POTENTIAL APPLICATIONS FOR EXPANDABLE AND INFLATABLE STRUCTURES FOR RE-ENTRY VEHICLES

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LIST OF SYMBOLS

V	flight velocity (ft/sec)
ALT	altitude (ft)
W	gross weight of vehicle (lb)
S_B	basic body planform area (ft^2)
S_{Total}	basic body planform area plus added area (ft^2)
A	projected area of drag unit (ft^2)
D	diameter (ft)
F_D	drag force (lb)
C_D	drag coefficient
Q	stagnation point heating rate (BTU/ft^2-sec)
q	dynamic pressure $1/2 \rho V^2$ (lb ft^2)
G	acceleration of gravity (ft/sec^2)
CG	center of gravity
CP	center of pressure
l/D	trailing cable length/drag unit diameter ratio
L/D	lift/drag ratio

INTRODUCTION

At present, space exploration is essentially still in its initial phases. Most re-entry vehicle designs have been approached with relatively unsophisticated structural concepts that require extensive recovery operations. Parachute deceleration and brute force of the structure are relied upon to reduce potential damage to test data and equipment.

Future vehicles (figure 1) will be manned, and expected to fulfill varying missions such as service for ferry vehicles, to supply and maintain unmanned orbiting reconnaissance and military command posts, as well as commercial missions. These vehicles will be required to land more or less conventionally, be reserviced, and re-used without extensive rebuilding of the airframe. They will have the potential which will give the crews adequate capability to correct re-entry errors, select any of several landing sites, and change flight paths from long-range glide to short-range glide after re-entry. These are features that the lifting body re-entry vehicle with stowable variable geometry lifting surfaces and expendable or inflatable structures can provide. Figure 2 illustrates typical optional vehicle re-entry and terminal phases.

The conception of these vehicles that meet future mission requirements will present unforeseen new challenges for research and development in numerous unexplored areas of technology and structural design. The application of inflatable and expandable structures will play a major role in space exploration, and shows much promise in terms of space and re-entry vehicle structures.

POTENTIAL MISSIONS FOR RE-ENTRY VEHICLES

Figure 3 is a mission profile for a typical lifting body re-entry vehicle. As studies have indicated, the re-entry phase of the mission is the most severe. The environment imposed upon the vehicle largely determines its overall design in terms of aerodynamic performance and structural requirements. It is noted that the velocity and angle of attack at re-entry creates severe aerodynamic heating problems. Coupled with this is the restriction of a bank roll maneuver required to prohibit the vehicle from skipping back into orbit. The remainder of the mission is now limited by more or less aerodynamic characteristics of a nonvariable geometry configuration. This limits maneuverability into the terminal footprint area. Figure 4 shows the potential mission profile and advantages of a typical lifting body re-entry vehicle mission utilizing a remote drag device and variable geometry lifting surfaces. If deployed prior to re-entry the trailing drag device aids in the re-entry phase by decreasing the severe heating problem resulting from the velocity, and required high angle of attack. A more gradual re-entry is possible which eliminates the necessity for the pullout bank roll maneuver. A drag device that has the capability of modulating its force will result in variable descent times. The forces acting upon this device can also be exploited for the power to extend variable geometry lifting surfaces for improvement of terminal phase characteristics.

VEHICLE DESIGN CONCEPTS

GENERAL DESIGN CRITERIA FOR RE-ENTRY VEHICLES

Listed in the following are some of the items to be considered in the proposed design of re-entry space vehicles that land conventionally and have variable aerodynamic characteristics induced by the use of trailing, and extendable, expandable, and inflatable aerodynamic surfaces and devices.

1. Location of inflatable devices

2. Allowable weight and space available for deployable surfaces, devices, and inflation units

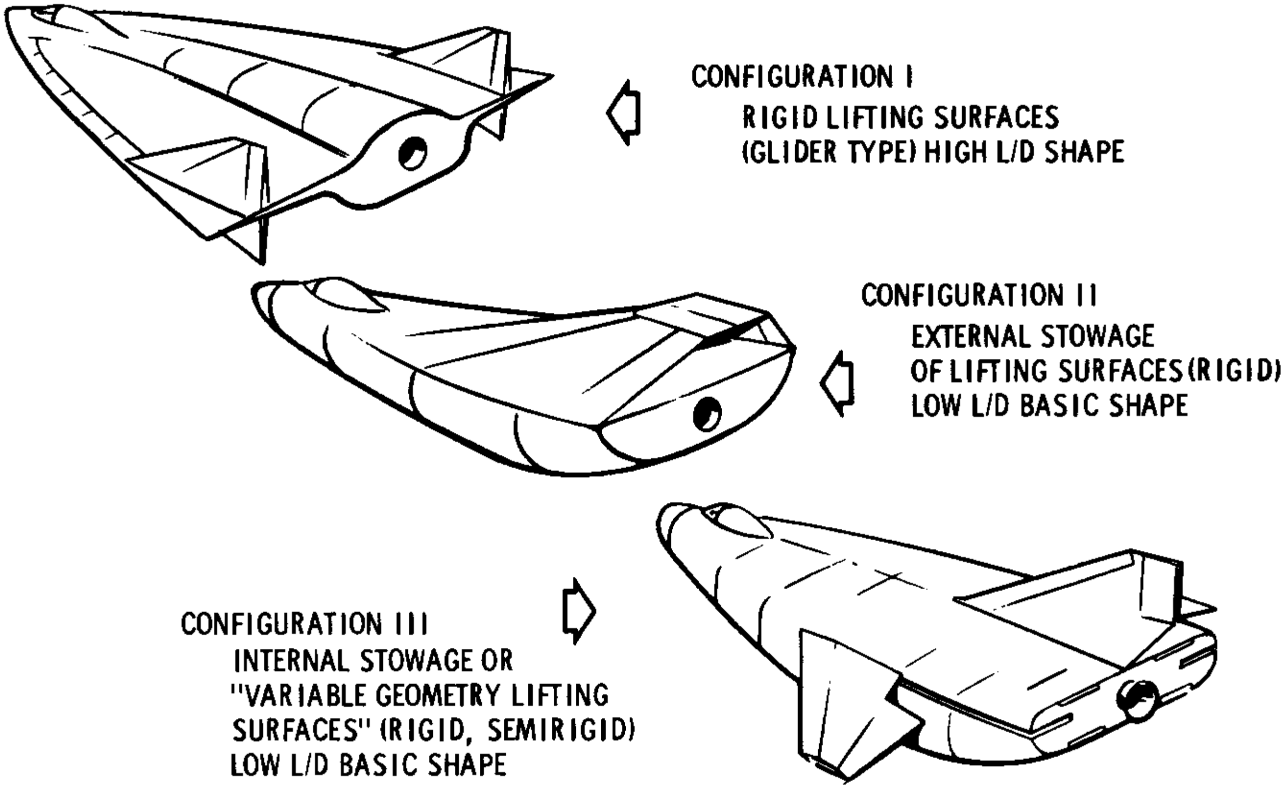


Figure 1. Typical Re-entry Vehicle Lifting Body Configuration

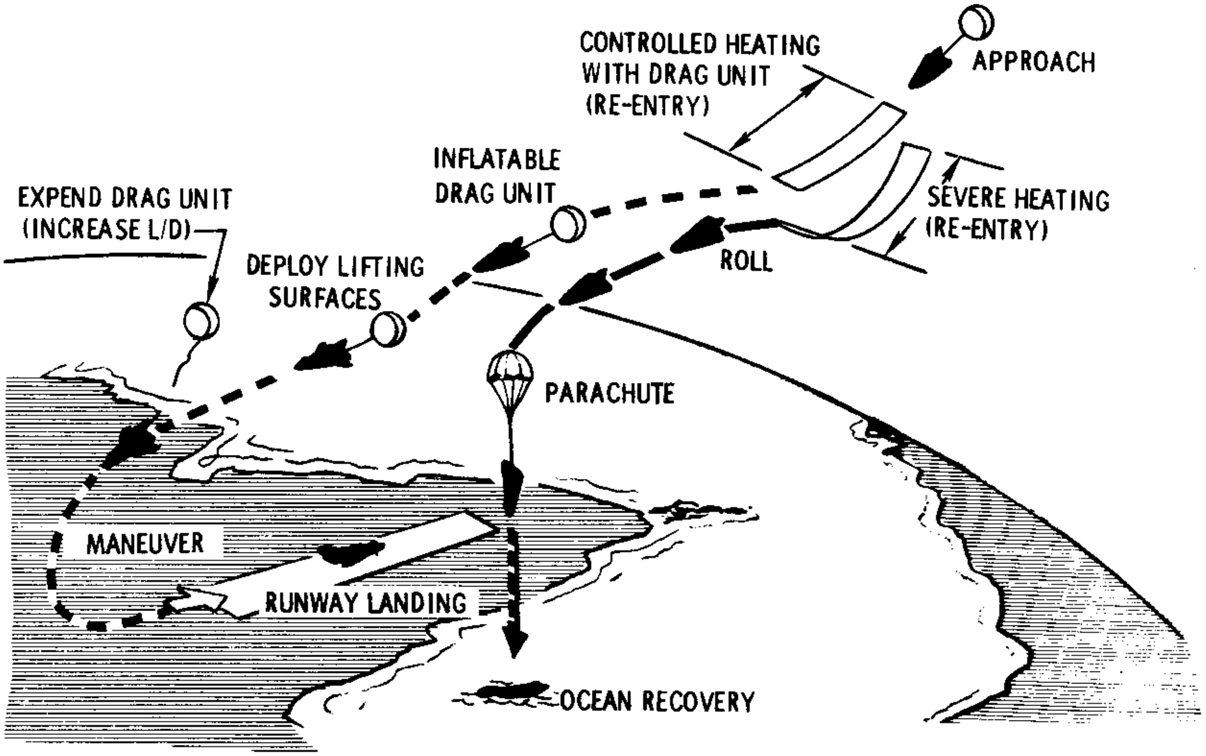


Figure 2. Missions and Terminal Phases for Existing and
Potential Re-entry Vehicles

