AN APPRAISAL OF STRUCTURES TECHNOLOGY - 1964

by

ROGER A. ANDERSON
National Aeronautics and Space Administration
Hampton, Virginia

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Roger A. Anderson
Assistant Chief, Structures Research Division
NASA Langley Research Center

Introduction

The purpose of this paper is to report progress as well as problem areas in the field of aerospace structures and in so doing provide some perspective on the state of the technology. Structural progress is usually measured by the achievement of reliable lightweight designs in the face of new functional requirements and flight environments. Many sources contribute to a steady advance in the art and these have been placed in five broad categories shown in figure 1.

The first two categories - development of more effective construction materials coupled with advances in fabrication and joining techniques - are obviously important. Similarly, lessons learned from operational experience with existing vehicles and the application of new theory and test data have an important influence on subsequent design. Recent developments in each of these areas will be discussed.

The fifth category, new flight vehicle concepts, provides a continuing stimulus and in many ways determines the priority of effort and rate of progress in the previous areas. Because of the importance of this last item, I have chosen to approach this appraisal from the vehicle concept point of view and will discuss, in turn, the technology for atmospheric flight, space flight, and reentry.

Atmospheric Flight

Atmospheric flight provides the major structural design criteria for three types of vehicles - subsonic and supersonic aircraft, launch vehicles, and hypersonic aircraft.

Subsonic and Supersonic Aircraft

The most evident characteristic of current efforts on subsonic and supersonic aircraft is the emphasis on providing reliability and economical performance for useful lifetimes measured in thousands of flight hours. Substantial test programs continue to be conducted in such areas as fatigue crack propagation in components representative of wing and pressure cabins, residual strength of cracked members, and development of fabrication procedures compatible with new materials. A trend toward selection of materials on the basis of favorable fatigue life, tear strength, and corrosion resistance rather than only least weight in a static strength comparison is more noticeable now than at any time in the past.

There has been an extensive evaluation of materials and construction procedures for a proposed supersonic transport. Several titanium alloys offer promise of providing more efficient structures than aluminum alloys although some problem areas require more investigation, the chief one being salt stress corrosion.

An unresolved problem of major proportions for supersonic aircraft is the conduct of proof tests at elevated temperatures. Because fatigue design procedures are not as well developed as those for static loads, it has become customary to subject full-scale aircraft to a simulation of the expected life history of flight loads. As indicated in figure 2, the time required for such tests could mount sharply in the supersonic flight region where elevated temperatures superpose thermal stress cycles on the stresses from flight loads. In this example, the desired life is that expected of a commercial transport. The projection of test time reflects around-the-clock testing with real-time simulation of the thermal cycles. The cost and time involved in carrying out a test program of this nature points out a strong need for continuing efforts to improve fatigue and elevated temperature design procedures.

Launch Vehicles

The construction of large-diameter launch vehicles and a consideration of even larger sizes has stimulated a reexamination of the whole field of shell technology. Empirical design procedures, arising from deficiencies in the analysis of shell structures, have come under scrutiny because of unprecedented shell proportions and complex load and temperature environments encountered during launch.

The basic types of construction and conditions for their least-weight application are illustrated in figure 3. The figure considers only the cylindrical shell and two primary loading conditions, internal pressure and bending moment, but it serves to indicate the variety of construction currently in use. The filament-wound pressure chamber provides an efficient structure for the solid-propellant rocket motor with its high combustion pressures. The high specific strength of glass fibers under tensile loadings and the economy in achieving highly efficient distribution of material with the filament winding process has led to a variety of pressure-vessel applications.

There is increasing interest in the behavior of filament-reinforced composites under loading conditions where substantial compressive and shear stresses must also be carried. Analysis methods have recently been provided for calculating the stiffness properties of composite materials so that some assessment can be made of their structural potential under loading conditions which lead to buckling instability rather than tensile failure.

In figure 4 the weight of filament-reinforced resin monocoque shells is compared with unstiffened shells of several metallic materials. The calculations cover a range of elastic modulus for filaments up to five times that of currently used high-modulus glass fibers. The shell proportions are typical of launch vehicle structure with compressive failure occurring in an elastic buckling mode as illustrated by the photograph of the scale model test shown in the figure. Under this loading condition it is seen that fiber glass shells compete in weight with shells of steel and titanium, but that substantial improvements in filament modulus are required to surpass the performance of the light alloys, aluminum and magnesium.

Beryllium, with its extraordinarily high modulus and low density, is in a class by itself. It is noteworthy that the advantageous properties of this difficult-to-fabricate material are now being exploited in the structure of an upper-stage launch vehicle.

Development of filaments with advanced properties has been under way but no data are yet available on the performance of these filaments in a composite structure. Available data on the performance of glass-filament-wound shells loaded in compression have revealed a shear mode of failure in the resin which inhibits attainment of predicted strength of the structure. These tests alert us to the probability that currently available resin matrix materials may be inadequate to exploit the properties of advanced filamentary materials. Considerably more work is required before the dramatic properties of materials in filamentary form can be translated into structures applicable to the wide range of environmental and loading conditions encountered in flight vehicle design.

Referring back to figure 3, there have been significant developments in two different areas which affect the outlook for application of stringer stiffened and sandwich shells to launch vehicles. One of these pertains to fabrication procedures and the other to new theory and test data.

It has long been recognized that high production costs and lack of reliability have hindered more extensive application of sandwich materials in flight structures. New production processes involving joining by diffusion may help to overcome some of the shortcomings of sandwich construction. Truss core sandwiches of high quality have been produced in pilot plant quantities by a roll welding process which produces sound metallurgical joints between the sandwich elements. It is claimed that the finished panel cost is only slightly greater than twice the raw material cost.

With regard to new test data, figure 5 presents some results for large-diameter sandwich shells with honeycomb core. The data suggest that the strength of properly constructed shells has been underestimated by current design procedures and is indeed predictable by classical linear theory. The figure shows axial buckling load of sandwich cylinders plotted as a function of shear flexibility of the honeycomb core. The dashed curve is recommended for design by MIL Handbook 23 and is based upon the observation that thin-wall monocoque cylinders generally fail at a fraction of the strength predicted by classical theory. Sandwich shells, however, even in the proportions associated with large launch vehicles, are not in the thin-wall cylinder class. Sandwich cylinders are potentially very efficient for many launch-vehicle applications and a clear need exists to establish a more rational basis for their design.

With regard to stringer-stiffened shells, it is customary in aeronautical practice to place the stringers on the inside surface of the shell. An exterior location of stringers to avoid interference with circumferential rings, however, has been used in launch-vehicle construction where aerodynamic cleanliness requirements are not severe. Aside from construction advantages, this change inevitably led to examination of a possible strength advantage for exterior stringers. Comparative tests are in progress with the initial results shown in figure 6.

In this figure are summarized the relative strengths of cylinders of identical cross section but with different placement of the stringers and with two different cylinder length-radius (L/R) ratios. In each case the compressive buckling strength was increased by a factor greater than two when the stringers were on the outside rather than on the inside of the shell $\left(\text{that is, } \sigma_{cr_o}/\sigma_{cr_i} > 2\right)$. Recent theoretical analysis of the behavior of stiffened cylinders which takes into account the eccentricity of the stringers with respect to the midplane of the shell wall qualitatively supports the experimental results.

The foregoing examples are only part of an extensive effort to correct some of the long recognized deficiencies in design procedures for shell structures. This effort has led to new ring-stiffness criteria, refinements in analysis for buckling of spherical shells, and a greatly increased appreciation for the subtleties in specification of shell boundary conditions. The high-speed computer is playing a significant role in the process from the standpoint of encouraging solution of highly complex problems in shell analysis that were previously shunned because of excessive computation time.

Hypersonic Aircraft

Hypersonic aircraft that may constitute one stage of a reusable launch system are still in the structural concept stage and have been given considerable attention during the past year. This type of aircraft provides a difficult challenge for the structural designer because of the combination of a severe aerodynamic heating environment and the requirement for a very low structural weight fraction.

Three of the construction concepts that are being investigated are illustrated in figure 7. Each represents a way to accommodate liquid hydrogen fuel in flight structure which must withstand temperatures in the range 1500° to about 2500° F for substantial flight times. In the hot-monocoque design fuel tankage is isolated from the exterior load-carrying structure by insulation and a carbon dioxide purge system. The purge system is required to prevent cryogenic pumping of air during ground fueling operations. Carbon dioxide frost which forms in the insulation provides cooling by sublimation during the flight portion of the mission.

