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AEROASSISTED ORBIT TRANSFER VEHICLE TRAJECTORY ANALYSIS

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ABSTRACT

The emphasis in this study was on the use of multiple pass trajectories for aerobraking. However, for comparison, single pass trajectories, trajectories using ballutes, and trajectories corrupted by atmospheric anomolies were run. A two pass trajectory was chosen for determining the relation between sensitivity to errors and payload to orbit. Trajectories that used only aerodynamic forces for maneuvering could put more weight into the target orbits but were very sensitive to variations from the planned trajectors. Using some thrust control resulted in less payload to orbit, but greatly reduced the sensitivity to variations from nominal trajectories. When compared to the non-thrusting trajectories investigated, the judicious use of thrusting resulted in multiple pass trajectories that gave 97 percent of the payload to orbit with almost none of the sensitivity to variations from the nominal.

INTRODUCTION

With the advent of a fully operational space station in low earth orbit (LEO), the concept of a reusable vehicle capable of achieving geosynchronous orbit (GEO), performing specified satellite functions, and then returning to LEO will be feasible. Through a Hohmann transfer, this vehicle could accomplish the required orbital changes propulsively. Although this is the most efficient way for the spacecraft to reach GEO, a more economical method exists for the vehicle's return to the Space Station. By entering the earth's atmosphere and taking advantage of the spacecraft's aerodynamically induced drag, energy (in the form of heat) may be lost without expending any propellant. This method of energy loss is termed aerobraking, and the craft is considered an aeroassisted orbit transfer vehicle (AOTV) (Reference 1).

Ideally, the spacecraft remains in the atmosphere just long enough to achieve the necessary energy decrement before escaping on a new trajectory with apogee at LEO. Once reaching this altitude, a single propulsive maneuver is required to circularize the orbit. However, remaining in the earth's atmosphere too long results in extremely high heat rates, and the spacecraft will either burn up or lose so much energy that escape is impossible. Thus, the problem is to obtain a trajectory based upon a perigee altitude low enough to achieve the required energy decrement, but still high enough so as not to exceed the vehicle's known heating constraints. The purpose of this paper is to study those aerobraking trajectories which met the specified altitude and heating constraints.

The present analysis was performed using a computer program called the Program for Optimizing Simulated Trajectories (POST). POST was appropriate, not only because the program is designed to perform trajectory optimizations, but also because the sensitivities of specified mission parameters are calculated as part of the trajectory optimization. These data help to identify variables which could most influence a guidance, control, and navigation system design.

This investigation brings together five individual studies dealing with various aspects of a simulated AOTV mission. The topics addressed in the order they will be presented are:

1. Aerodynamic Versus Orbital Influence.
2. Atmospheric Density Variations.
3. Energy Decrement Possibilities.

4. Multiple Aeropass Missions.
5. Sensitivity Analysis.

APPROACH

As stated in the introduction, the purpose of the study was to investigate aerobraking trajectories that met heating and apogee altitude constraints. The POST program was used to determine the deorbit thrust from GEO and an angle-of-attack and bank angle combination that would result in a perigee of the braking orbit that would not exceed the heat rate constraint by more than 5 percent. For runs where thrust other than that required to deorbit from GEO was needed, POST was used to determine the burn times based on apogee altitude constraints.

It was assumed in this study that the missions were unmanned and, hence, time was not a constraint. Therefore, both missions utilizing a single atmospheric pass (fig. 1) and missions employing multiple atmospheric passes (fig. 2) were considered. A typical vehicle of the type used for this study is shown as figure 3. The vehicle had an L/D of about .3 and the lift and drag characteristics of the vehicle were determined from wind-tunnel tests (Reference 2).

The guidelines used in the study were as follows: 1) the atmosphere was assumed to either begin or end at 400,000 feet, 2) the braking trajectories studied had 1, 2, or 3 passes, 3) all trajectories were targeted to end with an apogee of 165 nm, 4) the bank angle was used as the aerodynamic control in most instances while supplemental thrusting was used occasionally, and, 5) the orbits were circularized at an apogee as close to 160 nm as possible for each orbit studied.

RESULTS AND DISCUSSION

Aerodynamic Versus Orbital Influences

A significant aspect of any AOTV mission is the amount of lift-induced control that the vehicle will possess once in the earth's atmosphere. One possible trajectory which utilizes lift as a means of control allows the spacecraft to dive into the lower regions of the earth's atmosphere until excess heating becomes a concern. At this point, the vehicle climbs to a less dense atmospheric region so it may cool. Multiple passes through the atmosphere may be used if a single pass exceeds problem constraints such as heat rate and/or apogee altitude.

The projected perigee was found to exert a significant influence on the vehicle's actual flight path. The projected perigee refers to the minimum altitude that would be achieved if the atmosphere did not influence the AOTV's trajectory. This projected perigee altitude is a function of the deorbit thrust from the geocentric orbit.

The maximum heat rate is dependent on the perigee altitude. Although heat rate can be adjusted by various combinations of angle-of-attack and bank angle while the vehicle is in the atmosphere, the single most important parameter affecting heat rate is the projected perigee.

Figure 4 shows that a predicted perigee of 42.6 nautical miles corresponds to the flight path which will meet, but not exceed, the given heating constraints. This figure also shows that a linear relationship exists over a portion of predicted perigees (41 to 44 nautical miles). The most significant result of Figure 4 is the extremely low tolerance that exists in choosing a predicted perigee. (If the perigee is too high, not enough energy will be lost; while a perigee that is too low causes the vehicle to burn up.) It should be noted that varying this parameter by only a single nautical mile, causes the maximum achieved heat rate to change by 10 Btu/(Sq. Ft.-Sec.). Thus, an accurate perigee prediction is needed to insure a successful mission unless additional controls are introduced.

Atmospheric Density Variations

Recent space shuttle flights have shown that atmospheric predictions based on a model do not always reflect the actual flight conditions. Density variations known as density shears were found to occur at various altitudes. To determine possible effects of these shears, 20-percent density variations were input to the atmospheric model.