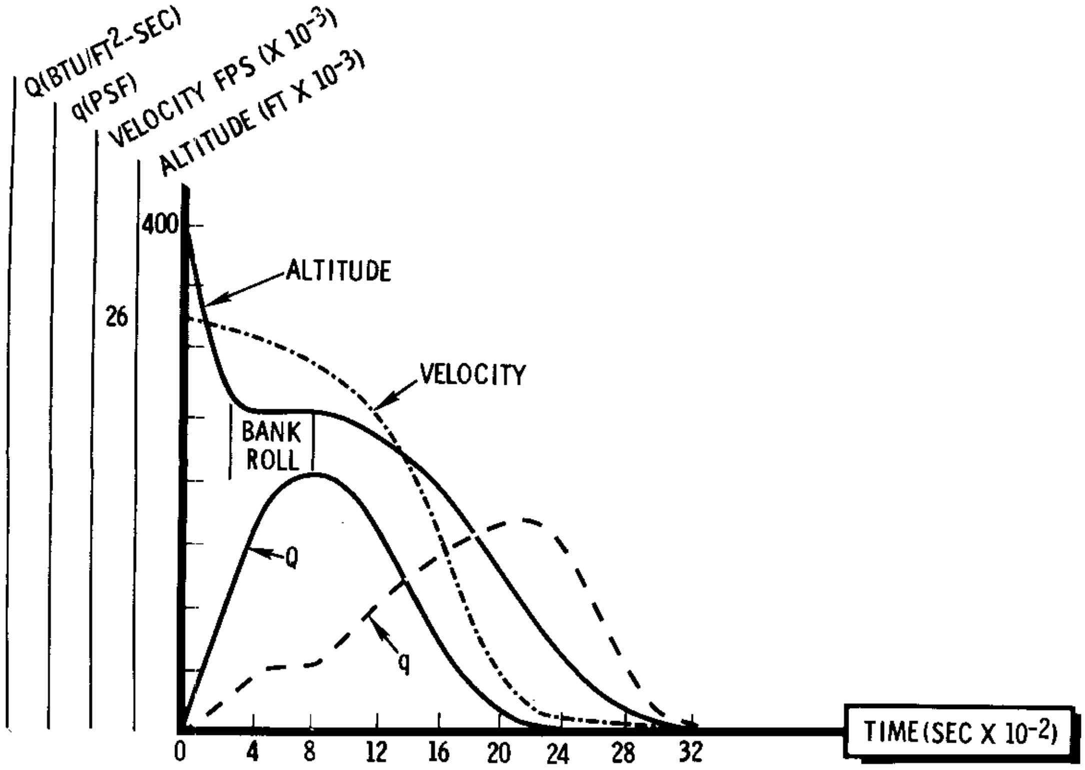


Figure 3. Typical Lifting Body Re-entry Mission Profile
L/D 1.2 (No Drag Unit - No Wing Extension)

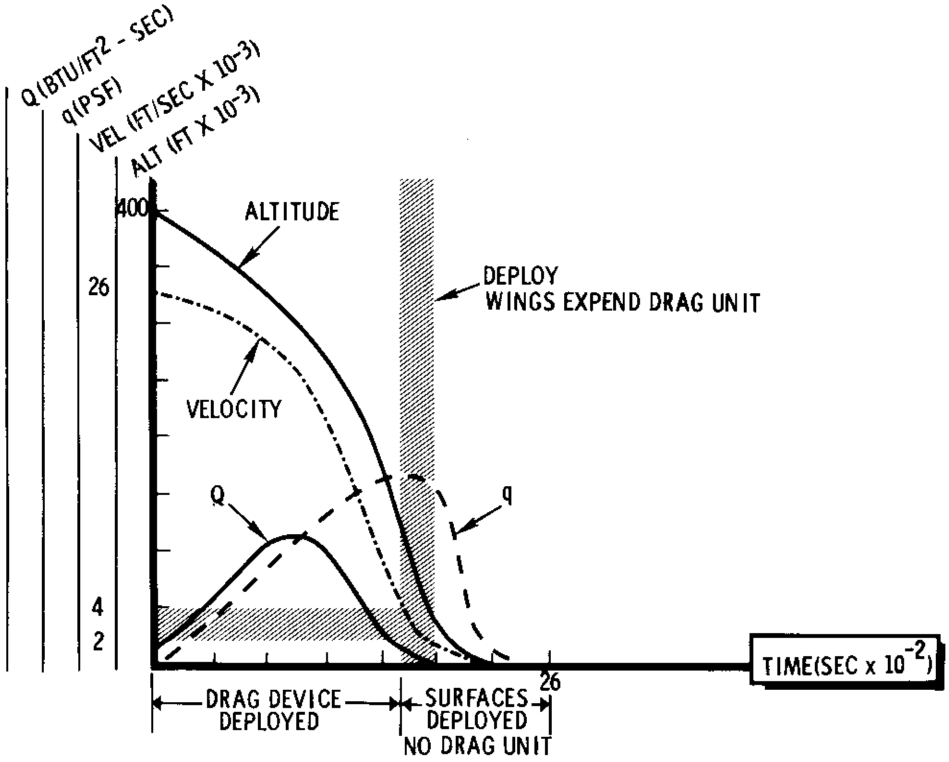


Figure 4. Mission, Using Drag Device and Extension of Lifting Surfaces

3. Provision for sufficient reliable power sources and mechanisms for deployment of lifting surfaces
4. Retention of aerodynamic smoothness of vehicle after surface extension and device deployment
5. Total vehicle configuration (stable or unstable) throughout the entire mission
6. Aerodynamic heating during re-entry phase
7. Possible range, speed, and altitude at initial deployment of surfaces and devices
8. Maximum G-tolerances of vehicle and rate of G-onset
9. Desirable stability, angle of approach and rate of descent on impact
10. Weight of vehicle at terminal phase
11. High L/D, low wing loading, and low terminal velocity.

Expandable and inflatable structures have the desired potential for solving the major problems related to the preceding design criteria. Future development and reliability of expandable and inflatable structures are inevitable, and their potential applications are now being intensively explored. The design of space and re-entry vehicles presents a rewarding area of unlimited scope for conceptual applications of inflated, rigid, and semirigid expandable structures.

The following presents the possible evolution of a typical lifting body re-entry vehicle configuration utilizing expandable and inflatable structures.

For illustrative purposes, configuration III, figure 1, is selected for this basic body shape of the typical re-entry vehicle. This vehicle will have an assumed L/D of approximately 1.2 for re-entry and a desired L/D of 5.0 plus for supersonic and subsonic flight.

To obtain this relatively large increase in L/D, it is necessary to increase the vehicle's planform area. This can be accomplished by means of extendable surfaces stowed in the main body of the vehicle. The stowage and actuation of these surfaces present problems that require unique innovations to conventional design concepts that will result in a total vehicle configuration that is feasible for required re-entry missions.

APPLICATIONS FOR INFLATABLE AND EXPANDABLE STRUCTURE AND BALLUTE-TYPE DRAG DEVICES

As previously mentioned, existing studies have indicated that the environment created by aerodynamic heating during the re-entry phase is a critical problem. The high velocities and high angles of attack encountered during the hypersonic phase of current re-entry vehicles produce aerodynamic heating, thermal protection, material, structural stability, and dynamic problems. These problems can be mitigated over a large portion of the re-entry phase of the mission by the deployment of an inflatable, or expandable aerodynamically stable, high-drag device. The spherical segment type (AVCO drag brake), figure 5, appears to be best suited for the re-entry phase, as it lends itself to drag modulation plus having a fairly constant C_D at high Mach numbers. An added advantage to this concept is that the energy is dissipated remotely from the basic vehicle structure. The large radius of the device reduces the aerodynamic heating problems. An analysis should be made for each desired vehicle mission to realize the trade-offs between thermal protection weight and controlled remote aerodynamic drag and energy dissipating unit.

Another outstanding problem inherent to existing hypersonic lifting body re-entry vehicle configurations is the low L/D ratio (1.2 to 3.0). This limits the maneuverability of the vehicle, and results in a decreased terminal footprint area. The variable geometry lifting surface concept is a relatively new approach to achieving substantial increase in L/D ratios when most desired. Heretofore, heavy on-board power sources have been proposed as the actuation units for the extension of rigid or semirigid lifting surfaces. This investigation proposes concepts exploring the use of high-drag, aerodynamically stable, expandable or inflatable units as the power source for associated mechanisms used for the deployment or extension of lifting surfaces during the flight regime of supersonic velocities.

DESIRED DESIGN REQUIREMENTS FOR INFLATABLE OR EXPANDABLE DRAG DEVICES

1. High drag, low weight, low bulk
2. High degree of stability
3. High degree of reliability (over-all system)
4. Reliable means for inflation
5. Adequate strength for applied loadings
6. Ability to withstand environmental conditions (space and deployment)
7. Feasibility of fabrication

CONFIGURATIONS FOR DEPLOYABLE AND INFLATABLE AND EXPANDABLE AERODYNAMIC DECELERATORS AND POWER SOURCE

The requirement for inflatable-balloon-type decelerators was originated as a result of the problems inherent with the operation of parachutes at supersonic speeds. The erratic inflation and poor stability characteristics of conventional parachutes at these speeds necessitated investigation of other methods of deceleration.

Various shapes and configurations have been tested to arrive at maximum stability and drag at a minimum weight and bulk cost. Initial investigations of unit shapes ranging from conical to spherical, and intermediate combinations of both (figure 5) have been performed by forced inflation and subjecting them to simulated flight conditions corresponding to typical re-entry and aerodynamic environments.