In the remaining two cases the fuel tankage is integrated with the primary structure and both are protected by insulating shields. Significant weight can be saved relative to the hot-monocoque design. The insulated structure is an adaptation of the technology developed for the X-20 vehicle. The multiwall structure represents complete integration of tankage, structure, and insulation through use of multiple layers of plain and dimpled metallic sheets forming a structural heat barrier. Large-scale structural sections incorporating each of these wall concepts are under construction to assess fabrication problems and to provide suitable models for test under simulated flight environments.

For the stagnation areas of a hypersonic aircraft, the technology involved in producing high-temperature nose cap and leading-edge structure for the X-20 and ASSET vehicle programs should be applicable. A typical example of a high-service-temperature component is shown in figure 8. In this nose cap, a refractory metal backup structure is protected by an oxidation-resistant layer of thoria. Reinforcement of the thoria and attachment to the metallic structure is achieved with tungsten wire and numerous retainer pins. Although cracking of the thoria layer occurs during a temperature cycle, integrity of the layer is maintained by the metallic reinforcement system.

Reusability of high-temperature structures typified by the nose cap is questionable. Because the feasibility of economic operations at hypersonic speeds depends in part on reusable structure, activities related to transpiration cooling and internal convective cooling of stagnation-area structure are of significance. However, a large gap still remains between current experimentation with cooling techniques and practical application to large-scale structural components. Until these and other related technology programs are more advanced, a realistic appraisal of the state of the structural art for construction of a lightweight reusable hypersonic aircraft cannot be made.

Spacecraft

Satellites and deep-space probes launched to date have displayed a wide variety of structural configurations employing both fixed and expandable geometry. The new knowledge acquired during their design and the space environmental data gathered by these spacecraft are now being assembled as design criteria for future missions. The discussion here is limited to technology applicable to manned space cabins and to expandable structures.

Space Cabins

Application of newly acquired data to design of a manned space cabin is illustrated in figure 9 where the required cabin wall weight is appraised in terms of the principal space hazards and as a function of mission duration. Pressure containment is seen to require a constant nominal weight. An evaluation of the assembled data for the meteoroid encounter hazard in near-earth orbits combined with current knowledge of the penetration resistance of various wall configurations leads us to believe that the indicated weight variation with mission duration would provide a high probability of no pressure cabin penetrations. Our knowledge of penetration phenomena, of course, is still limited by the unavailability of data on impacts at meteoroid velocities. Progress is being made in development of particle-accelerator techniques that will more nearly simulate the meteoroid environment.

The long-dashed curves in figure 9 apply to the radiation hazard offered by the trapped protons in the Van Allen belts. The weight required to limit man to a 200-rad skin dose in a 30° inclination orbit is shown for several orbiting altitudes. Both altitude and mission duration are seen to be of critical importance. With our present technology and knowledge of the radiation environment, we are fairly confident that structure designed for the meteoroid hazard will provide adequate radiation shielding for manned operations at altitudes up to about 250 nautical miles for missions of the order of one year (ignoring the artificial electron belt).

The radiation hazard is also a function of orbit inclination. The hazard from trapped protons is slightly less at higher orbit inclinations, but solar protons and galactic cosmic rays penetrating to low altitudes near the magnetic poles may contribute substantially to the total flux. The latter hazards may limit the duration of manned missions during periods of high solar activity. Efforts are currently under way to better assess the effect of random solar events on the structural shielding requirements for manned cabins.

The problem of integrating the many functional requirements for a cabin wall in an efficient design has been studied and configurations of the type illustrated in figure 10 have evolved. The construction shown in the left-hand photograph weighs 2.5 pounds per square foot and is believed to be compatible with the hazards to be encountered in a low orbit. A corrugation-stiffened outer wall of aluminum alloy carries the launch loads and serves as the meteoroid shield for the pressure-tight inner wall. Coolant passages, which carry excess heat from the cabin to the outer wall for radiation into space, are also protected from the meteoroid environment. Lightweight superinsulation consisting of many layers of thin aluminized mylar is used for thermal insulation between the interior and the exterior surface. Although not indicated in the figure, the distribution of material in the pressure wall should be designed to provide a high resistance to crack propagation.

The wall design shown in the right-hand photograph of figure 10 is dominated by a severe requirement for radiation protection in the higher orbits and weighs 10 pounds per square foot. This weight is more than adequate for all other functions. The space between the inner and outer wall is filled with a hydrocarbon plastic for efficiency in stopping protons. It also provides the thermal insulation for the cabin.

Expandable Structures

An evaluation of recent literature reveals a substantial technology in methods for deployment in space of folded or packaged structures and their subsequent rigidization. Various techniques such as inflation by release of stored gases or subliming solids, and release of the stored potential energy of the packaged structure have been developed and applied in existing spacecraft. Procedures have also been developed for conducting preplanned brazing of joints in structural members that were launched in a folded configuration. Novel techniques for stabilizing fabric structures with plastic foams which are activated and cured by naturally occurring phenomena in space, such as vacuum, solar heat, or ultraviolet radiation are also being explored. Much of the latter effort appears to be oriented toward possible application to space shelters, lunar construction, and reentry deceleration devices.

Another portion of the expandable space structures effort is directed toward the problems of erecting large antennae for communications and solar energy concentrators for solar power conversion devices. In these instances we are dealing with structures in which rather precise geometry is required in the expanded condition. The problem of achieving highly accurate surfaces with lightweight construction can be illustrated by reference to the solar concentrator development program.

Figure 11 shows the efficiency with which solar energy can be collected and focused onto the heat absorbing element of the power conversion device as a function of the required temperature of the absorber. Three state-of-the-art expandable designs for reflecting mirrors are compared with a one-piece paraboloidal mirror of electroformed nickel which has near perfect geometry. The curves for the expandable designs are based on data from 5- to 30-foot-diameter working models of flight-weight construction. The loss of efficiency of the expandable designs relative to a one-piece design is attributed to fabrication and structural problems, such as control of distortion along edges of petal designs and difficulties in obtaining accurate paraboloids by inflation techniques. Some structural problems common to all concentrator designs are handling, vibrations in the launch environment, and thermal distortions in the space environment. Degradation of the concentrator reflective surfaces in space is another problem of undetermined magnitude that requires additional investigation.

In spite of the problems cited, progress continues to be made in this application for an expandable structure. The attained efficiencies of the expandable solar concentrators at absorber temperatures less than 2500° R are adequate for application to dynamic power systems and it remains to be seen if these efficiencies can be maintained in the 50- to 100-foot-diameter range desired for space vehicles.

Reentry

Current and future space missions continue to confront the field of reentry structures with new problems and goals. Reentry vehicle development as a whole tends to be paced by structures and materials technology with each advance promptly offset by a new and more demanding set of vehicle operating parameters. The net effect is increased vehicle sophistication with structural weight fractions tending to remain constant. Technology developments relevant to vehicles for manned missions and for planetary exploration will be discussed.

Manned Vehicles

In the manned vehicle class, the Gemini spacecraft generally continues the basic structural approach of the Mercury spacecraft. The increased heating duration encountered in its slightly lifting reentry trajectory is more than compensated for by the introduction of an efficient low-density elastomeric heat shield. This development is another milestone along the road to an ablative heat shield suitable for higher lift-drag-ratio entry vehicles.

The extension of the ablative design approach to the entire surface of the Apollo command module is providing a large-scale exercise of critical aspects of the technology; that is, how to deal with cold-soak conditions encountered in the lunar mission and how to design with numerous interruptions to shield continuity in the form of protuberances and access panels. These vehicle programs along with the refractory metal design and fabrication experience contributed by the X-20 and ASSET programs have substantially broadened the technology for future manned mission vehicles.

Current research and development programs suggest that manned vehicles will ultimately have a horizontal landing capability and may be designed for reuse. With current materials, reuse of an entry vehicle implies repair and refurbishment of the highly heated surfaces. Some information on the extent of this problem for metallic surfaces should be provided by examination of recovered test vehicles in the current ASSET program. Design of an ablation-cooled vehicle for economic refurbishment introduces new considerations in materials selection and integration with vehicle structure. This problem has been under study, and ablation materials with relatively easy application and removal procedures have been developed.

An opportunity for practical exercise of these procedures is now being provided in flights of the X-15 research airplane. Figure 12 shows views of a portion of the X-15 ventral fin which has been used as a test area. In the left-hand view, the leading edge of the fin has been fitted with a premolded section of an elastomeric ablator. The pliable nature of the material permits application to complex and irregular vehicle contours without close tolerance controls in the molding procedure. With the use of premolded panels and a room temperature curing adhesive, the procedure can be compared, in principle at least, with the application of rubber floor tiles. The right-hand view shows the test area after return from a flight. The condition of the material reflects the flight environment of the X-15 and is not necessarily indicative of its behavior under high-enthalpy reentry conditions. However, it provides a basis for an appraisal of various procedures for removing degraded material in the field under a simulated operational environment.