In this study, the simulated density shears were input at an altitude of 250,000 feet when maximum heat rate was achieved. This simulation was performed twice, with the variation being either 80 percent or 120 percent of the standard atmospheric density and lasting for a duration of 30 seconds. Since 80-percent density shears were encountered at approximately this altitude on both STS-2 and STS-4, as well as a 120-percent shear during STS-6, this 250,000 ft. altitude was a realistic point for the shears to occur.

Figures 5a, 5b, and 5c show this density shear reflected in dynamic pressure, acceleration, and heat rate, respectively. The upper of the two dashed curves represents the 120-percent variation, while the lower curve represents the 80-percent shear. When the density shears were applied, the dynamic pressure, acceleration, and heat rate all reacted instantaneously. As the density increased, the three parameters shown in figure 5 increased, and when the density decreased, they all decreased. The most important feature of figure 5 is that a 20-percent density increase results in raising the maximum heat rate to 200 Btu/(Sq. Ft.-Sec.). Since the possibility of encountering such a density shear in flight is quite probable, this effect must be accounted for. It should also be noted that due to the vehicle's negligible lift forces, the change in minimum altitude resulting from a density shear is very small (on the order of 500 feet).

Energy Decrement Possibilities

When the vehicle used for this study is in a 165-nautical mile low earth orbit (LEO), it has an energy mass ratio -3.21×10^{8}. The same vehicle, as it enters the atmosphere on returning from a geocentric orbit (GEO), has an energy mass ratio of -8.79×10^{7}. Thus, a large energy decrement is required for the vehicle to achieve LEO. The decrement could not be achieved in a single atmospheric pass due to the vehicle's present constraints unless out-of-plane maneuvers were performed during the pass. Therefore, various options which increase the presently insufficient energy decrement produced in a single atmospheric pass were analyzed.

The simplest concept involved relaxing the vehicle's current heat rate constraint. Tests were run in which the maximum heat rate was raised to 200, 210, 220, and 240 Btu/(Sq. Ft.-Sec.). For a GEO return, it was shown that a linear relationship exists between the vehicle's maximum achieved heat rate and its energy on leaving the atmosphere. This linear relation is shown in figure 6. Point A refers to the vehicle's exit energy after a single atmospheric pass with heat rate constraints of 180 Btu/(Sq. Ft.-Sec.); whereas, point C represents the energy required (Point B will be referred to later).

From figure 6, it can be seen that the vehicle's maximum heat rate would have to be raised to 280 Btu/(Sq. Ft.-Sec.) in order to lose the required amount of energy in a single pass without special maneuvers. Due to the tremendous size of the increase needed, this idea of raising the heat rate restrictions was discarded and other possibilities were investigated.

One such approach is to utilize the atmosphere's braking potential more efficiently. Figure 7 shows the present AOTV's energy loss as a function of altitude. Due to the low atmospheric density that exists at high altitudes, this mission profile does not start to utilize the benefits of aerobraking until it is below 300,000 feet. As a matter of fact, 80 percent of the vehicle's total energy loss occurs below 260,000 feet. By utilizing the upper regions of the atmosphere, a larger energy decrement may be obtained. This may be accomplished by sizeably increasing the spacecraft's drag through the use of a ballute.

A typical ballute is pictured in figure 8 (Reference 3). By expanding the spacecraft's surface area (increasing the drag) and reducing its L/D to 0.05 in the upper atmosphere, additional energy is lost. When the ballute's maximum heat rate is reached, it is discarded leaving the original AOTV configuration. This occurred at 260,000 feet. The AOTV may continue to fly in this configuration, or another ballute may be opened as the vehicle leaves the earth's atmosphere. In this way, even more energy is lost. The energy lost using the double ballute is represented by point B in figure 6.

The results of the double ballute simulation are shown in figures 9a, 9b, and 9c. These figures relate the dynamic pressure, vehicle acceleration, and vehicular heat rate to flight time (respectively).

Comparisons of figures 9 and 5 show that the double ballute concept does not significantly alter either the dynamic pressure experienced or the vehicle's heat rate. However, the vehicle's acceleration is significantly changed as shown in figures 9b and 5b. These sudden variations result from instantaneously changing the vehicle's L/D ratio when a ballute is either deployed or discarded. Such abrupt fluctuations must be accounted for in the design process and may limit missions to being unmanned.

The advantage of the ballute configuration is shown in figure 10. Curve A represents the energy profile of a single atmospheric pass using a non-ballute AOTV and is the curve shown as figure 7. Curve B shows the energy profile of a single ballute AOTV following the same trajectory. This ballute is deployed at 400,000 feet and released at 260,000 feet. Finally, curve C shows the energy profile for the double ballute case. Thus, a significant energy decrement may be achieved by deploying ballutes when the vehicle is in the earth's upper atmosphere.

Multiple Aeropass Missions

Another method of achieving a desired energy loss during a GEO return mission is the use of multiple passes through the earth's atmosphere (reference 4). Various multiple pass missions were simulated using an AOTV as pictured in figure 3. POST was used to determine the deorbit thrust at GEO and the angle-of-attack, bank angle combination required to keep the maximum heat rate below 180 Btu/ft^2-sec. The bank angle and angle-of-attack for the exit from the atmosphere were chosen based on experience with a number of runs. The bank angles and angle-of-attack were kept the same for all the trajectories discussed in the final sections of the paper. The goal of each mission was to obtain a final circular orbit at LEO without violating the vehicle's heat restrictions and with a minimal use of propellant. Since time was not a constraint, the number of atmospheric passes was not limited. The results of this analysis are shown in Table I.

In general, it can be seen that the more energy that is lost through aeropasses, the less propellant will be required for energy control. For comparison the Hohmann transfer case (Table I) shows the propellant required when the orbital change is accomplished propulsively without the use of aerobraking. The next two entries in Table I represent aeroassist trajectories that make use of a single atmospheric pass. The weight savings achieved through the use of this approach are small. This is mainly due to the heat rate restrictions imposed on the vehicle. However, when the aerobraking effect is summed through two or three atmospheric passes, the weight saved becomes more significant (approximately 7000 lbs). The vehicle may now transport a larger payload, although its flight time is increased. Therefore, depending on the individual mission requirements, (particularly the tradeoff between payload and flight time), multiple atmospheric passes may be advantageous.

