimum ballistic system to 30% for a flyback system as a result of added inert weight. Re-usable systems historically have matured more rapidly than expendable systems. The increased reliability reduces payload losses resulting from launch failures. Figure 5 shows the reliability growth, cost per launch, and cost per successful launch experienced on the Thor program from 1959 through 1962. A modest estimate of the effect of more rapid maturing with re-use is shown by the dotted lines. The savings in cost per successful launch is equal to approximately an 8% reduction in vehicle losses.

Table 2 Postulated NASA space program—S-IC utilization, balanced-budget constrained



# Vehicles by payload range / Year	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86–87
50–150K						1	4	4	2	3	3	3	3	2	1	2	4	2		34
150–250K	2	2	3	5	3	5	3	3	2	2	2	3	2	2	3					42
> 250K LBS											1	2	2	1	2	4	5	4		21
TOTAL	2	2	3	5	3	6	7	7	4	5	6	8	7	5	6	6	9	6		97

† Pre-launch test and checkout are included in launch costs.

Re-Usability Evaluation

Although a space program for the next two decades has not been defined, existing payload and planning studies indicate that the program will consist of lunar, earth orbital, and planetary missions. Table 2 shows a postulated NASA space program. The ticks on this chart represent discrete

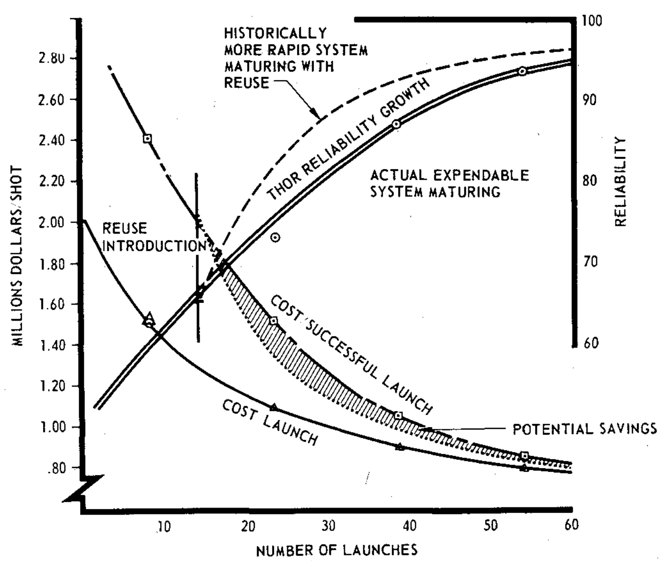


Fig. 5 Launch reliability.

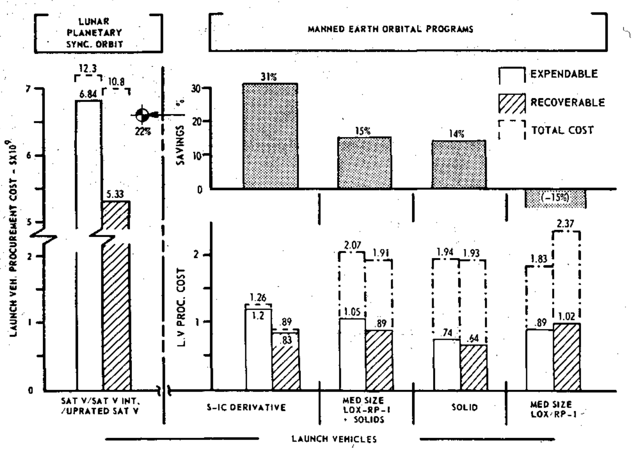


Fig. 6 Launch vehicle costs.

missions and are summarized by year and size of payload. To determine if re-usability is practical, a comparison was made between existing expendable and comparable re-usable vehicles. The expendable vehicles to do this program were Saturn V and uprated Saturn V vehicles for all payloads above 150 thousand lb. For payloads of 50 to 150 thousand lb four different launch vehicles, using a Saturn S-IVB second stage and the following first stages, were considered: 1) a medium-size LOX, RP-1 stage; 2) this stage uprated with solid strap-on rocket motors; 3) a large solid first stage; and 4) a large LOX RP-1 S-IC derivative stage. Because of the small program size a ballistic recovery system was developed for each of these stages to serve for the re-usability comparison. Evaluation was accomplished by using an IBM 360 computer and the Boeing "automated cost evaluating program Mark II."