Prior to more general application of ablative materials on the higher performance X-15A-2 airplane, a number of coatings applied by both spray and bonding techniques will have been evaluated from the standpoint of thermal protection effectiveness and refurbishment costs and procedures. It is expected that solutions to the practical operational problems uncovered in this research program will further broaden the technology base for reentry structures.

Independent studies of horizontal landing entry vehicles with a hypersonic lift-drag ratio of about unity have provided some insight into the structural approaches for this vehicle class. Figure 13 shows a weight comparison for three approaches. With current materials, both the all-ablative approach as well as one which utilizes nonablative metallic surfaces in lightly heated portions of the vehicle are significantly heavier than an approach which makes maximum utilization of metallic surfaces. In the latter case, refractory metals are operated at the temperature limits imposed by current protective coating technology and, in those vehicle areas where these limits would be exceeded during the entry maneuver, temporary protection is provided by an ablative layer. The attractiveness of the current weight saving in utilizing radiative cooling to the maximum possible extent tends to be offset by the high initial cost as well as refurbishment costs of refractory metal surfaces. Relative progress in both ablative and nonablative materials development suggests that the weight differences between these approaches will tend to become narrower.

Planetary Mission Vehicles

Consideration of unmanned missions to obtain information on the atmosphere and surface characteristics of neighboring planets has stimulated studies of suitable probe and lander vehicles. Uncertainties in atmospheric density suggest that the entry portion of such missions be accomplished with vehicles having unusually low values of the ballistic coefficient m/C_DA. Such bodies permit sufficient time for measurement of atmospheric properties and facilitate deployment of deceleration aids at reasonable speeds and altitudes prior to surface impact.

A recognized problem with entry vehicles of very low ballistic parameter is rapid growth of the structural weight fraction. Analyses have been conducted to determine shell proportions which minimize structural weight growth while retaining the desired high aerodynamic drag and stability coefficients. Figure 14 illustrates the basic principles of these analyses. A conventional blunt nose conical shell develops circumferential compressive stresses under the combined action of aerodynamic and inertial loadings during deceleration. Conversion to a structurally more efficient shape is accomplished by treating the cone as a membrane and solving for shapes which lead to tensile rather than compressive stresses in the side walls under entry loadings. Compressive stresses are concentrated in an aft ring, a condition highly favorable to reduction of weight of the overall design. The resulting shell is basically a tension member having less surface area than the original conical shell as well as significantly higher drag coefficients.

A payload weight comparison for Mars entry bodies employing a conventional and a tension shell design is provided in figure 15. Payload is defined in this instance as all weight not attributed to structure and heat shield. The calculations are applicable to vehicles in the 100-to-400-pound total weight category designed to survive a 26,000 fps entry at any angle between -90° and overshoot. Both curves display the characteristic reduction in payload capacity as the vehicle ballistic coefficient is reduced. However, application of the tension shell design principle is seen to provide a significant increase in payload weight fraction with the greatest benefit accruing at the very low values of the ballistic parameter.

Concluding Remarks

In conclusion, an attempt has been made in this brief survey to provide some feeling for the state of the technology applicable to major classes of flight vehicles. A number of the more critical problem areas confronting people in the field of aerospace structures have been discussed along with some of the contributions to their solution.

Structural advance is seen to be built upon a steady accumulation of experience and new data from many sources, with perhaps the greatest stimulus to technology growth provided by new flight vehicle concepts and availability of new structural materials.

- MORE EFFECTIVE CONSTRUCTION MATERIALS
- ADVANCE IN FABRICATION TECHNIQUES
- OPERATIONAL EXPERIENCE
- NEW THEORY AND TEST DATA
- NEW FLIGHT VEHICLE CONCEPTS

NASA

Figure 1.- Sources for advance in structures technology.

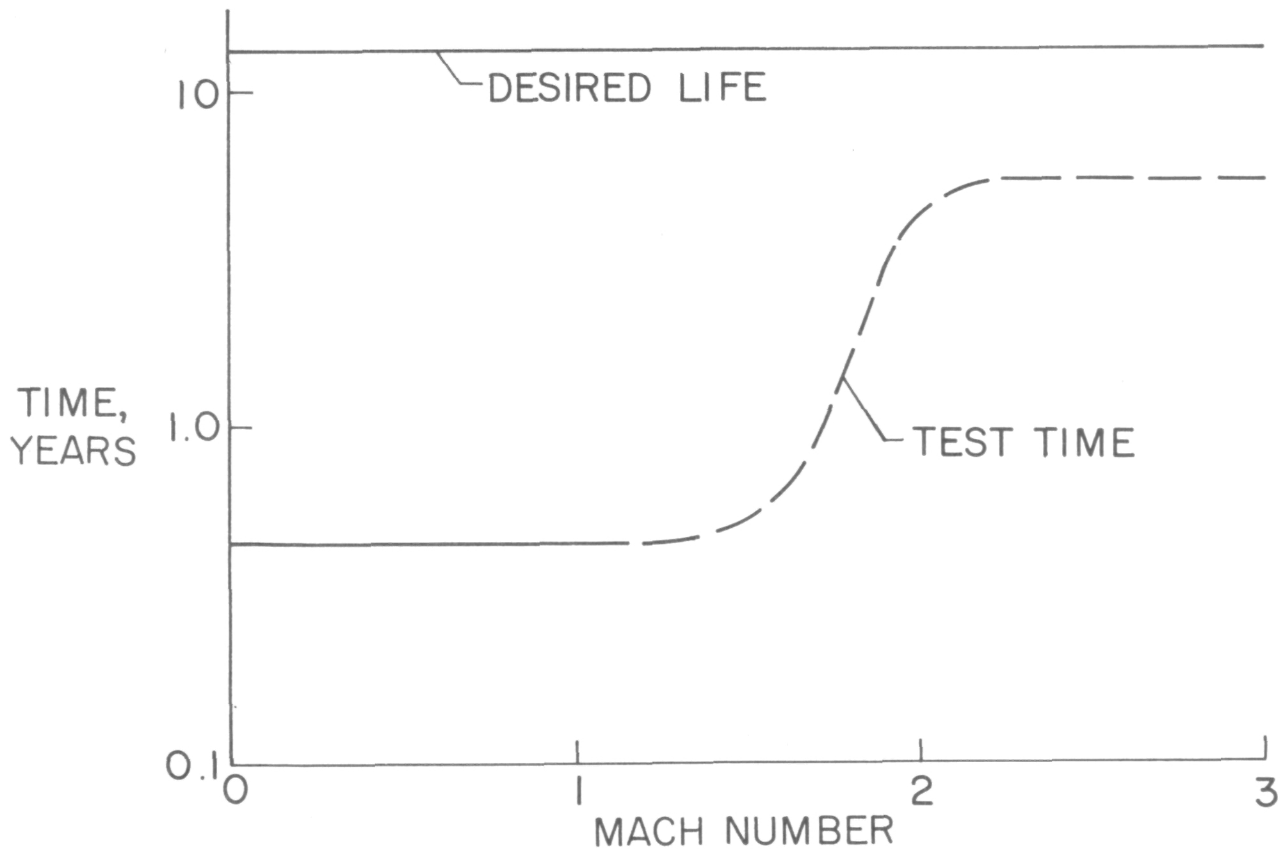

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Figure 2.- Time required for ground proof tests.