The burn for the one-thrust case was performed just after the vehicle left the atmosphere on the second pass. This maneuver insured that the vehicle would be within 5 nautical miles of the 165 nautical-mile target apogee. In the two-thrust case (appendix A), the propulsive maneuver was delayed until the vehicle reached apogee after the second pass, and then thrust was applied to raise the perigee of the orbit to 165 nautical miles. The vehicle then coasted to perigee where another burn adjusted the apogee to 165 nautical miles. As can be seen from Table II, this sequence resulted in an orbit that was nearly circular when the vehicle reached apogee. Although additional mission time was required to thrust at apogee and perigee, this propulsive sequence resulted in a greater weight-to-orbit.

As shown in Table I, a mission employing three atmospheric passes was simulated. While being slightly more fuel efficient, the greatest advantage of this mission over a double pass case is its maximum achieved heat rate. Throughout this analysis, the vehicle's heat rate restrictions have been a major problem. However, by employing three atmospheric passes, the maximum heat rate never exceeded 147 (Btu/Ft. Sq.-Sec.). Thus, depending on the heat transfer technology utilized in the final AOTV design, this may be a useful option.

Sensitivity Analysis

The issues effecting mission sensitivity are illustrated in Table II. As an example, a two-pass aerobraking mission is examined. The three types of two-pass missions shown are missions using no thrust, missions using a single thrusting period, and missions using two thrusting periods. In each instance, the vehicle was to achieve an orbit with a 165 nautical-mile apogee. In addition to the bank angle and angle-of-attack combinations that were common to all the trajectories, the no-thrust mission used POST to determine a time after maximum heating that the bank angle was allowed to be non-zero. This non-zero bank angle allowed the vehicle to spend more time in the higher density atmosphere to lose additional energy to achieve a 165 nautical-mile apogee for the final LEO.

As previously shown, an extremely important parameter in the design of any aerobraking maneuver is the perigee of the initial braking orbit. The second column of Table II shows how the final projected apogee changes with the perigee of the first braking pass. The example with no thrust showed a large potential error in final apogee with errors in the perigee of the initial braking orbit. When an extra control such as thrusting was added, the sensitivity of desired apogee to perigee errors was greatly reduced. The one-thrust example showed a very small sensitivity and the two-thrust case showed almost no sensitivity. The last three columns of Table II show final conditions for the various missions.

As shown in Table II, the no-thrust example delivers the most weight to orbit but has the greatest sensitivity to errors in critical parameters along the mission timeline. In the no-thrust example, a one-mile error at perigee would result in a 275-mile error at apogee. The one-thrust example delivered the least weight to orbit since the thrust was not applied near apogee or perigee. This example was included to show that an additional control would significantly reduce the sensitivity-to-mission-parameter errors even if it didn't improve performance. The two-thrust/two-pass example delivered 428 less pounds to orbit but showed almost no sensitivity to mission parameter errors. Also, the two-thrust mission was designed to end in an orbit that was very close to circular.

The main point from the sensitivity analysis is that there is a tradeoff between using only aerodynamic control versus using aerodynamic control plus thrust during a braking maneuver in determining the weight delivered to final orbit. Clearly, more payload can be delivered to orbit with only aerodynamic controls but at the cost of imposing strict accuracy requirements on guidance, control, and navigation systems as well as the instrumentation to support them. A secondary point indicated from the study is that careful incorporation of the propulsive thrusting with multiple orbits can maximize the efficiency of the thrust sequences. In these studies, there was not time to pursue this point, but other studies have indicated that small thrust at the first apogee could reduce the thrust required during the second orbit.

CONCLUSIONS

Through this investigation, five studies pertaining to various aspects of an AOTV mission were presented and several results were obtained.

When a low L/D vehicle is simulated, very little lift-induced control exists. As a result, the vehicle's flight path is almost completely determined by the trajectory's predicted perigee. The values chosen for the predicted perigee also determined the heat rate for a particular aeropass. Additionally, the apogee altitude attained was sensitive to errors in predicted perigee when only aerodynamic controls were used.

Since density shears may be encountered by the AOTV during its flight, their effect was considered. The effect of a shear upon the vehicle's heat rate is significant. If a density shear is encountered at the wrong moment, it could raise the vehicle's heat rate above its structural limit. Thus, a reasonable safety factor should be included in the AOTV's final design. Due to the small lift force, the vehicle's flight path is only slightly altered by the presence of a density shear.

The energy decrement needed to establish a circular orbit at LEO using atmospheric control alone and a single atmospheric pass and no out of plane maneuvers may be achieved by relaxing the heat rate restrictions. However, the allowable heat rates would have to be substantially increased. Energy decrement may also be achieved by adapting the AOTV so that it utilizes the atmosphere's aerobraking potential more efficiently. The use of ballutes, for example, resulted in a large additional energy decrement.

Many possible mission profiles exist. Among those considered were trajectories employing one, two, or three atmospheric passes. When compared to a Hohmann transfer, a single atmospheric pass was found to save very little propellant. On the other hand, multiple passes achieved large propellant reductions but required additional flight time. The greatest weight-to-orbit mission utilized three atmospheric passes.

The missions that resulted in the greatest weight delivered to the target orbit used only aerodynamic control, but proved to be extremely sensitive to errors. Therefore, guidance, control, and navigation requirements for such trajectories could be severe. However, a small amount of thrusting could reduce the sensitivity to errors and increase the reliability enough to offset the payload lost to propellant requirements.

FUTURE WORK

A few of the ideas discussed in this paper should be studied in greater detail. One such concept is the utilization of deployable ballutes. Although it was shown that a large energy decrement could be obtained through the use of ballutes, the feasibility of designing and constructing such a structure was not discussed.

Another interesting topic which was not investigated in this study is the use of a high L/D vehicle. Once in the earth's atmosphere, this vehicle would possess greater lift-induced control and could possibly skip in and out of the atmosphere without having to perform multiple trajectories.

Additionally, the trades between the selective use of thrusting versus nonthrusting could be performed to reduce mission error sensitivity and improve reliability. For a given payload these trades could be used to establish payload to orbit versus mission reliability criteria.

APPENDIX A

This appendix contains a description of the POST inputs for a Double-Pass, Two-Thrust mission. The initial deorbit thrust, the entry angle-of-attack and bank angle, and the exit angle-of-attack and bank angle were common to all missions.