80-DEGREE CONICAL BALLUTE (FIGURE 5, CONFIGURATION I)

Inflatable conical drag devices have been investigated for supersonic flight conditions (Mach No. 2.0 to 5.0). Various design configuration concepts have been tested to determine the most feasible and reliable methods for inflation. Some were preinflated, pressurized models, while others relied upon ram air. It was found that the preinflated, pressurized models performed satisfactorily, but difficulty with air mass pulsation at the air inlets required screen and reed type inlets. A side inlet screen valved 80-degree conical ballute showed the most promise as an optimum conical configuration. Drag coefficients (C_D) ranged from 0.8 to 1.0. (See figure 6.)

SPHERICAL-TYPE BALLUTE (FIGURE 5, CONFIGURATION II)

Test results reveal that the spherical shape is highly efficient with respect to high-drag and stability characteristics at high altitudes and Mach numbers. However, this configuration did show instability in the subsonic flow regimes, due to an unbalance of forces generated from the nonuniform pressure distribution variation caused by the unsteady release of vortices into the wake of the device. To relieve this problem, a burble fence was introduced to positively trip the flow over the spherical body from laminar to turbulent flow. The net effect of this was that in the supercritical regime (at subsonic and transonic speeds), the flow separates evenly and aft of the sphere, resulting in balanced forces and aerodynamic stability. Drag coefficient C_D ranges from 0.8 to 1.0. (See figure 6.)

SPHERICAL SEGMENT TYPE (FIGURE 5, CONFIGURATION III)

The spherical segment type configuration has been extensively investigated, both analytically and in wind tunnel tests under the direction of the Retardation and Recovery Branch of the Flight Accessories Laboratory. It has become known as the AVCO drag brake. This device differs from the previously mentioned devices in that it is a mechanically expandable structure, and in appearance is very similar to an inverted umbrella. This allows for the protection of the actuation container by placing it behind the expanded structure and shielding it from the extremely high re-entry temperatures.

The analytical investigations show that the use of such a device permits controlling of the maximum re-entry temperature and deceleration, and affords landing-point control within the orbital plane.

The drag coefficient (C_D) is slightly above unity in the supersonic and above regimes. However, it drops off in the subsonic region. This decelerator body can be utilized in all flight regimes from orbital velocities to touchdown, and is aerodynamically stable with self-aligning aerodynamic moments.

MATERIALS

The success of these proposed expandable and inflatable drag structures depends upon flexible, impermeable, thermally stable, high-strength, fibrous materials. A distinct advantage that these structures (formed with coated, woven materials) have over rigid structures are deployment control, compactibility, and reduced weight. In instances where aerodynamic heating may occur,

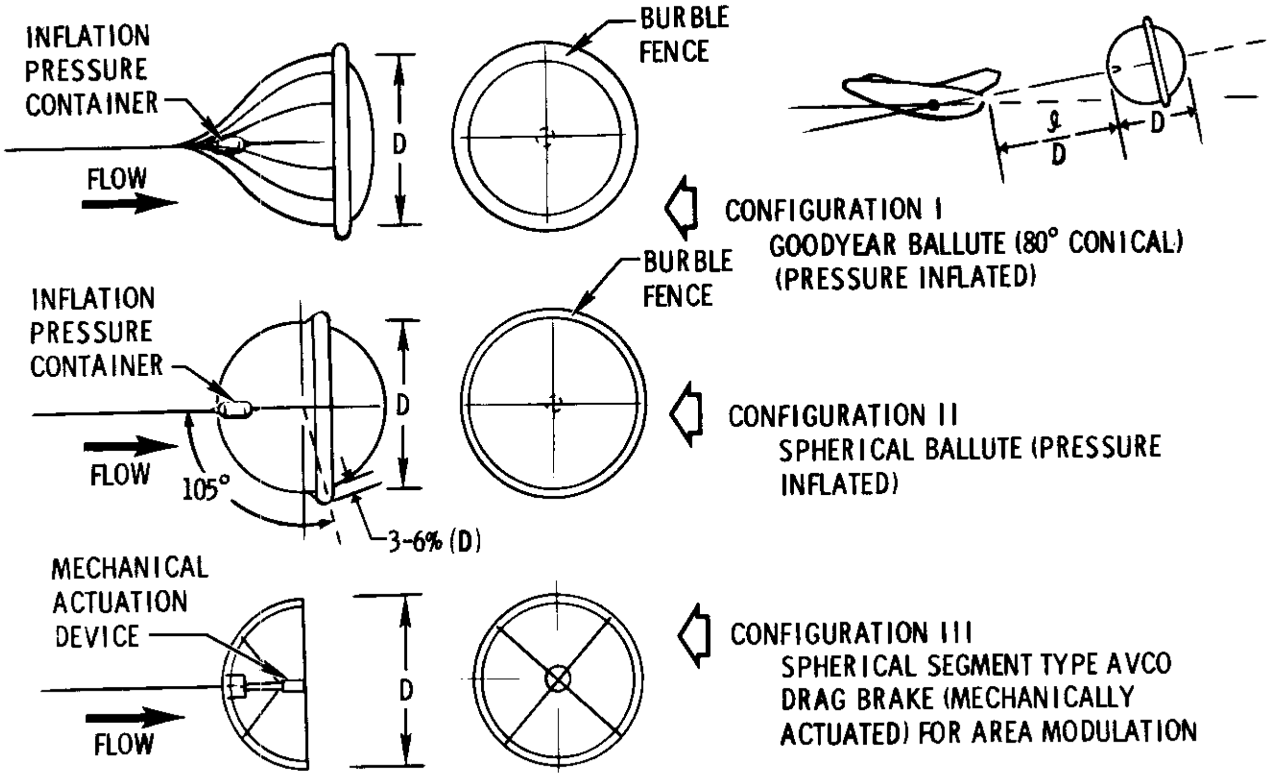
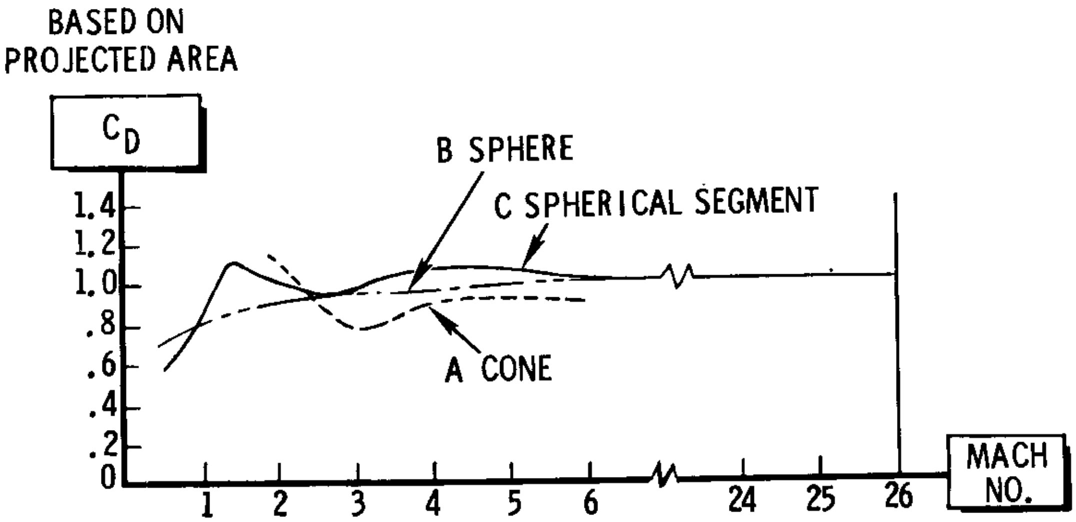


Figure 5. Typical Inflatable and Expandable Drag Units



A. 75% CONE BALLOON 6.3% FENCE (WIND TUNNEL TEST DATA)
REF. ASP-TR-61-579

B. SPHERICAL
REF. WADC TR 59-324

C. AVCO DRAG BRAKE (SPHERICAL SEGMENT)
WIND TUNNEL TEST DATA REF. ASD TR-61-579

Figure 6. Drag Coefficient Versus Mach Number for Typical Drag Devices

thermal stability can become a major problem with expandable structures, since re-entry temperatures range from 1500°F to 2500°F, depending upon the configuration. This criteria restricts the use of present-day textile fibers unless they are prohibitively thick or have a matrix of inflexible material. These requirements would seriously impair their potential compactibility and recoverability.

Boron-based fibers and nickel-based superalloys in ultrafine filament-form woven into a mesh appear to be the most suitable candidate materials. Seam welding is used to join segments to form desired configurations. The matrix (or coating) material, which restricts leakage and loss of internal pressure, is an area requiring extensive research and development. Coatings have been developed to withstand the temperature, but the results of cooling, shrinkage, or bending creates adverse effects on permeability.

LOCATION AND DEPLOYMENT OF DRAG DEVICE

The inflatable drag device compartment should be located at the extreme tail of the vehicle. While deployed, the developed force should pass through the vehicle's CG at the flight-path angle. This is to minimize induced moments imposed on the vehicle after deployment. If possible, the aft wall of the compartment should have a considerable slope, so as to aid in the expulsion or extraction of the unit. In general, the motion of the deploying device will be straight aft in relation to the flight path of the vehicle.