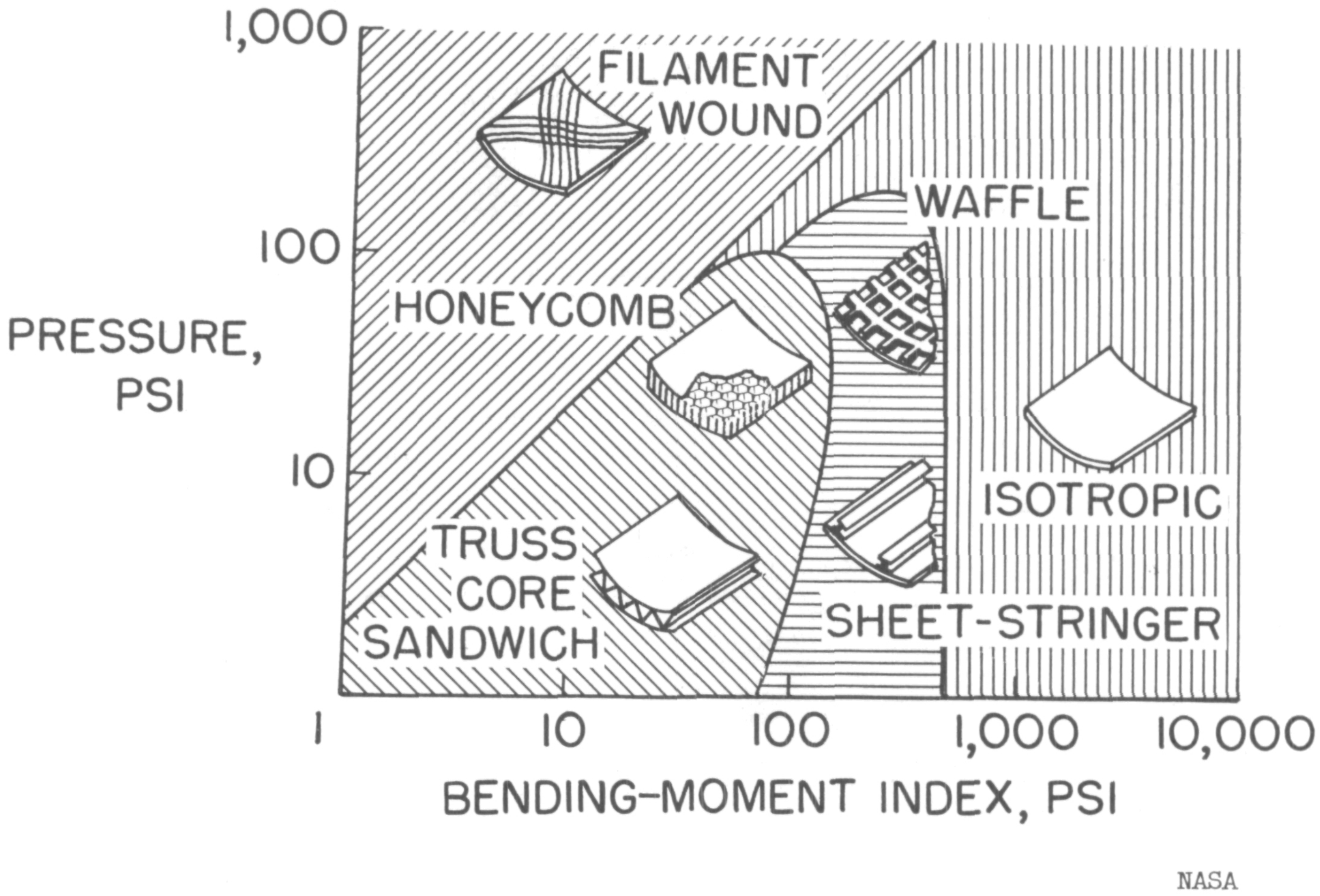

Figure 3.- Efficient forms of construction for launch vehicles.

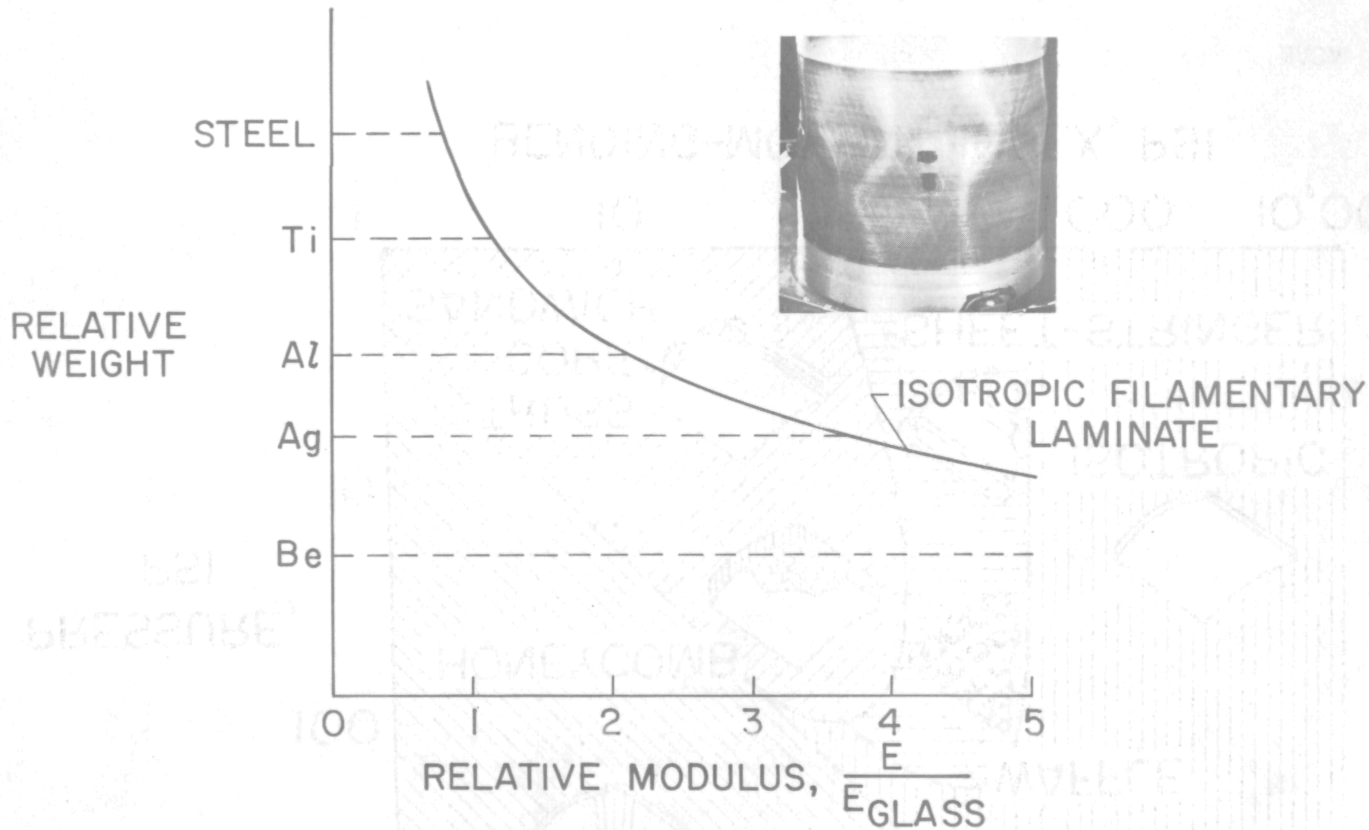

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Figure 4.- Influence of filament modulus on buckling strength of cylindrical shells.