Event 1:
In GEO, Alpha=180, Thrust activitated
Aiming for perigee of 42.14 Nautical Miles
Thrust for 77.4 Seconds, 7735 lbs. of propellant used
When perigee of 42.14 nautical miles projected
Thrust Off

Event 2:
Altitude=400,000 feet, Turn Atmospheric Model On
Set Alpha=25, Bank Angle=81
Descend Until Heat Rate=170 Btu/(Sq. Ft.-Sec.)

Event 3:
Heat Rate=170 Btu/(Sq. Ft.-Sec.), At Altitude=$2.568x10^5$
Set Alpha=60, Bank Angle=0
Maximum Achieved Heat Rate=184.4 Btu/(Sq. Ft.-Sec.)
Minimum Altitude is Achieved ($2.468x10^5$)
Coast Until Altitude=400,000 feet

Event 4:
Altitude=400,000 feet
Turn Atmospheric Model Off
Passes through Apogee=5680 Nautical Miles
Coast Until Altitude=400,000 feet

Event 5:
At 400,000 ft in second orbit
Set Alpha=25, Bank Angle=81
Atmospheric Model On
Coast Until Heat Rate=180 Btu/(Sq. Ft.-Sec.)

Event 6:
At Heat Rate=180 Btu/(Sq. Ft.-Sec.), At Altitude=$2.351x10^5$ ft.
Set Alpha=60, Bank Angle=0
Maximum Achieved Heat Rate=180.5 Btu/(Sq. Ft.-Sec.)
Minimum Altitude is Achieved ($2.312x10^5$)
Coast Until Altitude=400,000 feet

Event 7:
At Altitude=400,000 feet
Turn Atmospheric Model Off
Coast Until Apogee is reached, 675 Nautical Miles

Event 8:
At Apogee, Turn Thrust On
Set Alpha=180, Bank Angle=0
Thrust for 7.2 Seconds, 725 lbs. of propellant used
Thrust Until Perigee=160 Nautical Miles

Event 9:
When Perigee is 160 Nautical Miles
Thrust Off
Printing Parameters Varied
Coast Until Perigee is Reached

Event 10:
At Perigee, Turn Thrust On
Set Alpha=180, Bank Angle=0
Thrust for 10.4 Seconds, 1040 lbs. of propellant used
Until Apogee=165 Nautical Miles Predicted

Event 11:
Coast to Apogee

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TABLE I - A MISSION PROFILE SUMMARY

MISSION DESCRIPTION	TIME (Sec)	PROPELLANT REQUIRED (Lbs)
Hohmann Transfer	1.90×10^{4}	1.60×10^{4}
Single Pass, One Thrust	1.92×10^{4}	1.60×10^{4}
Single Pass, Two Thrusts	3.22×10^{4}	1.38×10^{4}
Double Pass, One Thrust	3.20×10^{4}	9.71×10^{3}
* Double Pass, Two Thrusts	3.73×10^{4}	9.00×10^{3}
Triple Pass, One Thrust	4.77×10^{4}	8.27×10^{3}

* A detailed description of this mission's specific events is presented in Appendix A.

TABLE II - TWO PASS SENSITIVITY STUDY

Mission Description	Apogee Nautical (miles)	$\frac{\Delta \text{ Apogee}}{\Delta \text{ 1st Perigee Alt}}$	Δ V to circularize (ft/sec.)	Weight Delivered to Orbit (lbs)
Double pass/No thrust	170.0	275.0	541.0	19028
Double pass/One thrust	162.0	1.0	686.0	17782
Double pass/Two thrust	165.0	.003	17.0	18600