INFLATION OF BALLUTE OR DRAG DEVICE

Several methods of inflation are available which are light, reliable, and easily packaged. The most familiar and most readily available method is to inflate the device by means of pressurized gas contained in either a metal or filament-wound, glass-fiber container. Various gases may be utilized such as helium, carbon dioxide, etc, for low-altitude - high q (dynamic pressure) inflations. Inflation time can be kept to a minimum by using a properly designed nozzle and valve arrangement. If a high-altitude inflation is desired, it can be achieved by means of a nonpressurized container filled with alcohol. Since temperatures will be relatively low until the actual re-entry occurs, the drag device can be lined with a very thin (separate unit) rubber or plastic bladder. Because of the low ambient pressure, the vapor pressure developed by vaporization of the alcohol will be sufficient to allow inflation to take place. The liquid volume and temperature will govern the resulting internal pressure of the inflated drag device. Inflated with the pressure developed by the vaporizing liquid, the device will be deployed and in a trailing position for re-entry. When re-entry occurs, and the dynamic ambient pressure increases, a ram air or bottled pressure inflation can take over. As the ram or container pressure increases sufficiently above the low initial inflation pressure, a collapsing of the internal bladder will occur, and it will be compressed to the rear portion of the ballute.

Mechanically actuated drag units can be deployed and modulated independent of the ambient pressure, and present no problems in this respect.

SOME POTENTIAL APPLICATIONS FOR INFLATABLE OR EXPANDABLE DRAG UNITS

The developed drag can be utilized twofold. The initial deployment will provide a decelerating force for the reduction of re-entry velocity and required angle of attack. The unit is deployed prior to, or during, the re-entry phase, and the trailing cable is extended until the optimum 1/D (length of cable to drag unit diameter ratio) is reached. At this point, a stop on the cable introduces the drag load into the vehicle's primary structure. It is possible to modulate the developed drag by increasing or decreasing the projected area of the unit.

When sufficient energy has been dissipated by means of the drag device and the programmed velocity and altitude for wing deployment has been reached, the cable stop is released. This allows the drag force to continue through the vehicle, and is equally divided and introduced into the lifting surface extension mechanism. Up to the present, hydraulic actuators and electric motors have been considered as the only means for providing the required forces to overcome the developed aerodynamic drag, inertia, and friction forces resulting from the extension of these surfaces. Each surface was provided with a heavy, on-board actuating unit and a common hydraulic pressure reservoir and associated accessories that ensured symmetrical surface extension.

A proposed solution to this problem is to exploit and control the existing aerodynamic drag forces that can be developed during or after re-entry of the vehicle. The controlled use of a remote, aerodynamically stable drag unit with a sufficient C_D during the entire flight regime can provide this required energy source. The deployment of a stowable, expandable or inflatable, lightweight, drag unit such as those previously mentioned appears to fulfill these requirements.

The release of this drag force and resulting moments must be programmed so that they will equal or exceed those developed by combined forces resulting from the extension of the lifting surfaces into the airstream. (See figures 7 and 8.) As shown in the typical mission profiles, the desired force is required at lower altitudes and Mach numbers to alleviate aerodynamic heating of small radius leading edges, and to obtain a sufficient dynamic pressure (q).

Using a specific deployment location on the mission profile just prior to the terminal phase, we can roughly compute the potential drag force of the unit. Using values derived from the known mission profile

C_D = Coefficient of drag for unit

q = Dynamic pressure

A = Projected area of drag unit

we can roughly compute the potential drag developed at this point.

$$F_D = C_D \, q \, A$$

Figure 9 shows typical potential drag forces developed for units of varying diameters and dynamic pressures.

After the actuation cycle has been completed, the surfaces are locked into position, and an explosive charge is initiated at a point on the cable beyond the basic vehicle. Thusly, the drag unit is severed and leaves the vehicle