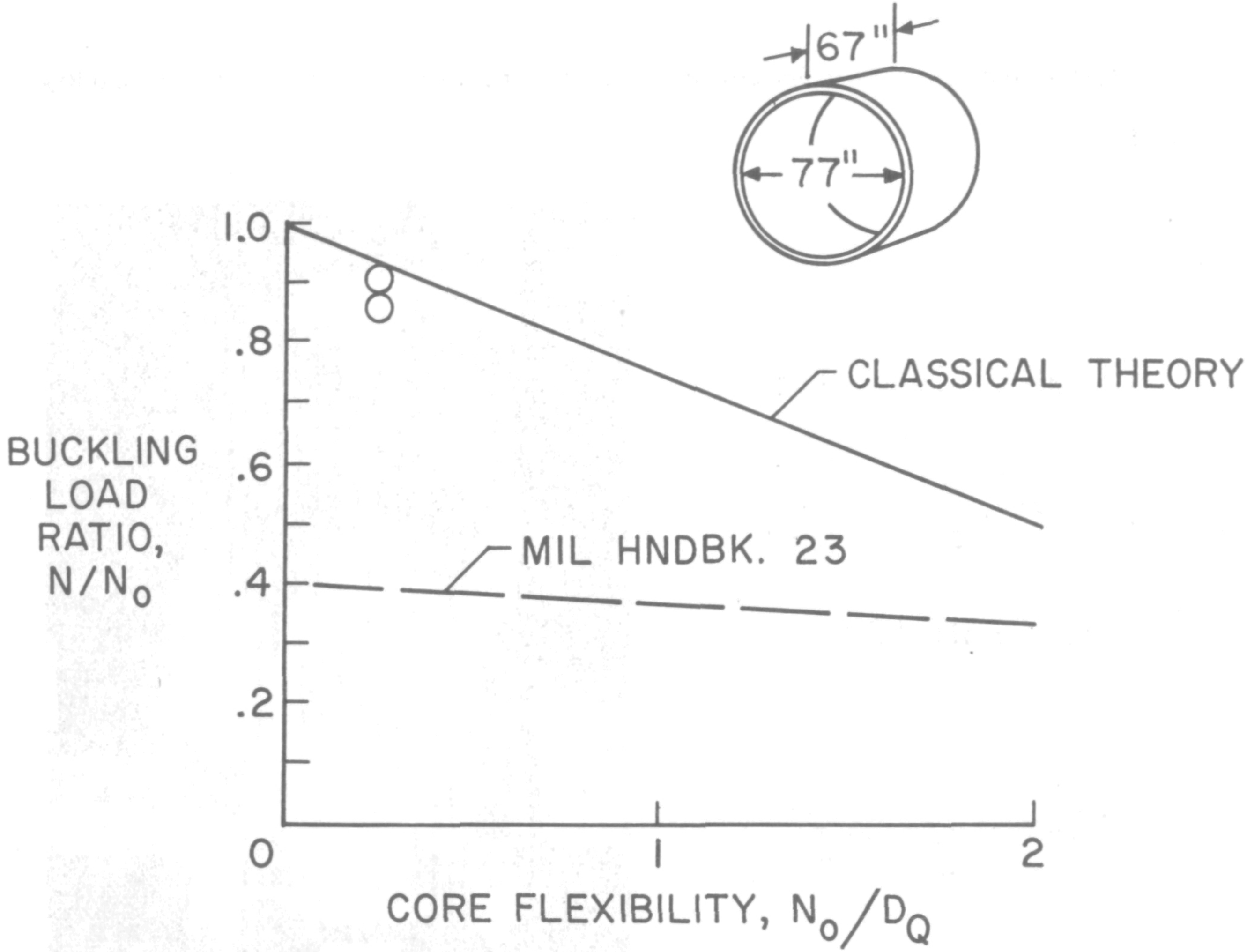

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Figure 5.- Discrepancy between theory and design practice for sandwich cylinders.

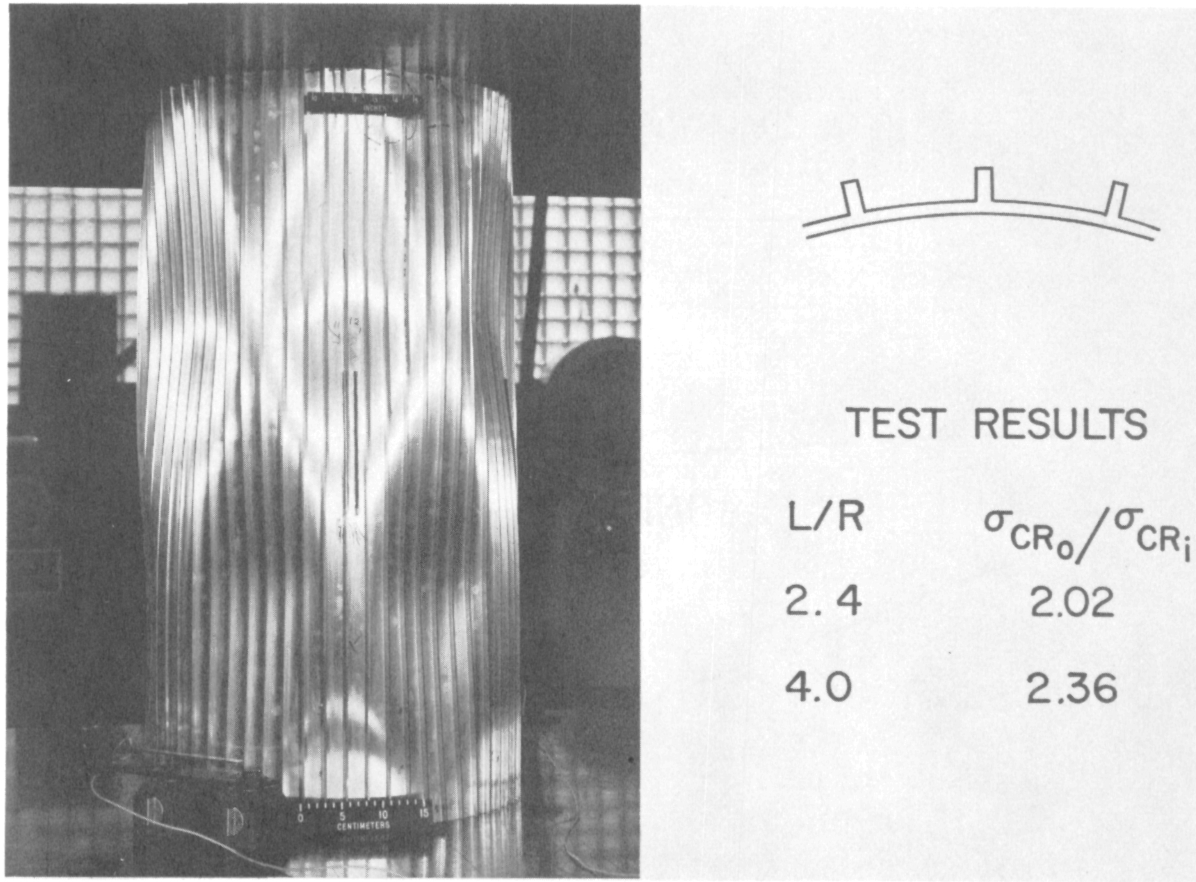

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Figure 6.- Influence of external stringers on strength of stiffened shells.

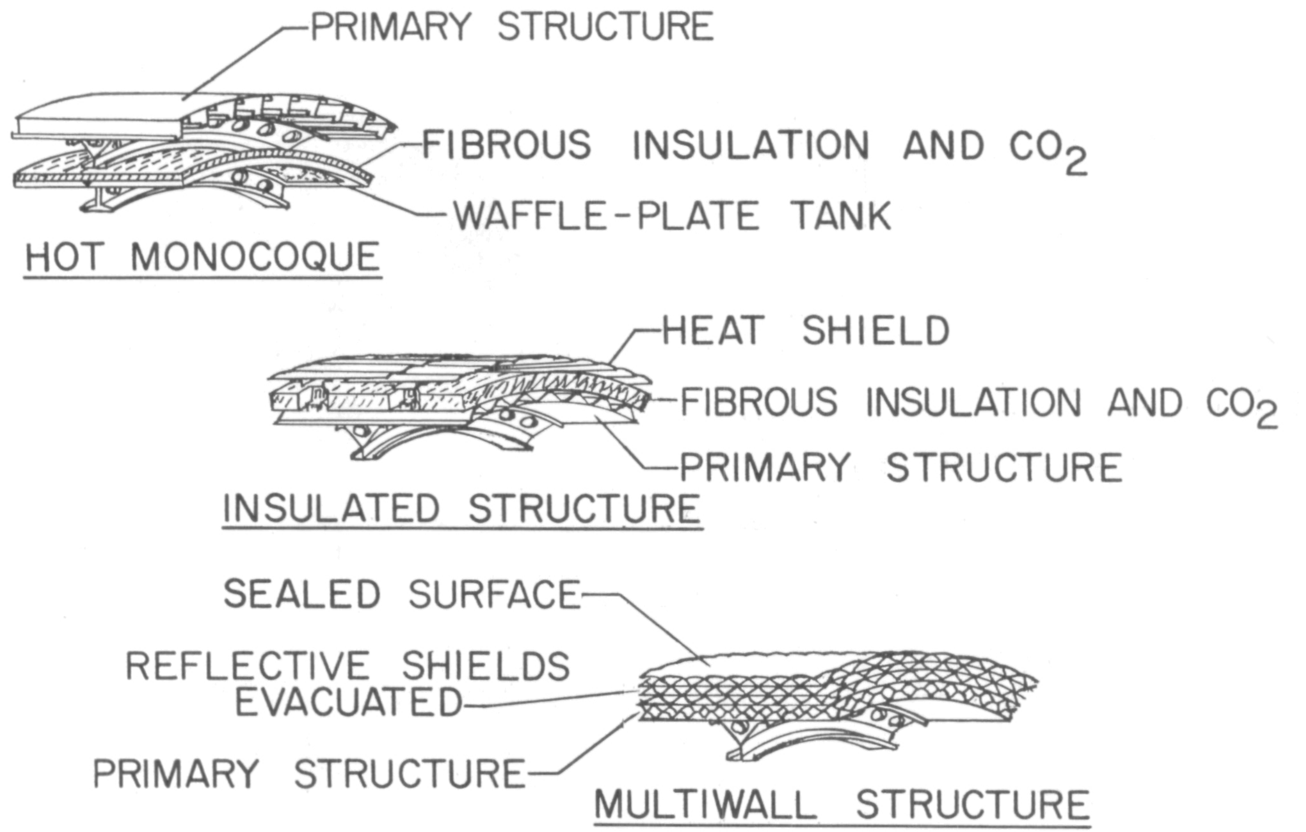

Figure 7.- Structural concepts for hypersonic aircraft.