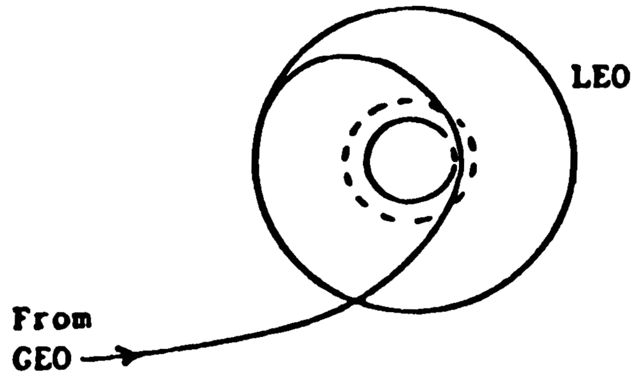


Figure 1. Single Pass Mission

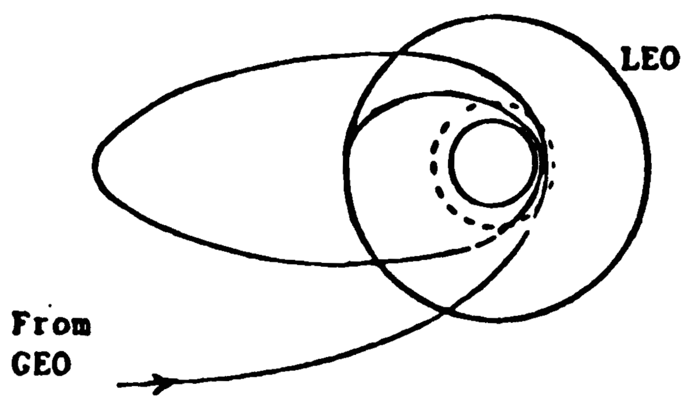


Figure 2. Double Pass Mission