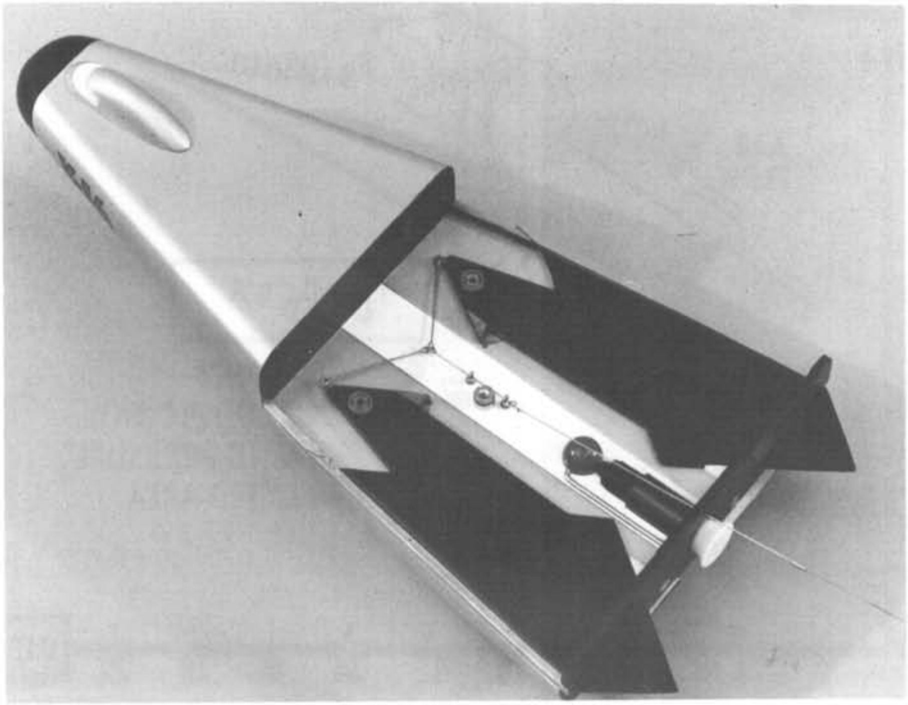


Figure 7. Lifting Surfaces Stowed

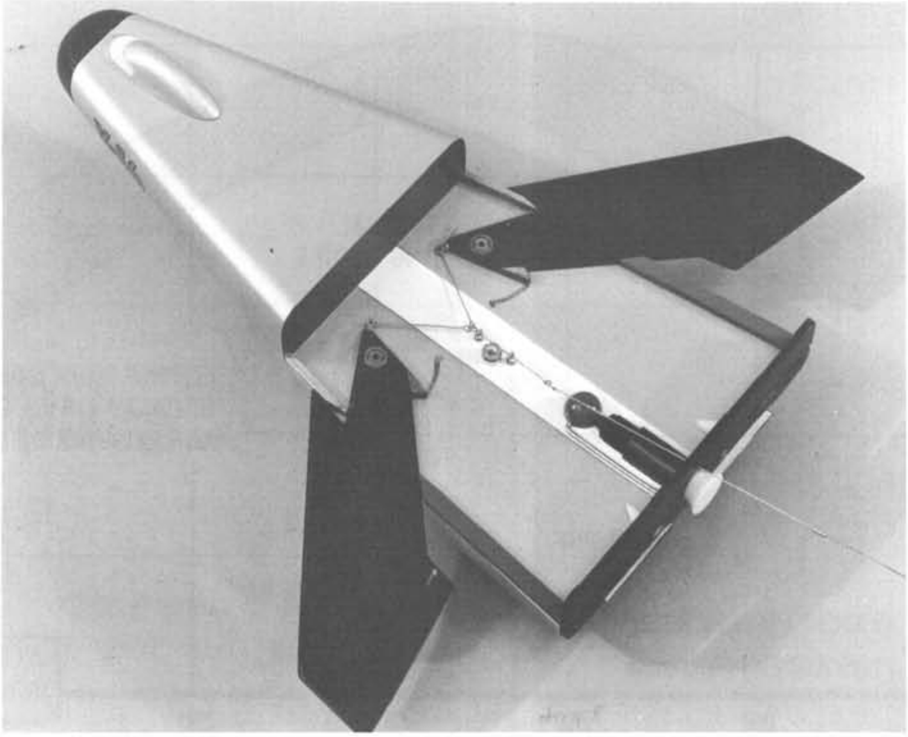


Figure 8. Lifting Surfaces Extended

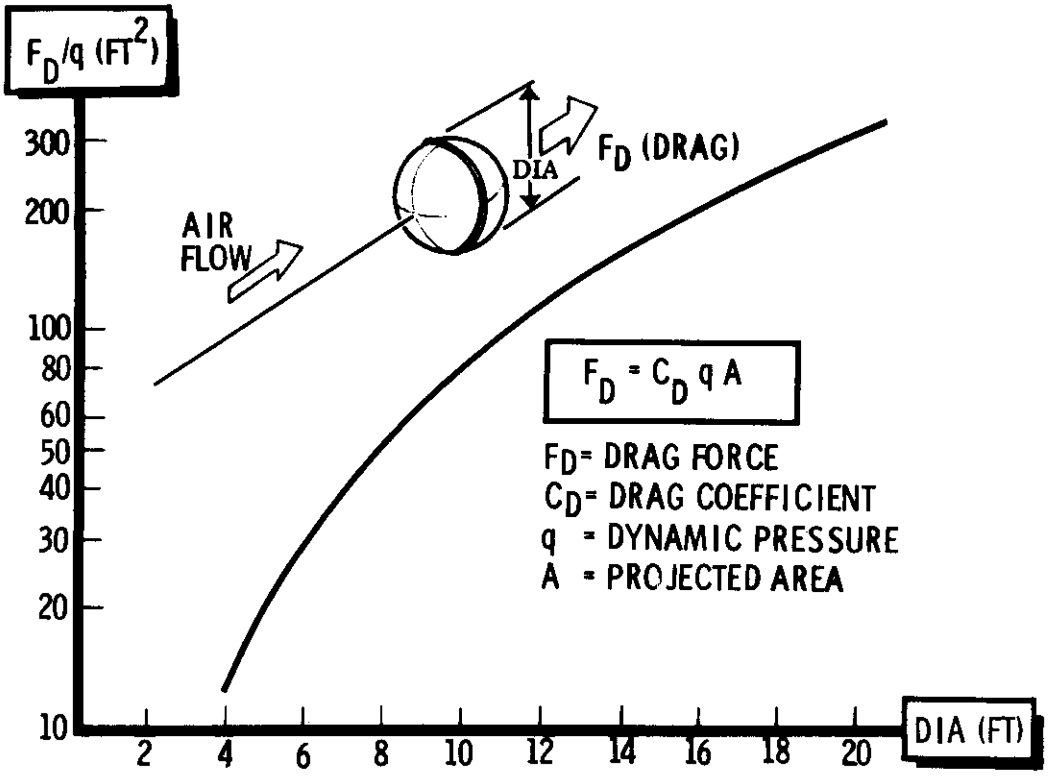


Figure 9. Drag Versus Diameter for Typical Drag Units

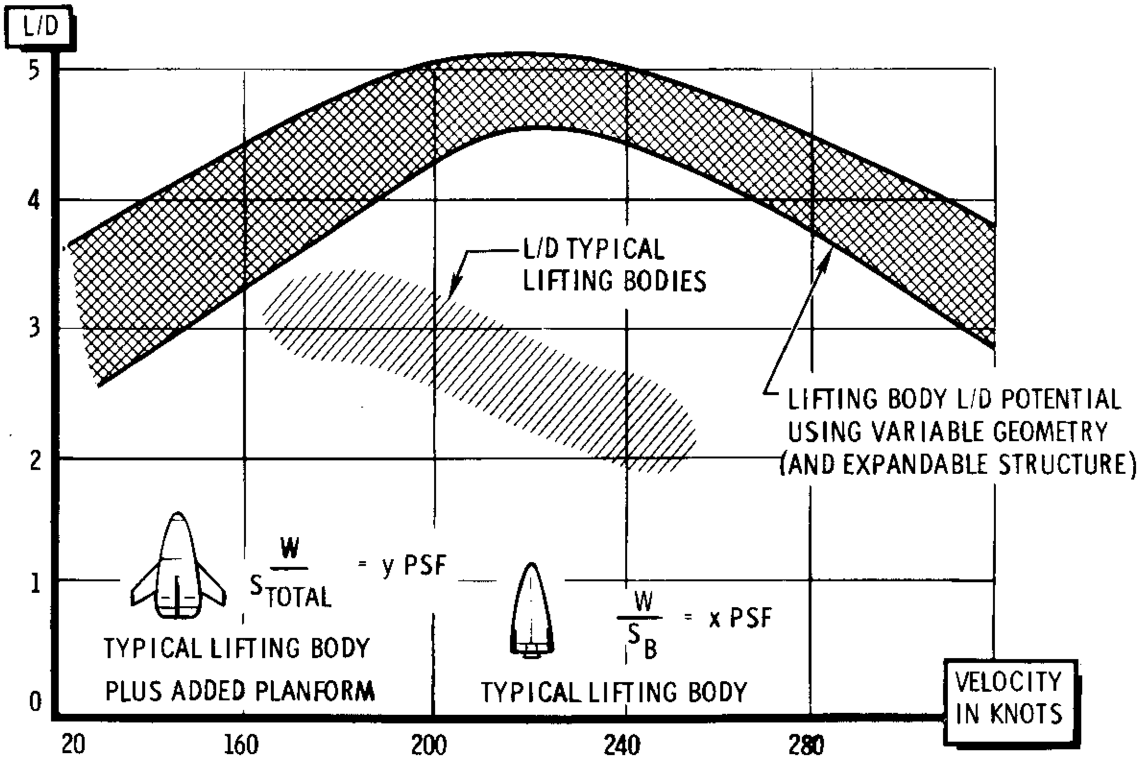


Figure 10. Lifting Body L/D Comparison

clean with an increased L/D and improved maneuverability at supersonic and terminal velocities. (See figure 10.)

Another added potential feature of utilizing a remote drag device is that of directional stability at hypersonic and supersonic velocities. This eliminates the necessity of large verticals having large angles of flare to produce the desired directional stability.

OPTIONAL DEPLOYMENTS OF DRAG UNIT TO VARY RE-ENTRY MISSIONS

1. Entire mission
2. During re-entry phase (only)
3. During re-entry phase and deployment of lifting surfaces (only)
4. During deployment of lifting surfaces (only)

SOME PROBLEM AREAS RELATED TO DEPLOYMENT OF TRAILING DRAG UNITS

All deployments of trailing aerodynamic decelerators or drag units create a force known as "snatch force," which arises from the differential deceleration rates of the basic vehicle load and the deploying drag unit. The rapid deceleration of the drag unit, in relation to the relatively slow deceleration of the basic vehicle, creates a sizable differential velocity which must be reduced to zero. The maximum deceleration force of the vehicle created by the drag device deployment should be programmed so as not to exceed the limits of human and structural tolerances.

A proposed solution to this problem is to absorb this shock force into an energy-absorbing reeling device that is used to gradually extend the trailing cable to its first-phase terminal length.

Optimum force vectors located at the cable juncture and cable-wing attachments and the cushioning effect of the aerodynamic drag and inertia forces will have a dampening effect on the initial shock imposed upon the actuating system by the release of the remote drag force into the wing actuation cycle.

Because of the differential in moments created by the associated forces of aerodynamic drag and inertia, the wing extension will have to be limited by a snubbing device before the locking mechanism can be initiated and the trailing drag unit is severed.

OTHER EXPANDABLE STRUCTURE

"Air Mat," a double-walled, inflatable structure, developed by Goodyear, has interesting possibilities for use as a drag device. Two layers of flexible material tied together with a large number of threads (30 to 60 per square inch) of the same material form a semirigid shape when inflated with low pressure. "Air Mat" can also be made from wire-cloth material such as René 41 and other superalloys. Advantages gained through the use of such construction methods would be the possibility of lightweight, large-surface area devices. Its foldability results in the ability to package the deflated device into about 3 percent to 5 percent of its inflated volume (figure 11) and to readily vary its inflated drag area. This concept has been developed to the point whereby these materials now can be woven into curved shapes, such as spheres and other symmetrical body shapes applicable to the previously proposed drag devices. This type of construction would eliminate the necessity of gores and joints and results in a lighter than conventionally constructed device of similar shape.

Another concept that may be utilized for lightweight, high-volume expandable filler is the variable geometry elastic recovery one. This concept is based upon the use of the recovery properties of a flexible polyurethane foam as the core material. The basic load-carrying outer skin can be either a woven fabric or a superalloy filament woven cloth. If rigidity is required, the skin may be lined with a nonpermeable bladder to eliminate porosity and internal gas pressure used for increased stabilization of the structure.

POSSIBLE APPLICATIONS FOR "AIR MAT" AND ELASTIC RECOVERY CORE

FILLER FOR AERODYNAMIC SMOOTHNESS (FIGURES 12 AND 13)

The location of extendable rigid or semirigid lifting surfaces sometimes present the problem of leaving voids in the basic vehicle structure that would have adverse effects on the aerodynamic characteristics of the over-all vehicle. This void is usually a considerable volume. "Air Mat" is an ideal filler. Figures 12 and 13 illustrate typical applications for upper- or lower-winged vehicle configurations that utilize it as an inflatable sandwich that pushes secondary structure to the original mold line. Midwing configurations (figure 12) result in smaller voids, but again "Air Mat" qualifies as the ideal lightweight, expandable filler.

AFTERBODY (FIGURE 14)

A basic lifting body shape and planform configuration sometimes results in a stability problem, due to CP and CG locations at subsonic speeds. The addition of an inflatable afterbody, using "Air Mat," shifts the CP and center of volume aft. This inflated structure also aids in the reduction of the basic aft-body aerodynamic drag when it is desirable.

SUBSONIC CONTROL AND STABILIZING SURFACES

After re-entry and the deployment of the variable geometry lifting surfaces (supersonic-subsonic velocities) an aerodynamic stability problem may arise for certain re-entry shapes or configurations. The addition of a forward canard or augmented vertical stabilizer surface area may be required. The "Air Mat" concept merged with a rigid expandable structure again can qualify to meet these requirements.

Figures 15, 16, 17, 18, and 19 illustrate each critical mission phase of a typical lifting body re-entry vehicle utilizing expandable and inflatable structures.