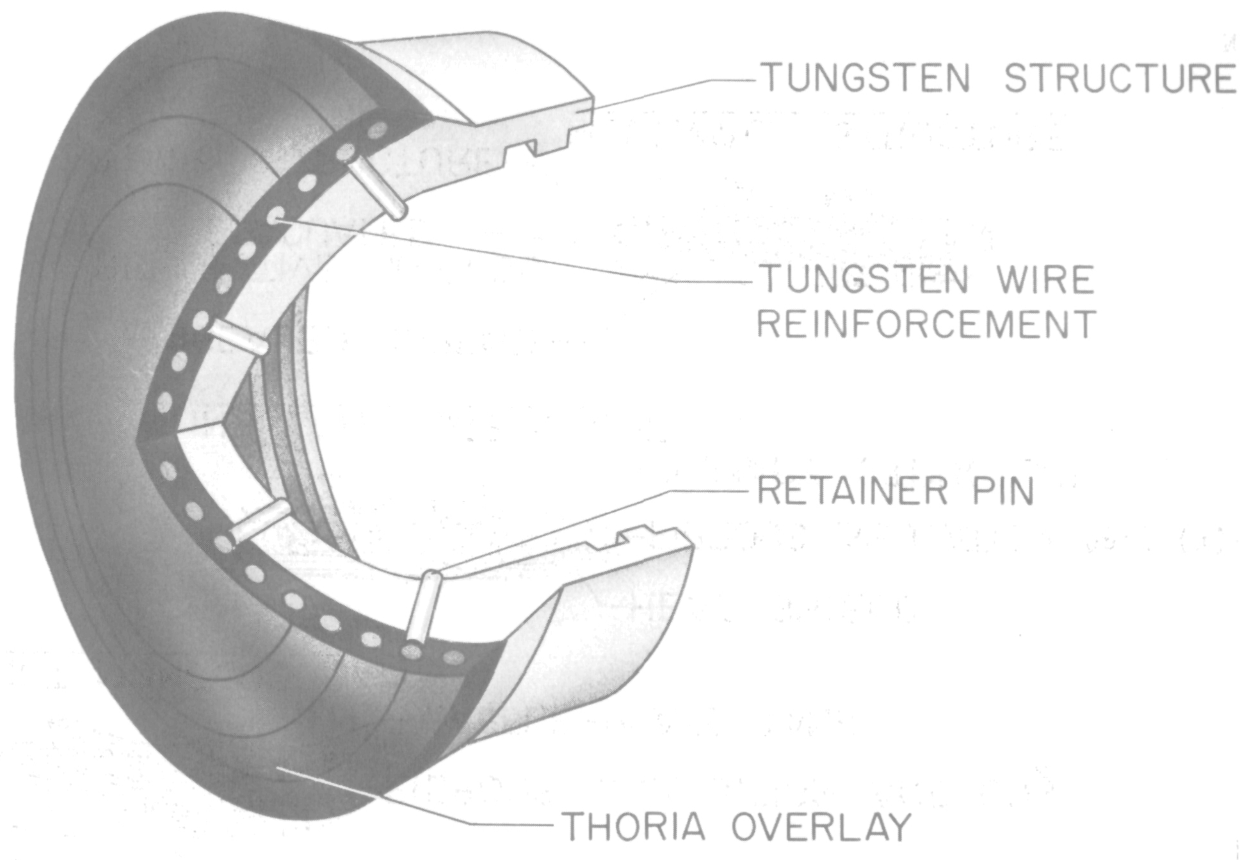

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Figure 8.- Example of high-temperature nose cap construction.

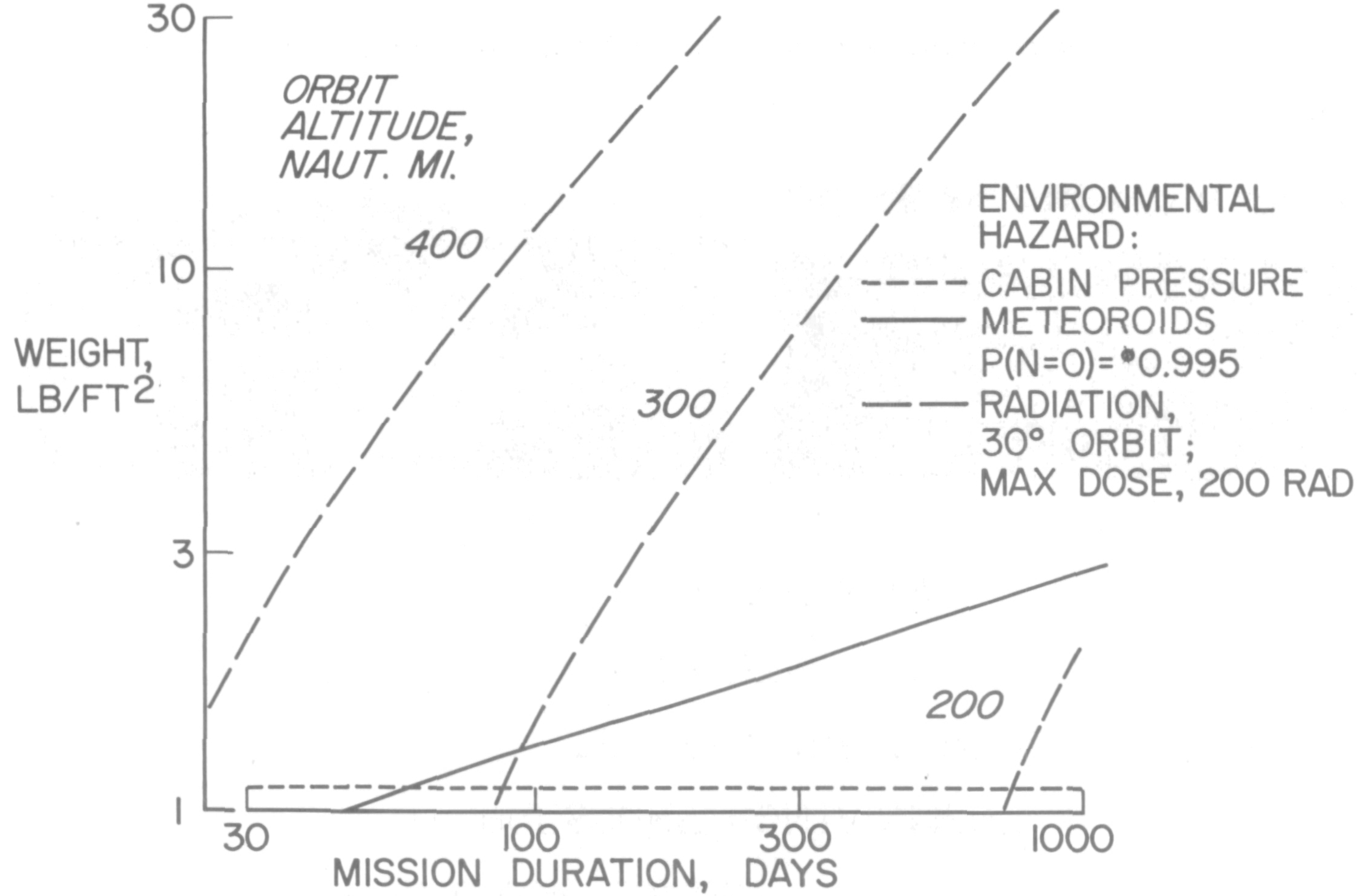

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Figure 9.- Evaluation of space hazards effect on space cabin wall weight.