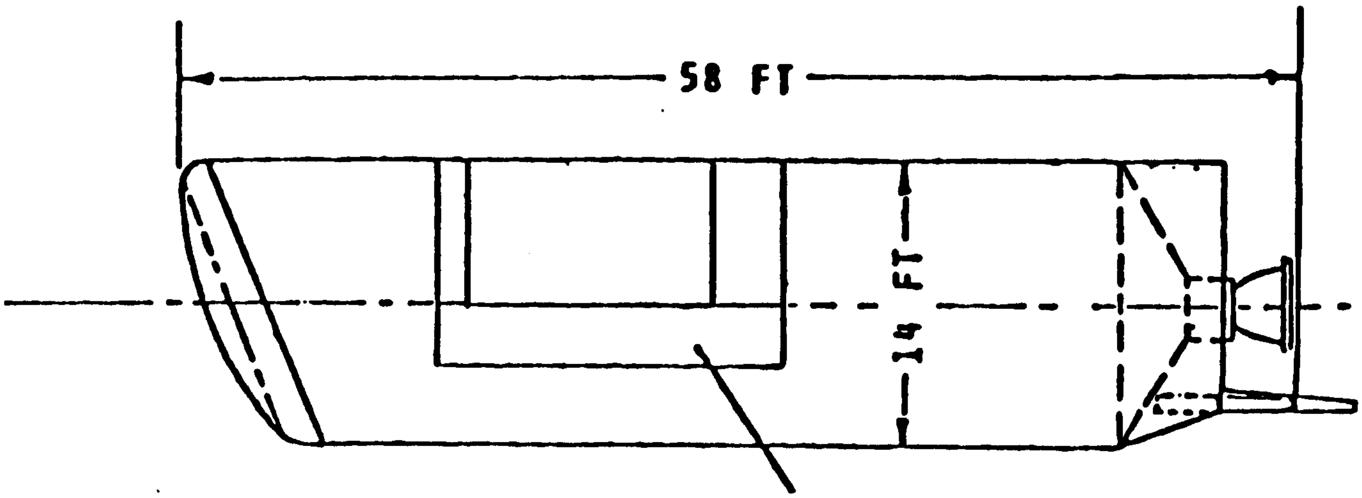


FIGURE 3. TYPICAL AOTV WITH L/D OF ABOUT .3

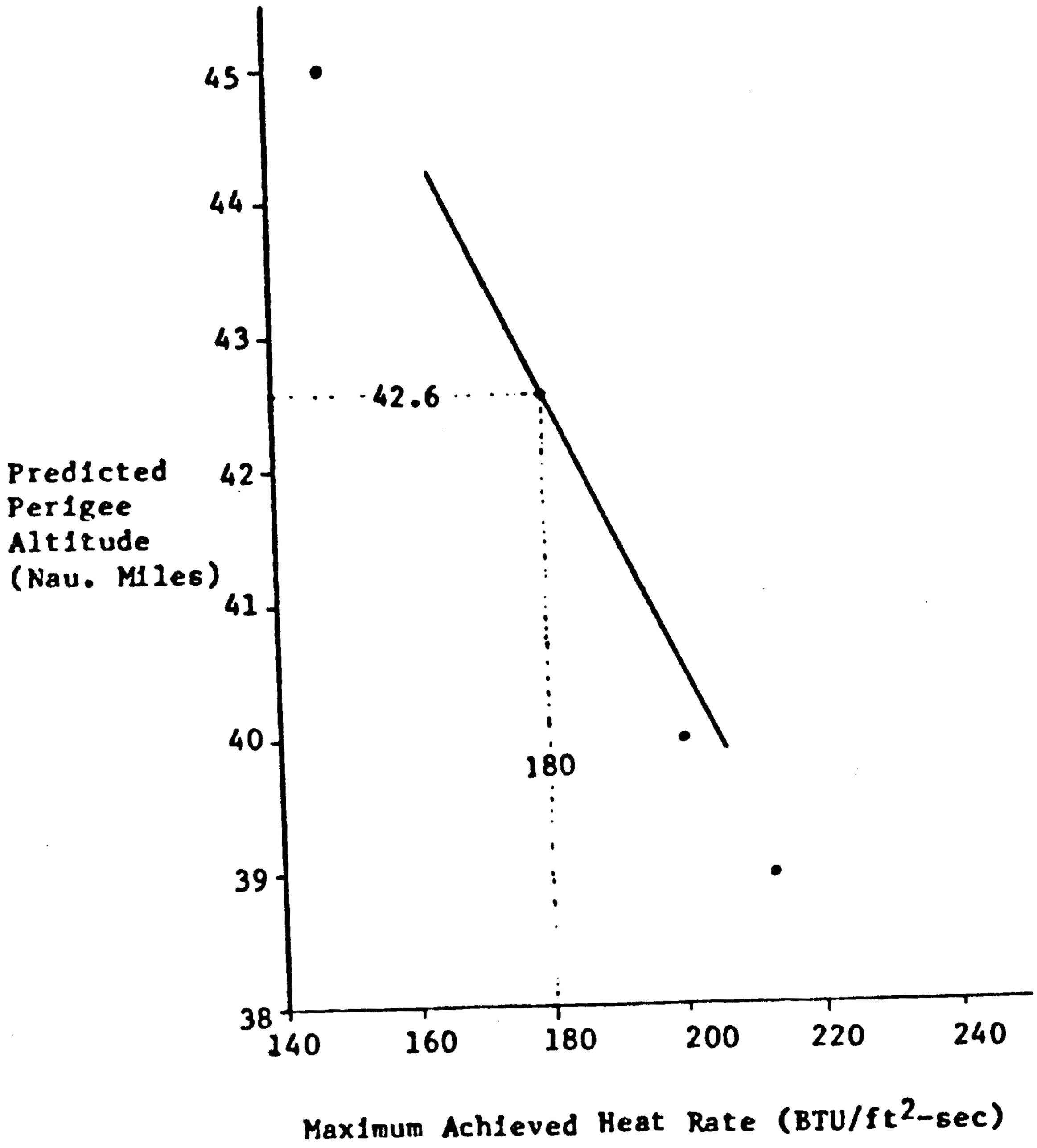
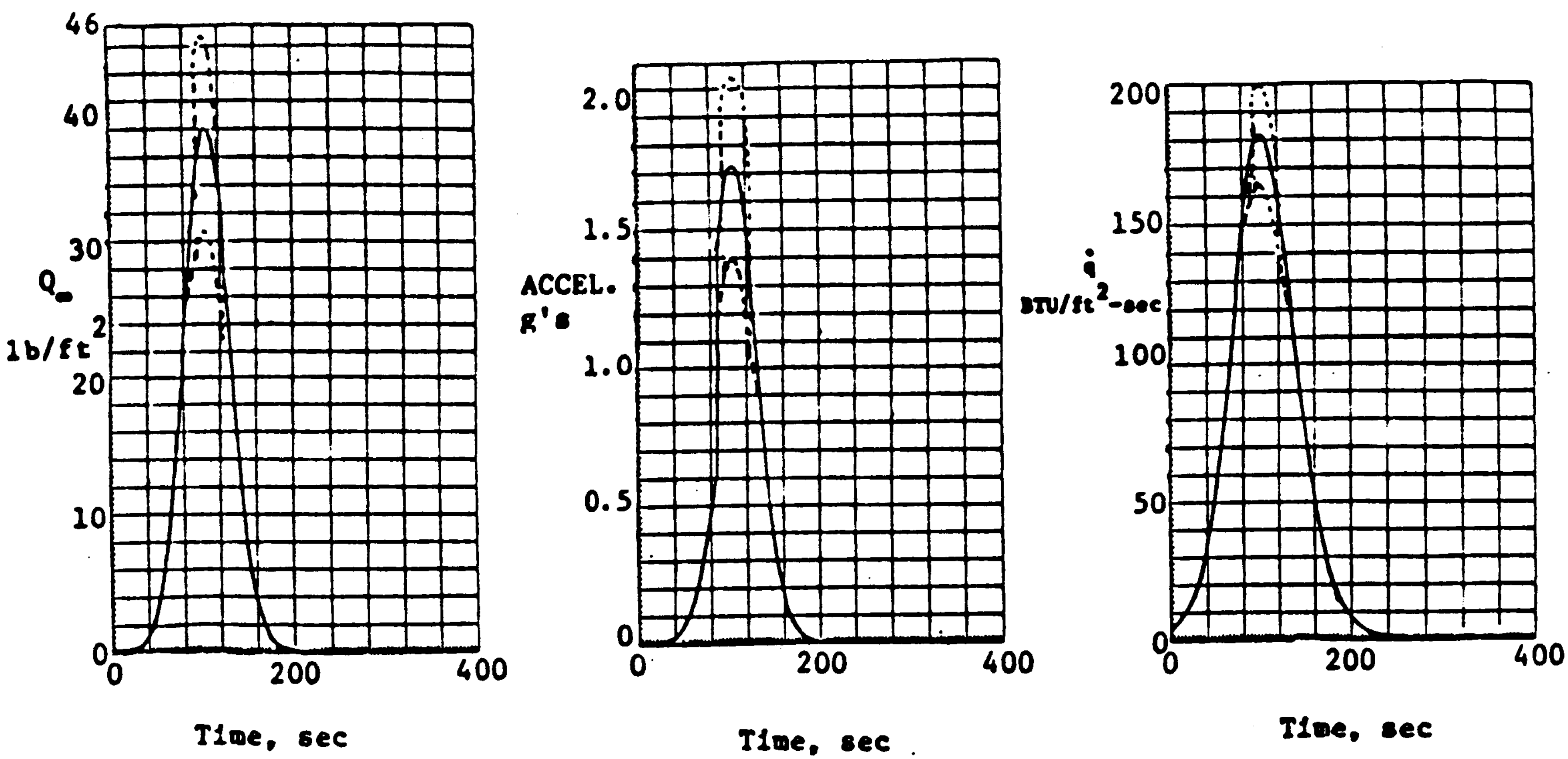