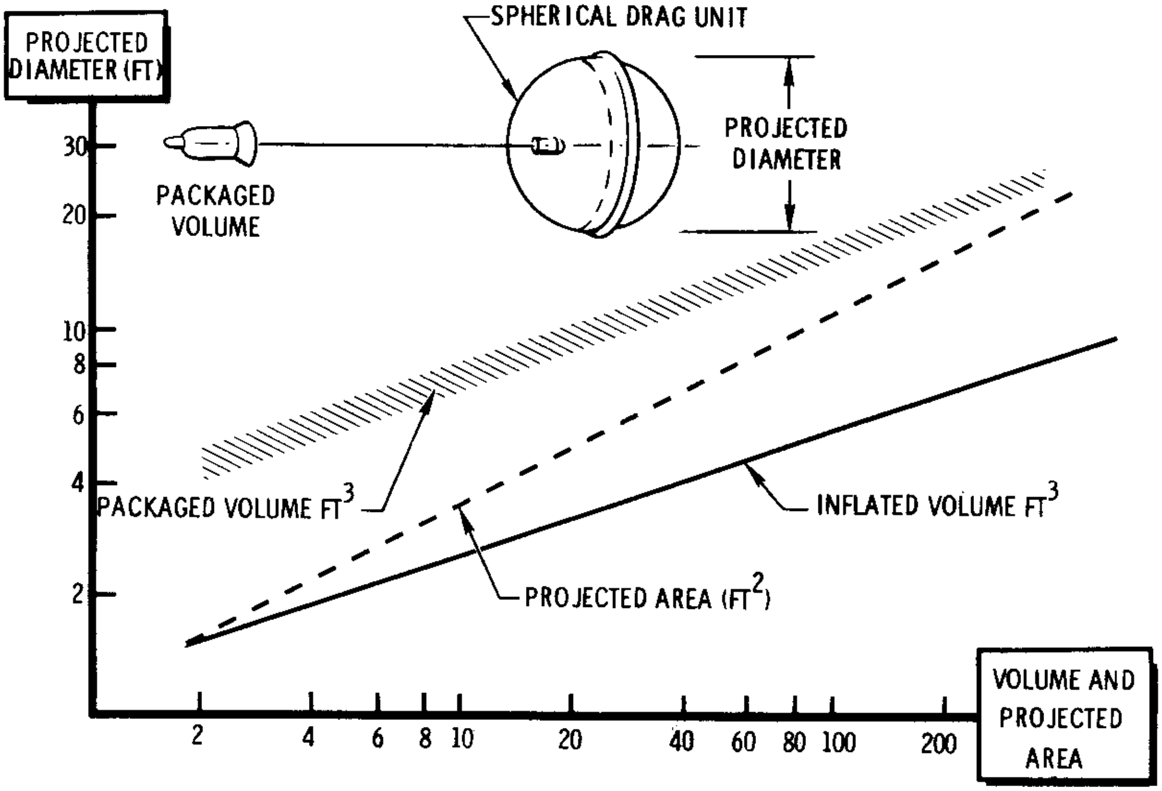


Figure 11. Geometry Versus Projected Area for Spherical Drag Unit

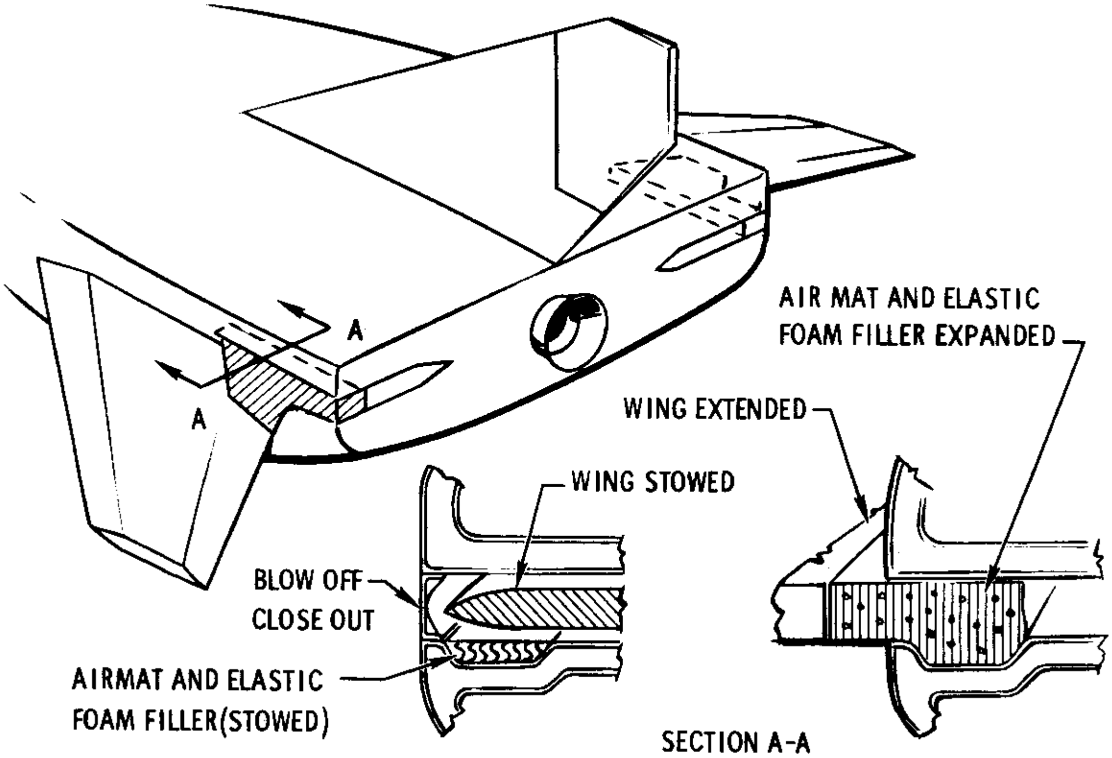


Figure 12. Aerodynamic Filler

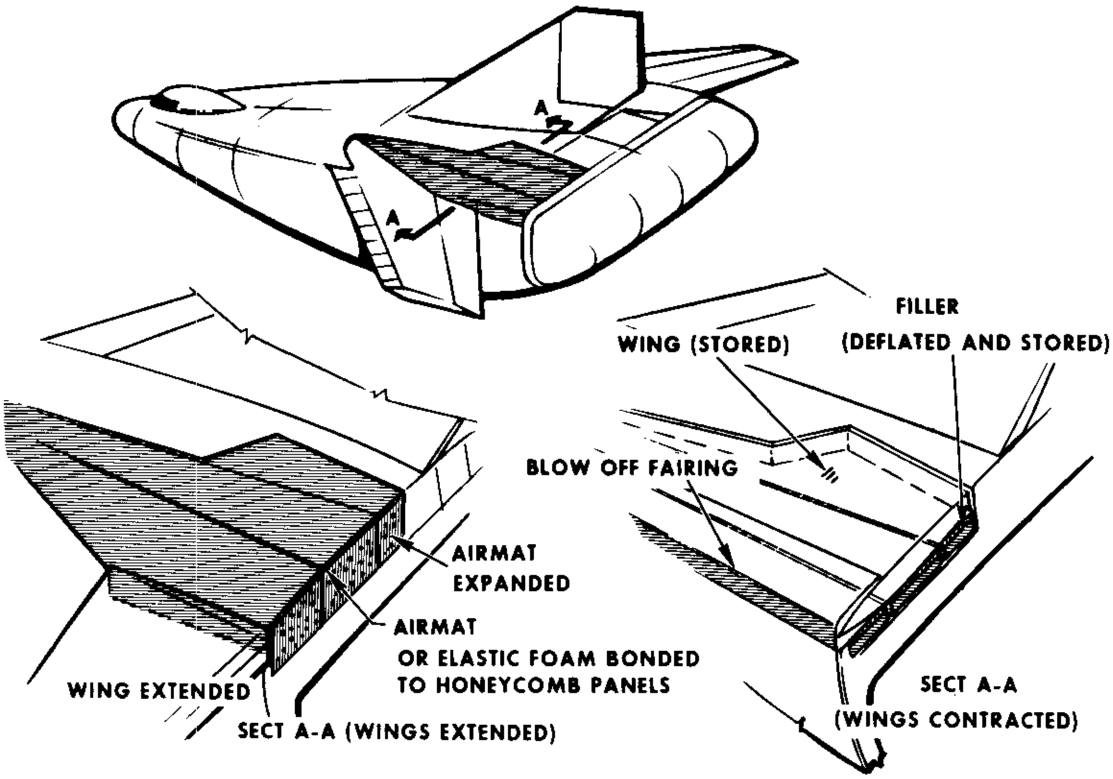


Figure 13. Filler for Aerodynamic Smoothness

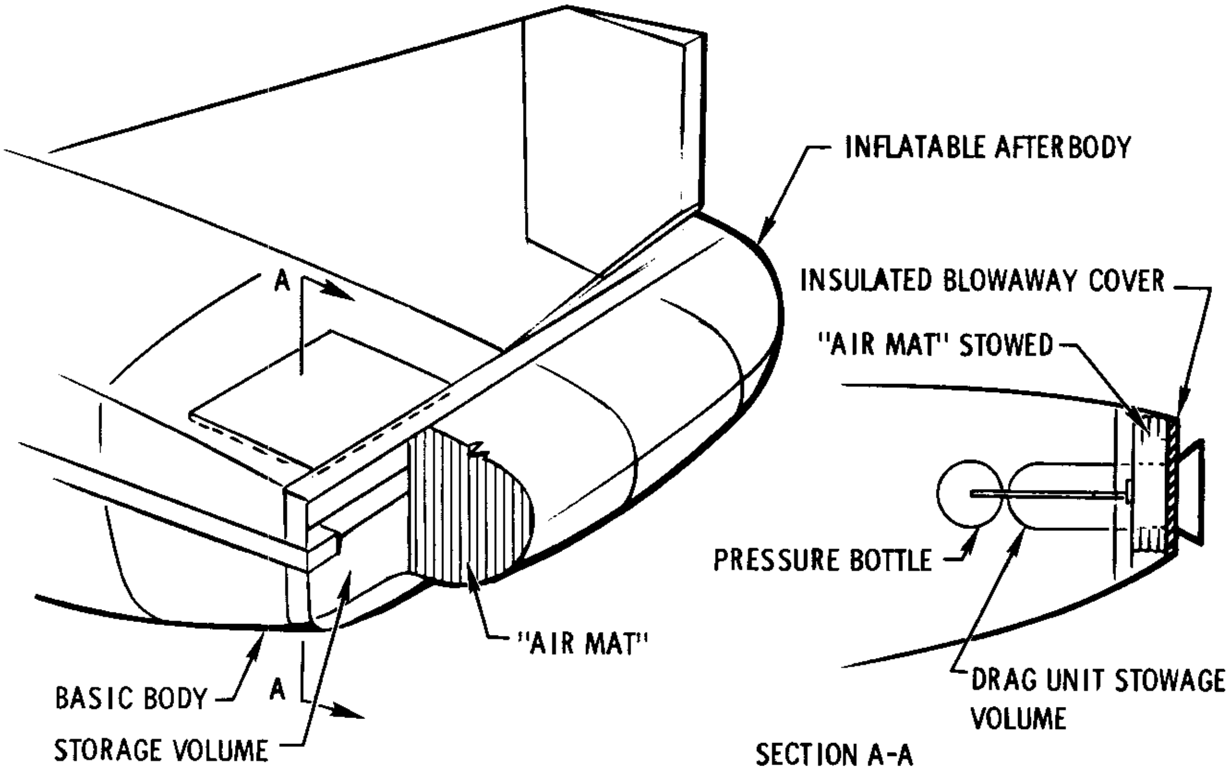


Figure 14. Inflatable Afterbody