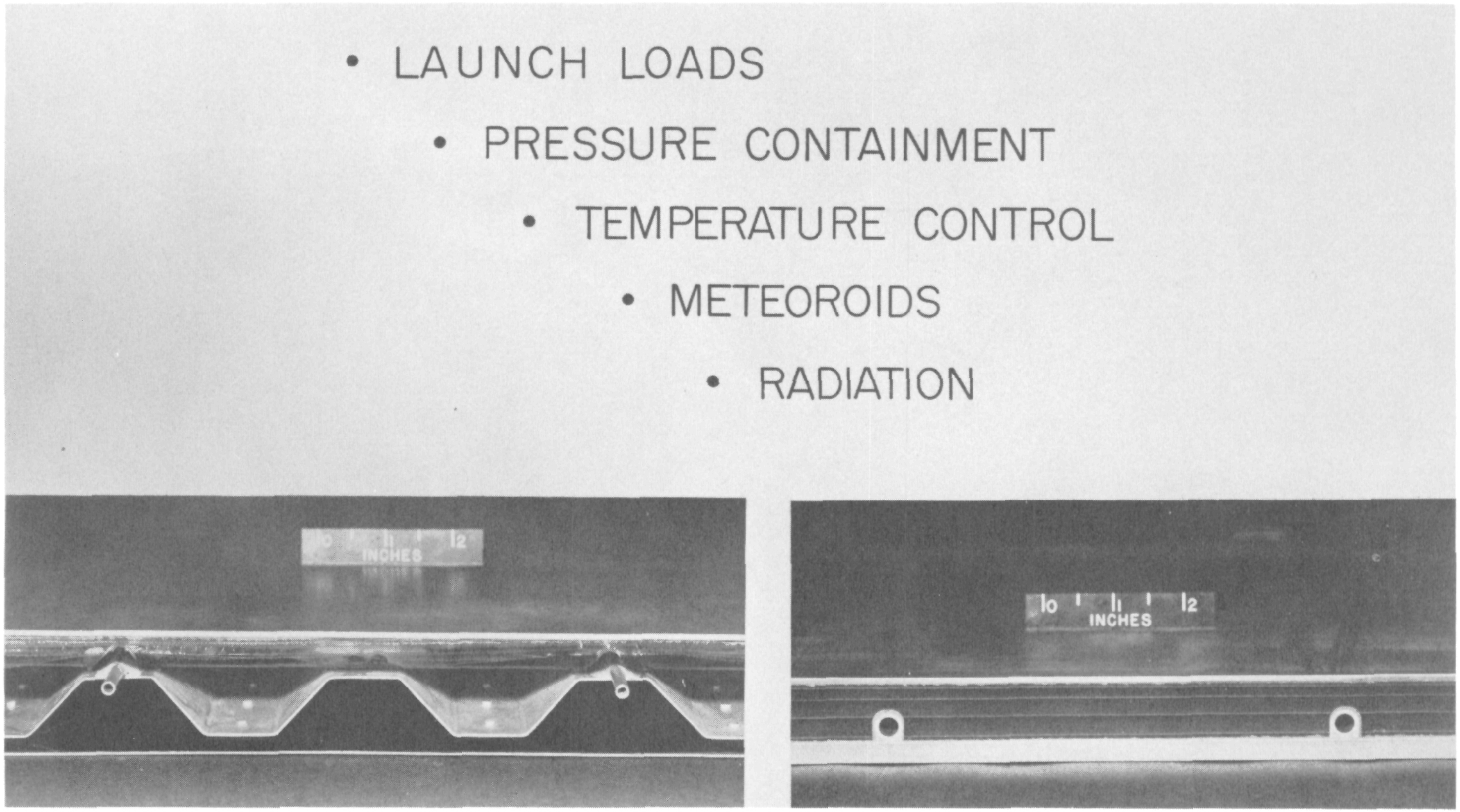

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Figure 10.- Examples of cabin wall construction.

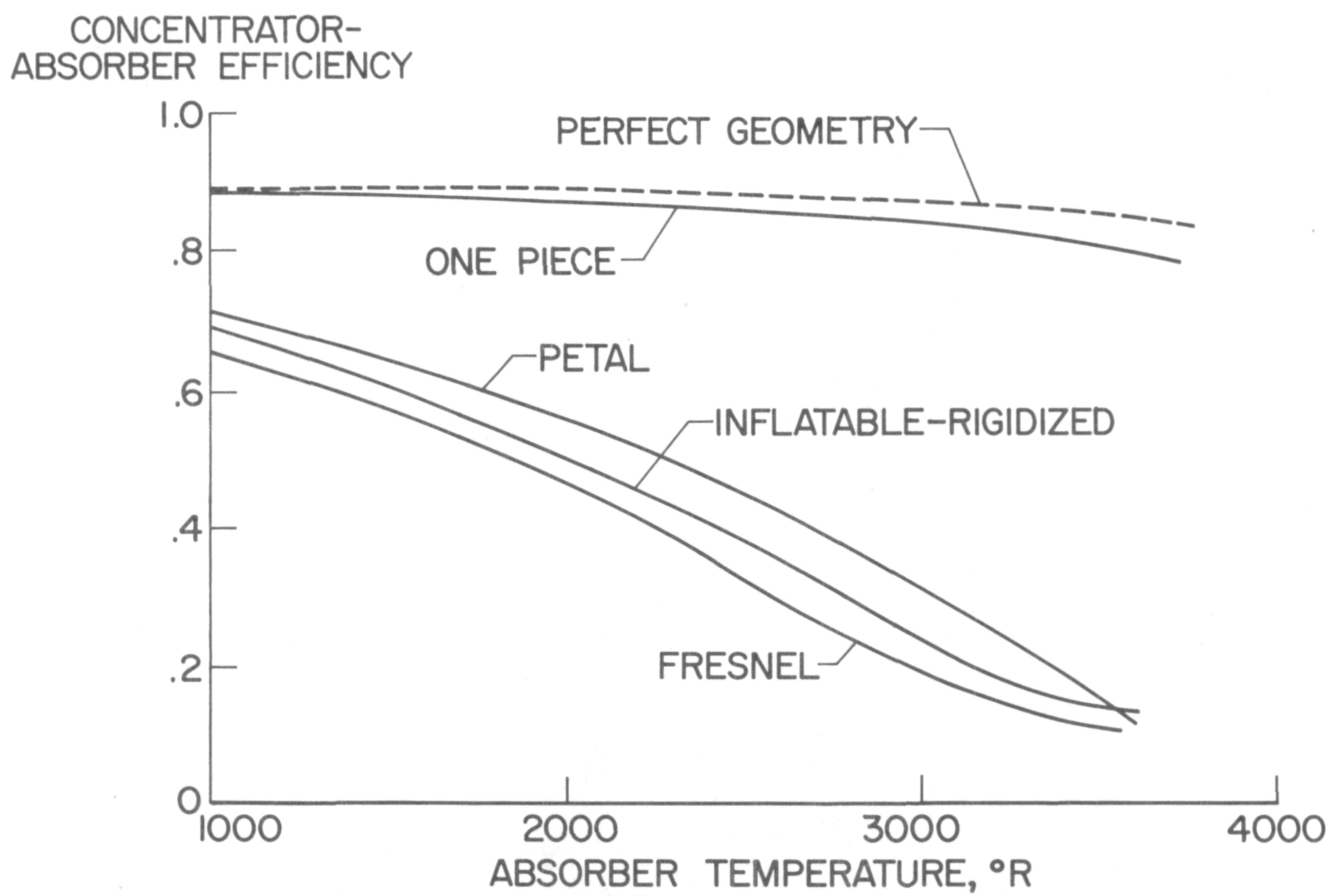

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Figure 11.- Efficiency of expandable and one-piece solar concentrators.