Figure 4. The Predicted Perigee's Linear Relationship to the Maximum Heat Rate



a:
Dynamic Pressure

b:
Acceleration

c:
Heat Rate

FIGURE 5. $\pm$ 20% DENSITY VARIATION ENCOUNTERED AT THE POINT OF MAXIMUM HEAT RATE

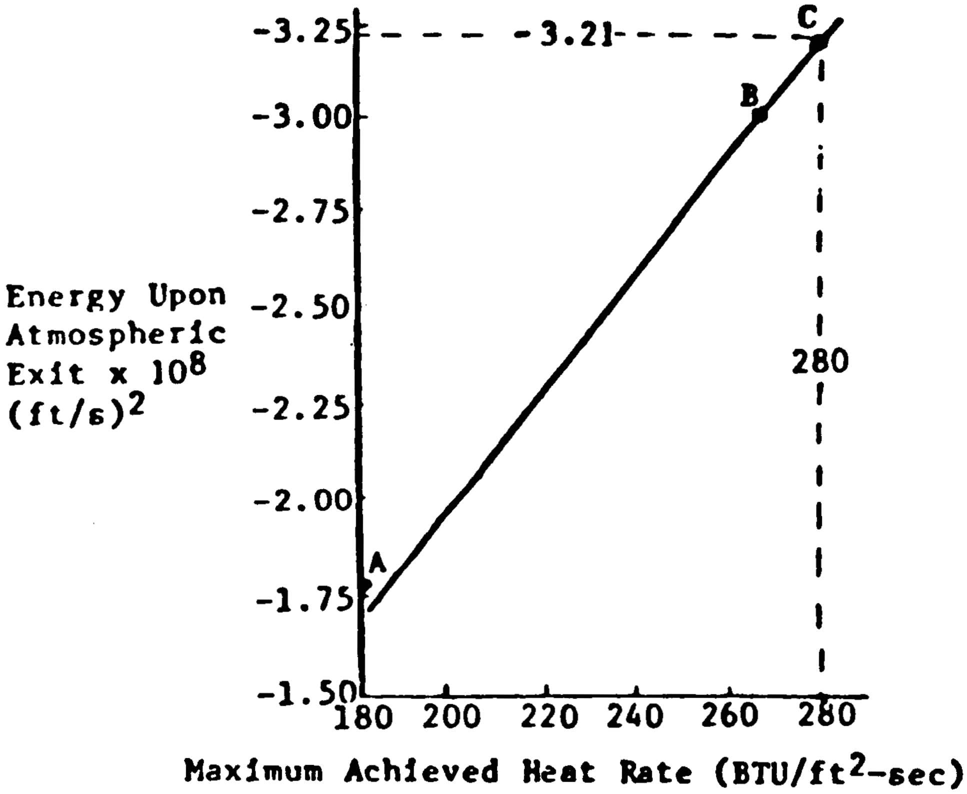


FIGURE 6. VEHICLE ENERGY AT EXIT VERSUS HEAT RATE

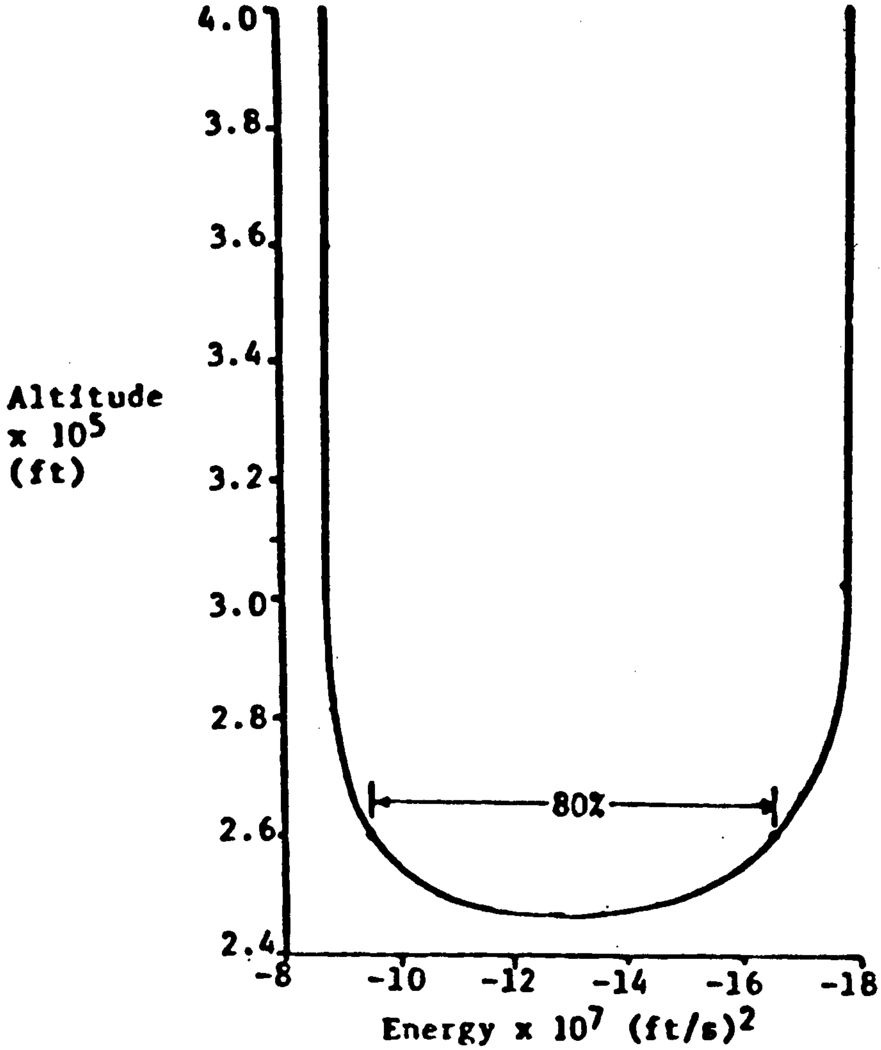


FIGURE 7. AOTV ENERGY LOSS FROM SINGLE ATMOSPHERIC PASS

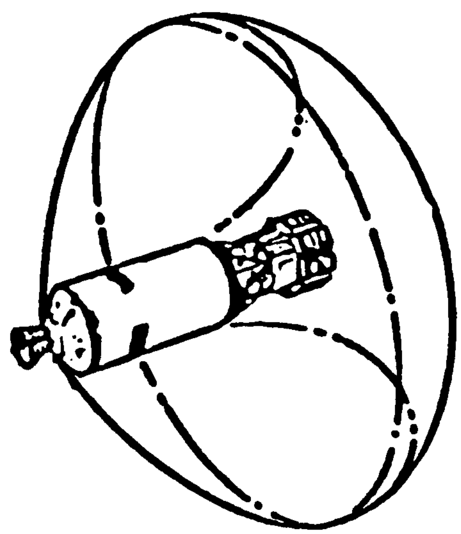
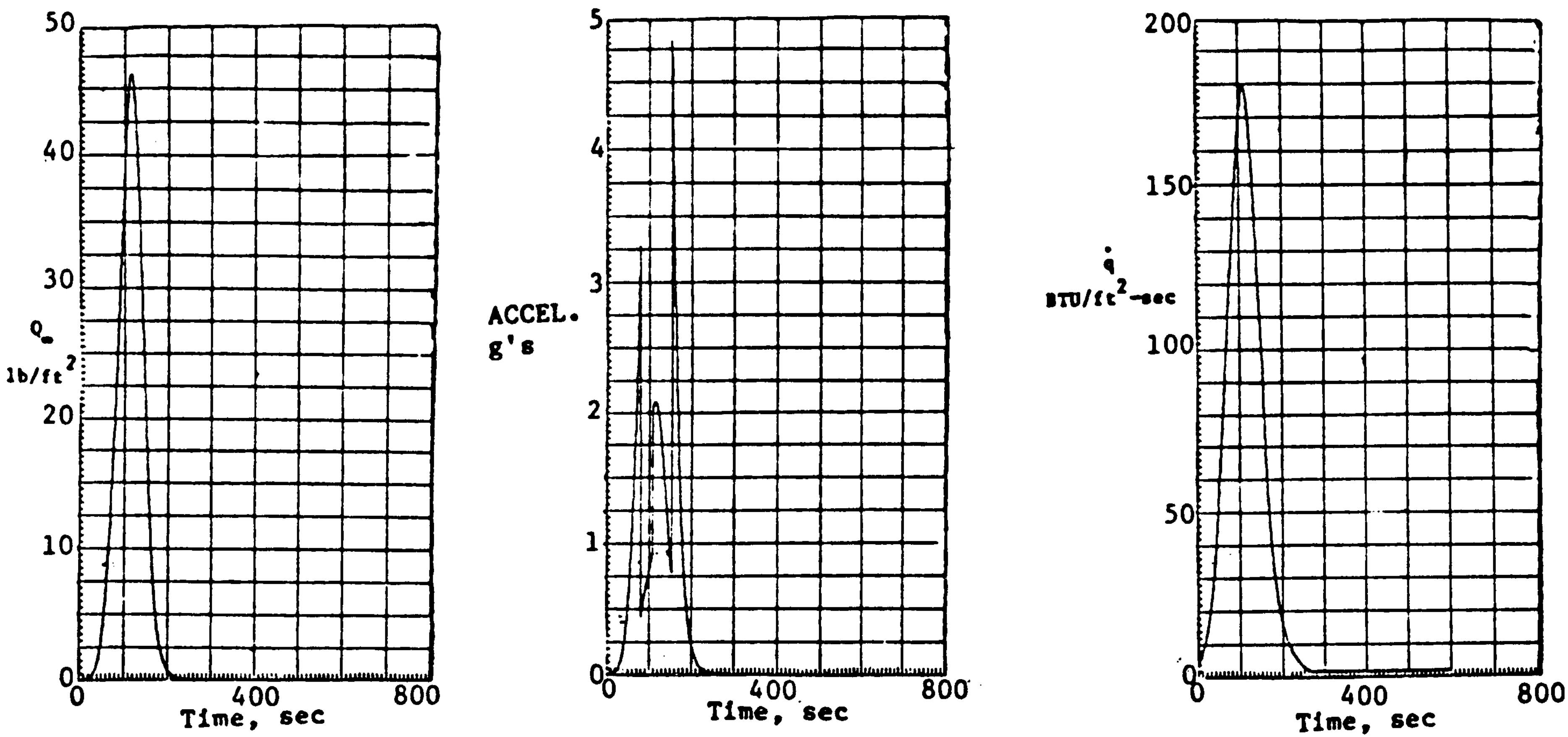