Launch vehicle costs are shown in Fig. 6. Solid line bars show launch vehicle procurement costs and the precentage differences between the expendable and re-usable systems. The dashed line bars show the additional vehicle launch and support costs that complete the total launch program costs. The first bar shows the costs for the Saturn V standard and uprated vehicles. For these vehicles the hardware cost is reduced by 22% by utilizing recovery. Recovery and re-use applied to the Saturn V/S-IC derivative vehicle show a 31% reduction in hardware costs. The medium-size LOX/RP-1 vehicle uprated with solid motor strap-ons and the solid first-stage vehicle show a smaller reduction in hardware cost as a result of the smaller proportion of re-usable hardware when recovery is applied. The payload capability of the medium-size LOX/RP-1 launch system was marginal as an expendable for the orbital program. Although the cost per launch wes reduced by 30%, the payload degradation associated with recovery required additional launches and resulted in a net program loss with the incorporation of recovery.

Conclusion

Application of launch vehicle recovery and re-use characteristics to a reasonable space program leads to the following conclusions: 1) Program requirements for the next one to two decades will not justify development of a flyback-type recovery system. 2) Existing requirements are adequate and technology is available to implement a practical ballistic recovery system for existing large boosters in the 1970's. 3) Total launch vehicle and hardware costs can be reduced significantly (up to 31%) through first-stage booster recovery and re-use. 4) The re-usable system potential savings is directly proportional to the percentage of launch cost represented by re-usable hardware. 5) Cost savings are sensitive to launch system utilization.

Stable Rotation States of Dual-Spin Spacecraft

Gerald J. Cloutier*
Sylvania Electronic Systems, Waltham, Mass.

Nomenclature

A = transverse moment of inertia, slug ft²
C = axial moment of inertia, slug ft²
R = nondimensional damper inertia
b = length, ft
c = damping constant, lb-sec/ft
f_n = natural frequency, rad/sec
k = spring constant, lb/ft
m = mass, slugs (lb-sec²/ft)
ξ = nondimensional damper coordinate
θ = nutation angle, rad
Ω = nutation frequency, rad/sec
ω = angular velocity, rad/sec

Introduction

THERE have been in the past several analyses of spin-stabilized spacecraft configurations in which the systems can end up in a state of motion other than spin about a symmetry axis or tumbling about a transverse axis. Haseltine[1] analyzed spacecraft with 2 or 4 pendulums as nutation dampers mounted normal to the spin axis; he found that the stable state of the system could be rotation about a canted axis. Auelmann and Lane[2] uncovered a similar anomaly in the motion of a spacecraft employing ball-in-tube dampers, in which a ball moving through a fluid in a curved tube serves as the damping element. Likins,[3] while studying the motion of a dual-spin spacecraft with a single-degree-of-freedom mass-spring damper which moves parallel to the spin axis, derived an analogous condition to the one to be discussed here (his condition e), although he did not expand on it since his concern was with more rigorously proving the basic tumbling criterion.

A recent paper by Meirovitch and Nelson[4] discussed the attitude stability of a spinning spacecraft with flexible antennas mounted on it. Since their idealized model for the antennas could equally well represent a number of nutation damper concepts, including mass-spring, pendulum, and cantilever beam dampers (the last two being aligned with the spin axis), an extension of their analysis was prompted.

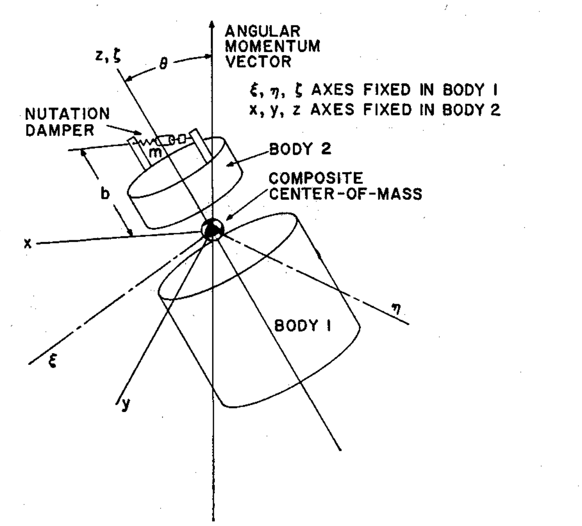


Fig. 1 Basic system parameters.

Received January 17, 1968.
* Advanced Development Engineer, Satellite Antenna Department, Eastern Division. Member AIAA.