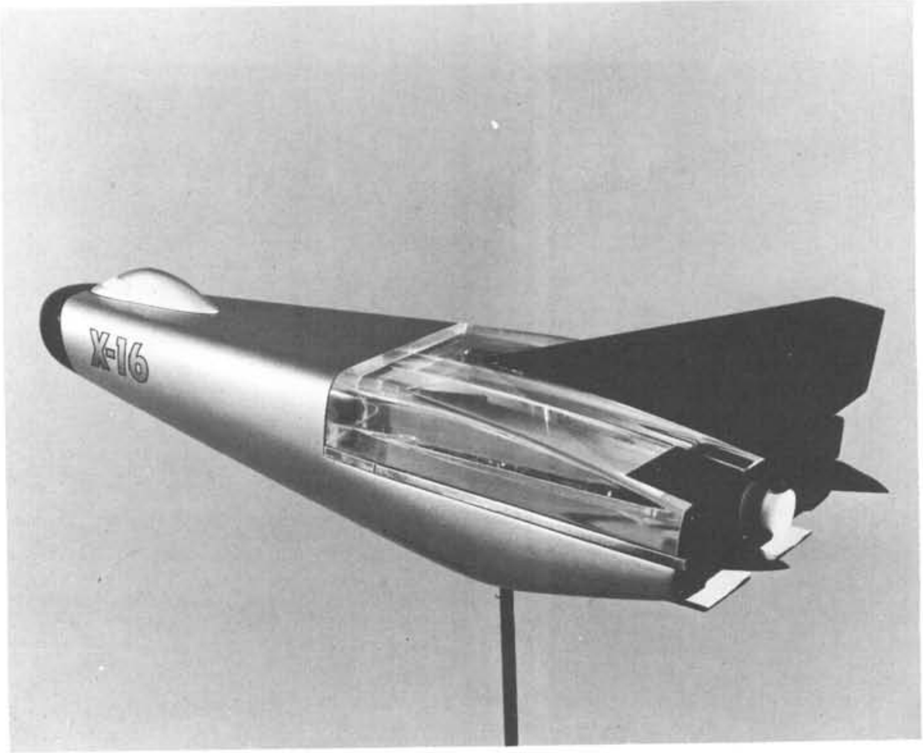


Figure 15. Vehicle Re-entry Approach Phase

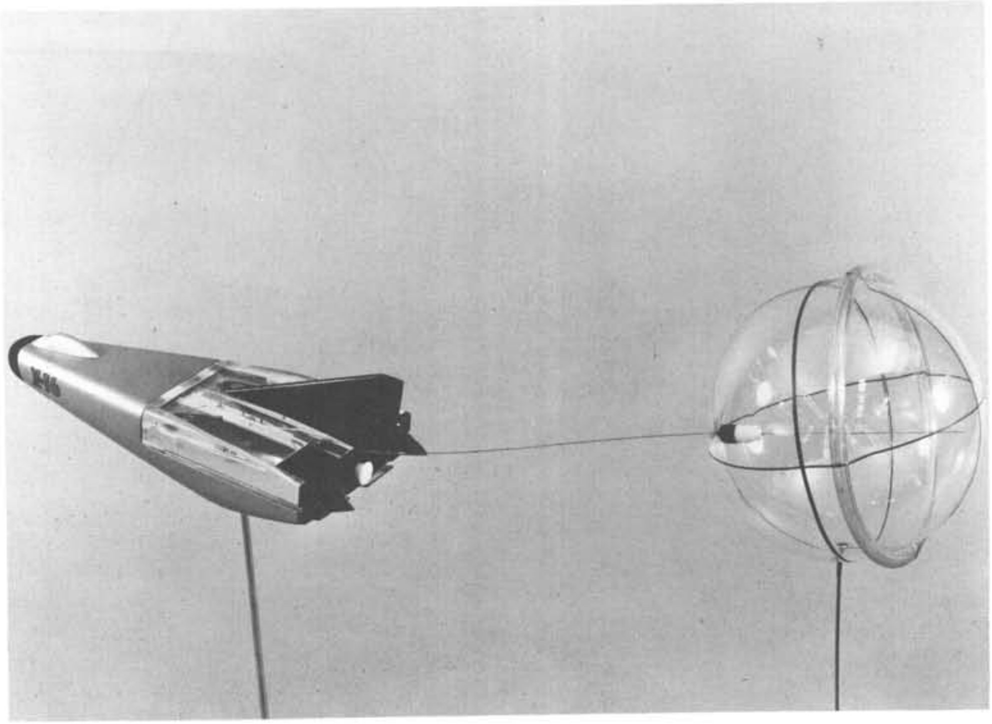


Figure 16. Vehicle Re-entry (Drag Unit Deployed)

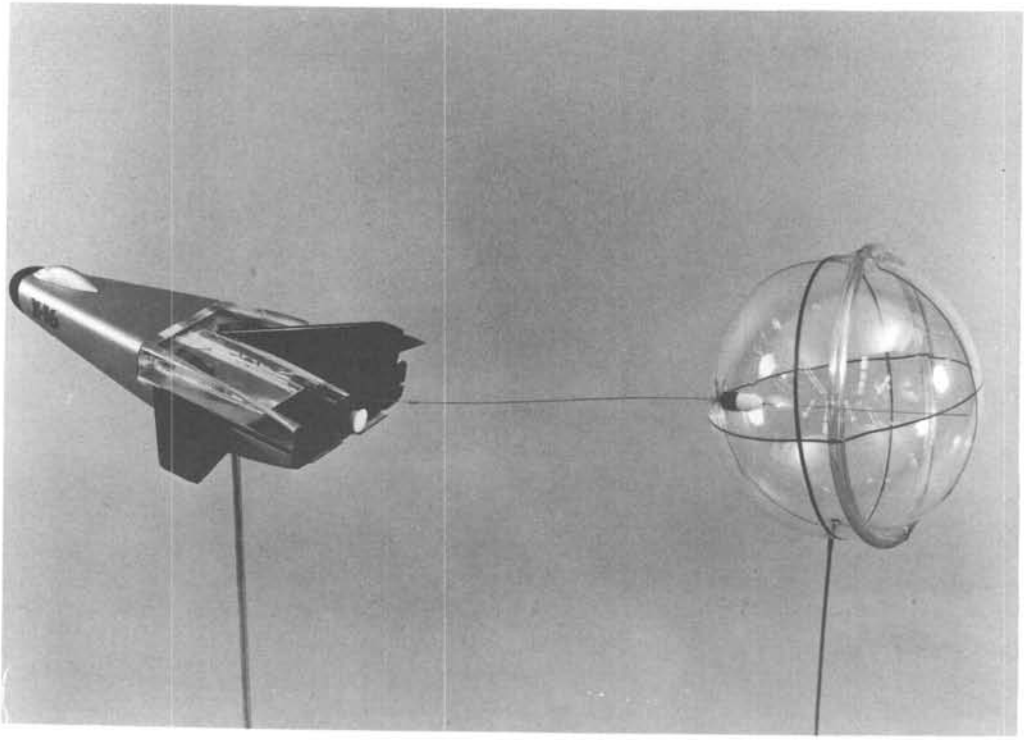


Figure 17. Vehicle Terminal Phase (Drag Force Extending Lifting Surfaces)

Figure 18. Vehicle With Surfaces Extended, Drag Unit Severed, and Afterbody Inflated