FIGURE 8. AOTV BALLUTE CONCEPT (REF 4).



a: Dynamic Pressure

b: Acceleration

c: Heat Rate

FIGURE 9. DOUBLE BALLUTE SIMULATION RESULTS

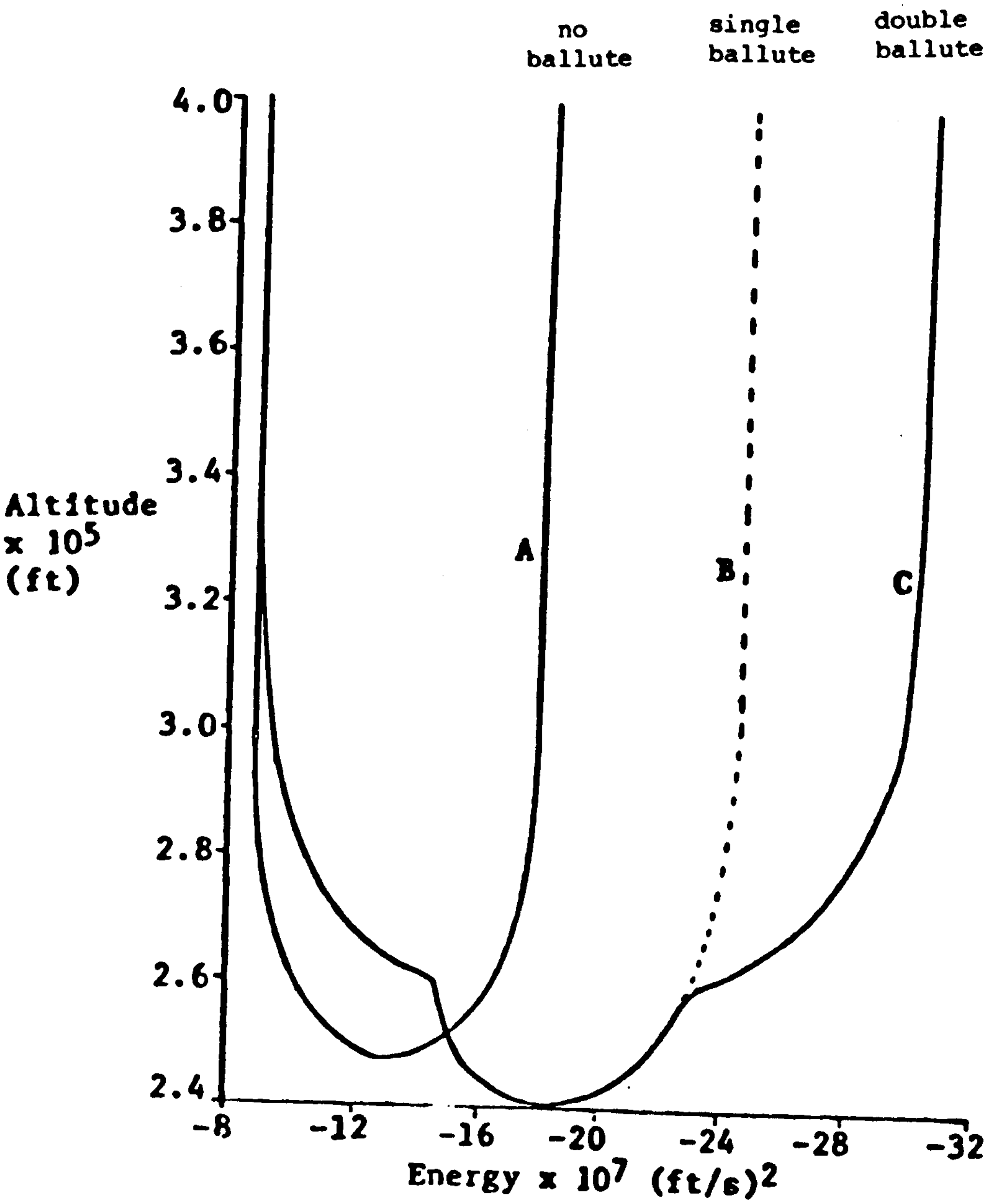


FIGURE 10. ENERGY DECREMENT COMPARISON

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16. Abstract

The emphasis in this study was on the use of multiple pass trajectories for aerobraking. However, for comparison, single pass trajectories, trajectories using ballutes, and trajectories corrupted by atmospheric anomolies were run. A two pass trajectory was chosen for determining the relation between sensitivity to errors and payload to orbit. Trajectories that used only aerodynamic forces for maneuvering could put more weight into the target orbits but were very sensitive to variations from the planned trajectors. Using some thrust control resulted in less payload to orbit, but greatly reduced the sensitivity to variations from nominal trajectories. When compared to the non-thrusting trajectories investigated, the judicious use of thrusting resulted in multiple pass trajectories that gave 97 percent of the payload to orbit with almost none of the sensitivity to variations from the nominal.

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