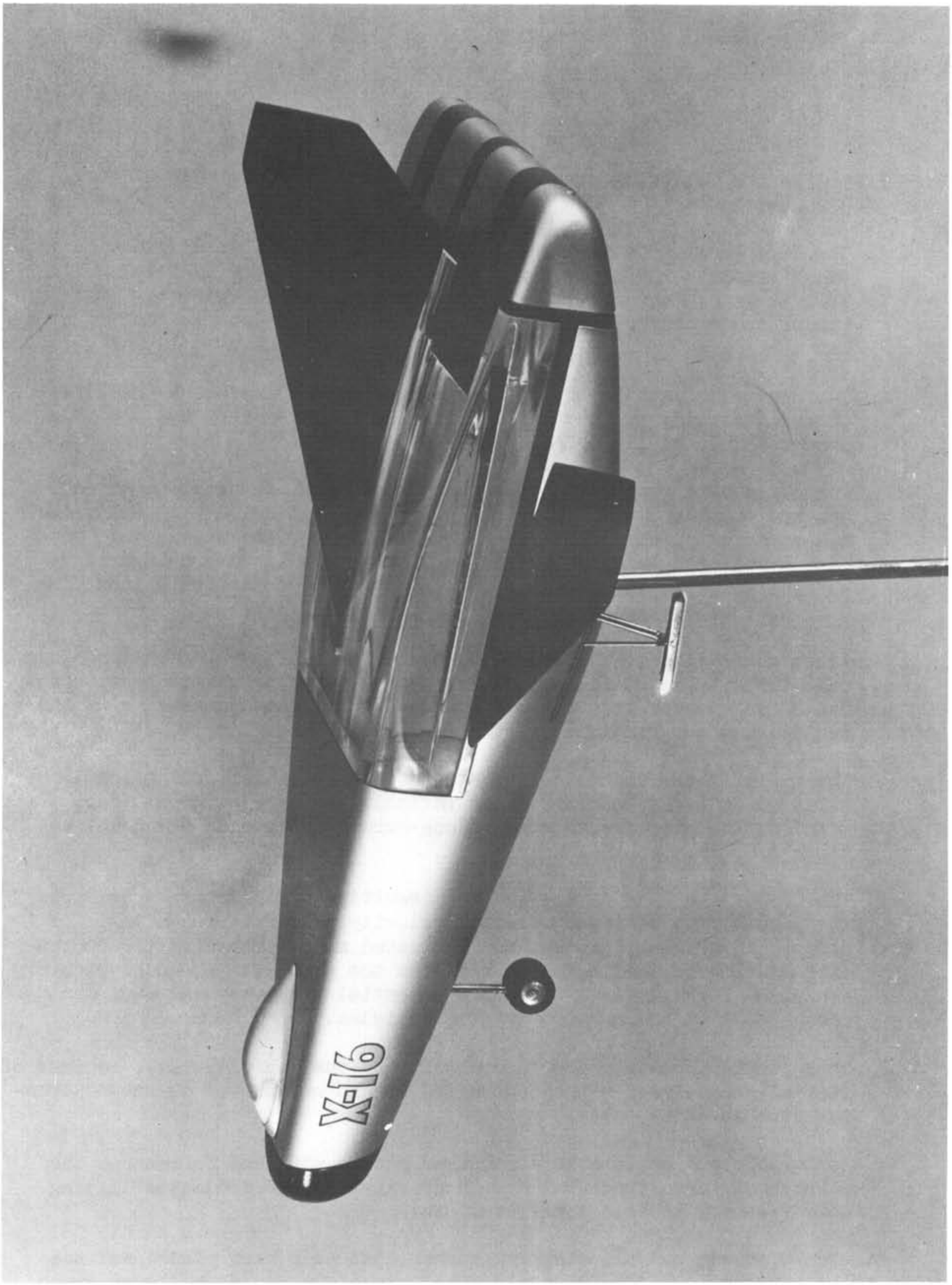


Figure 19. Vehicle Landing Approach

SUMMARY AND CONCLUSIONS

Listed in the following are some of the potential advantages of the presented concepts:

1. The deployment of a trailing inflatable or expandable drag device provides remote aerodynamic drag during re-entry of the vehicle. This results in a potential decrease in required vehicle re-entry angle of attack and a controlled reduction of vehicle aerodynamic heating problems.

2. The remote inflatable or expandable drag device increases the directional stability of the vehicle (reduces required vertical stabilizer area and locates it on the C_L of the vehicle).

3. These concepts remove the requirement for heavy on-board power sources and provide a single, remote, compact, lightweight, concentrated and efficient power source unit for lifting surface extension. This device and associated actuation mechanisms provide a counteracting and self-dissipating energy system that can be initiated at any time during or after re-entry of the vehicle.

4. After completion of the actuation cycle, the inflatable trailing drag unit (ballute, etc) is expendable through severing the cable with an explosive charge, thus increasing the L/D and maneuverability of the vehicle for the remainder of the flight mission.

5. The use of these concepts presents the possibilities for optional re-entry glide paths encountered in variable military or nonmilitary missions that require short- or long-duration descents and combinations of both.

6. The use of the drag device and the resulting L/D increase introduces the possibility of lower terminal velocity, lower approach angle of attack, lower wing loading, and increased maneuverability for conventional airstrip landings. It replaces the elaborate on-board recovery equipment formerly used to reduce potential structure and equipment damage on test and manned re-entry vehicles.

7. They provide booster launch capability of the vehicle, e.g., because of initial shape (with wings contracted it can be mounted on staged booster such as Atlas, etc).

8. Inflatable and expandable structures can be utilized to enhance the aerodynamic and structural design of existing and projected lifting body re-entry vehicle configurations.

Figure 20 points out the stepping stones that have been placed and the goals to be attained. Figure 21 again categorizes the major challenge areas and questions to be answered in the search for mastery of space and space travel.

As in any state-of-the-art advancement, many unsolved problems and undiscovered areas for improvements become evident. These concepts, using inflatable and expandable structures are but a sample of the potential that remain to be developed and expanded.

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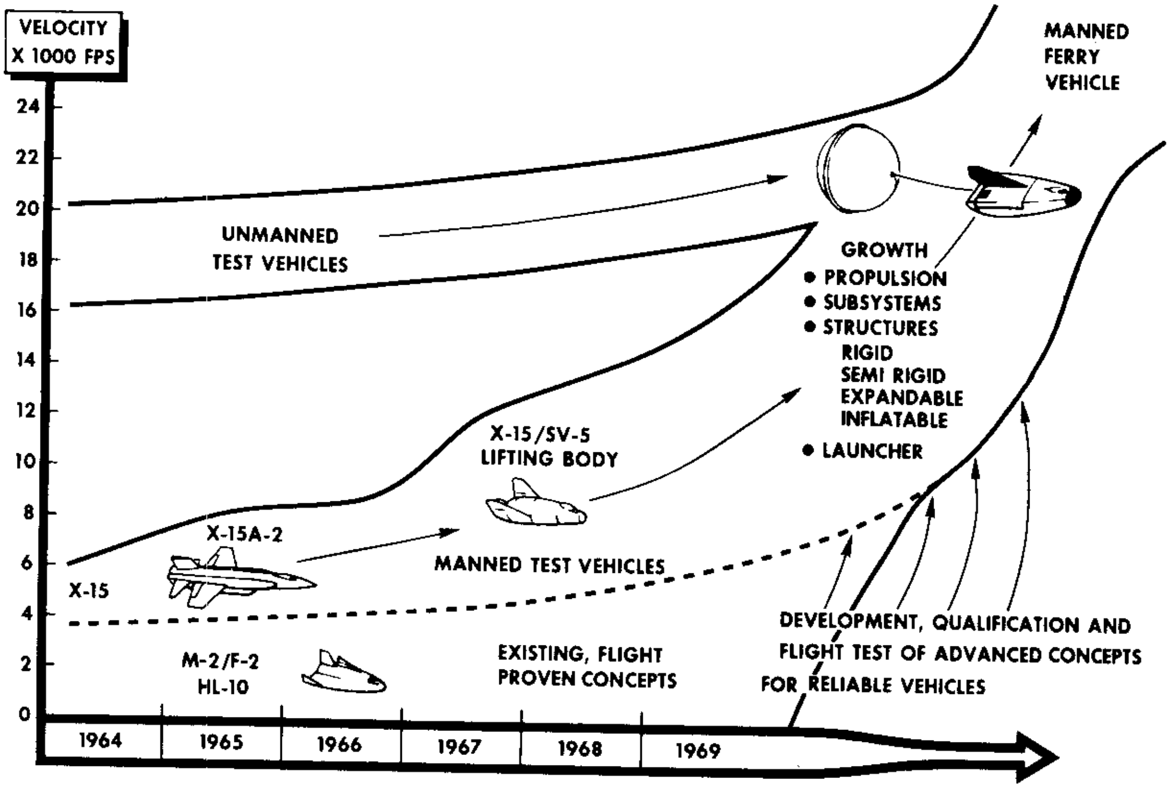

Figure 20. Future Re-entry Vehicle Flight Research and Technology Development

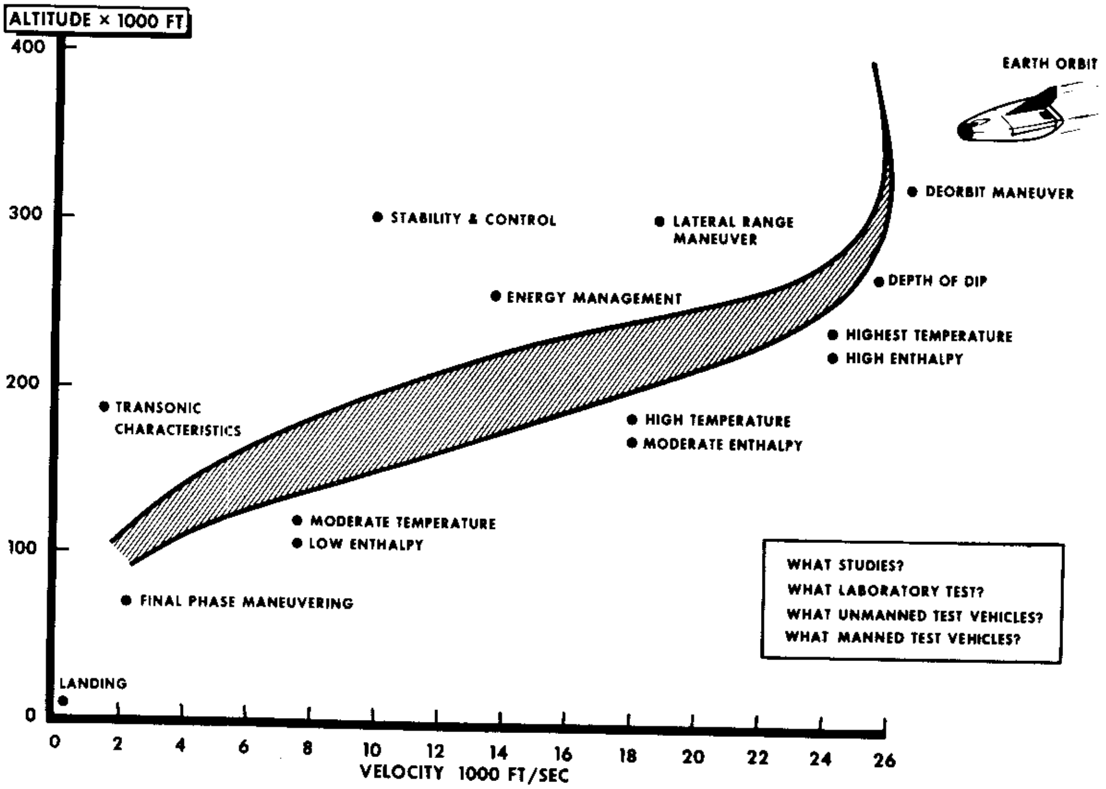

Figure 21. Re-entry Vehicle Hypersonic Environment Major Problems to Solve