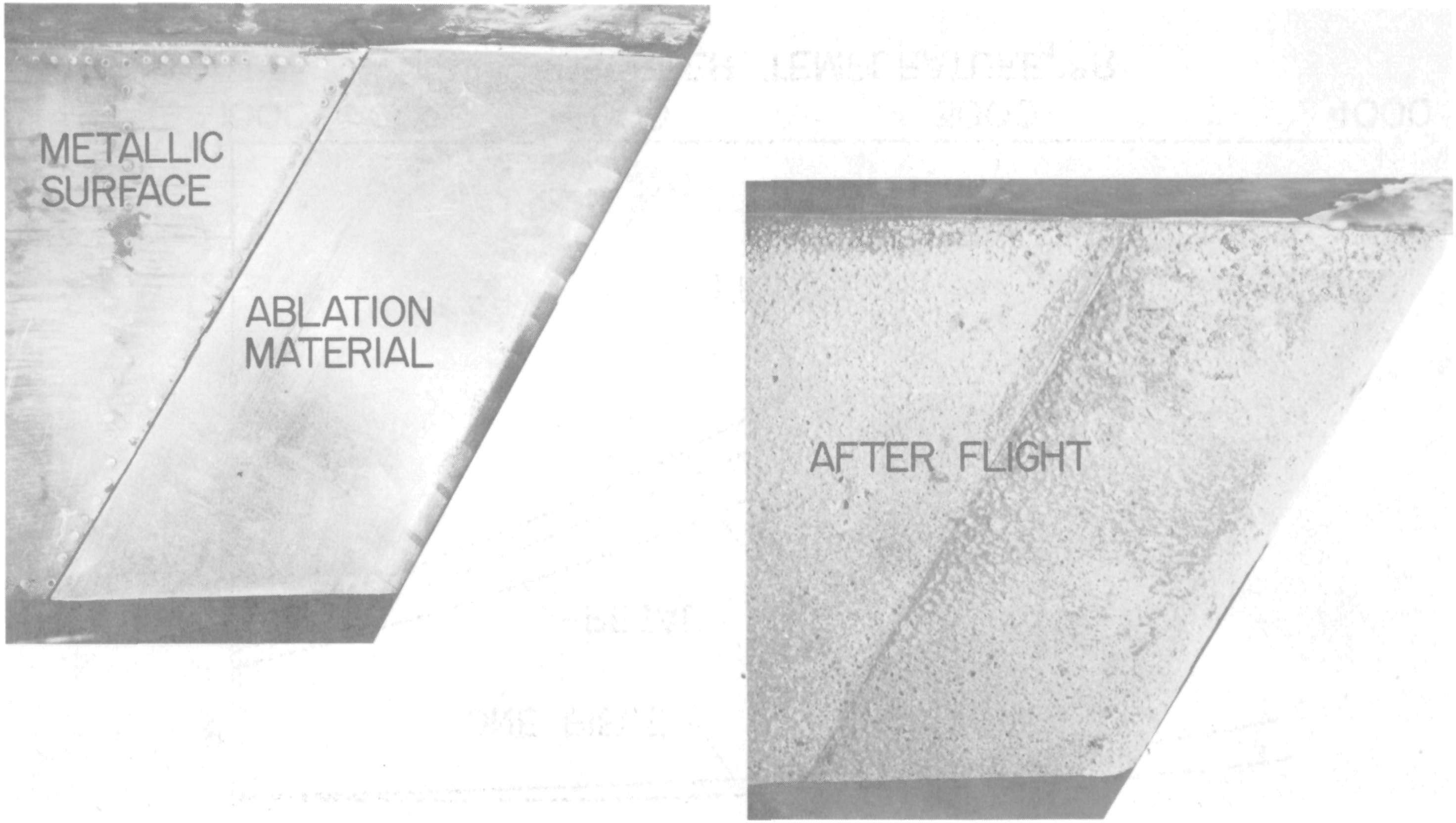

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Figure 12.- Refurbishable ablation system tests on X-15 airplane.

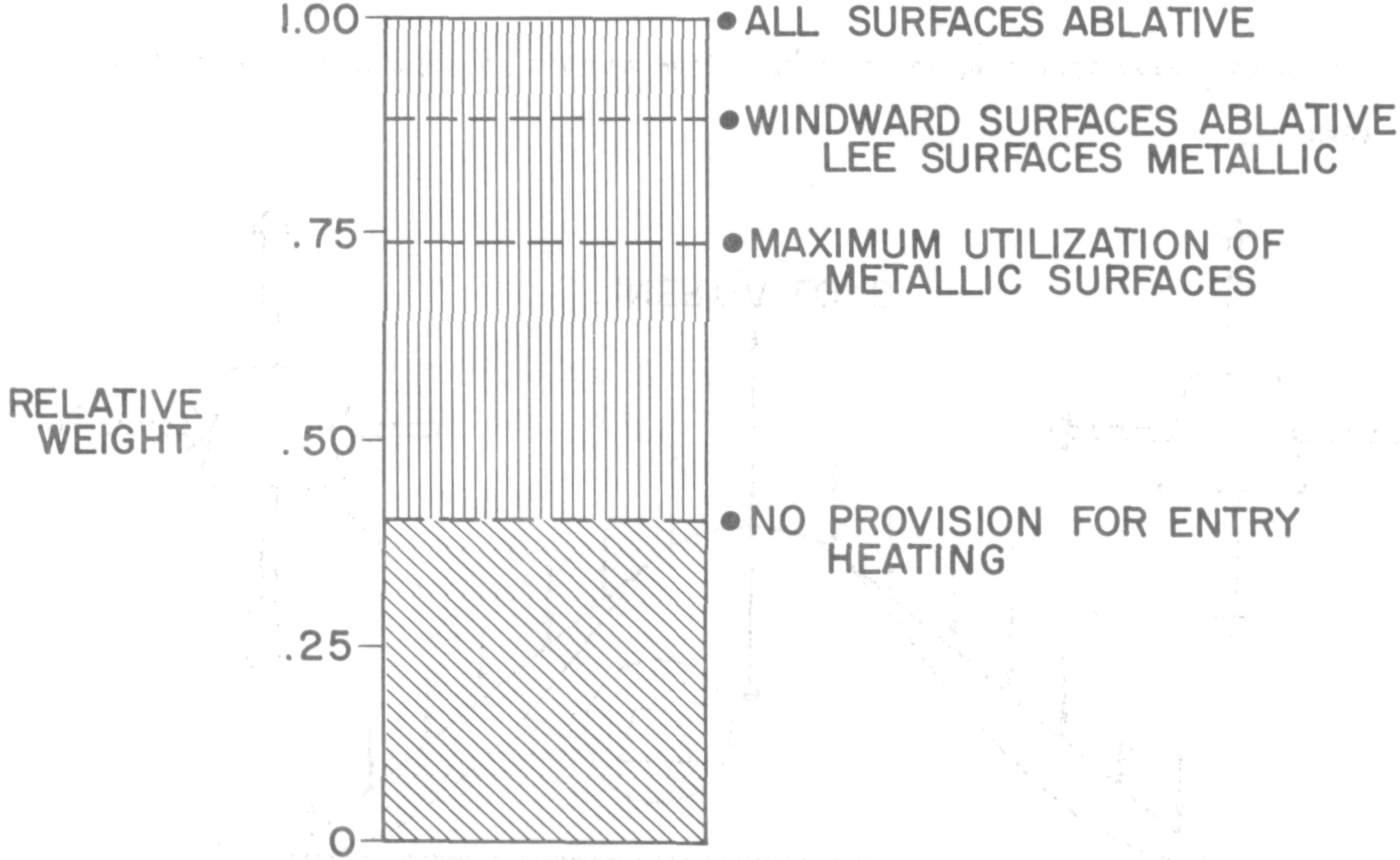

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Figure 13.- Weight comparison of structural approaches for horizontal landing entry vehicle.

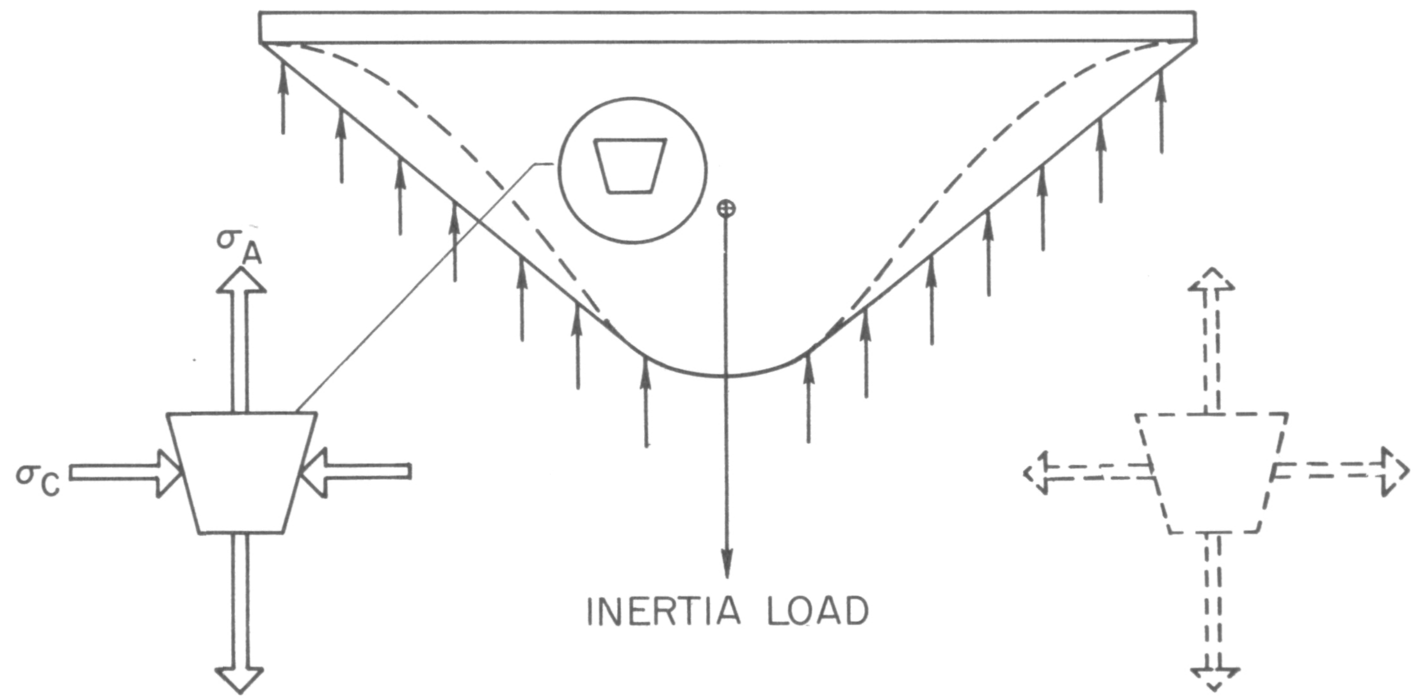

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Figure 14.- Derivation of minimum weight designs for ballistic entry vehicles.

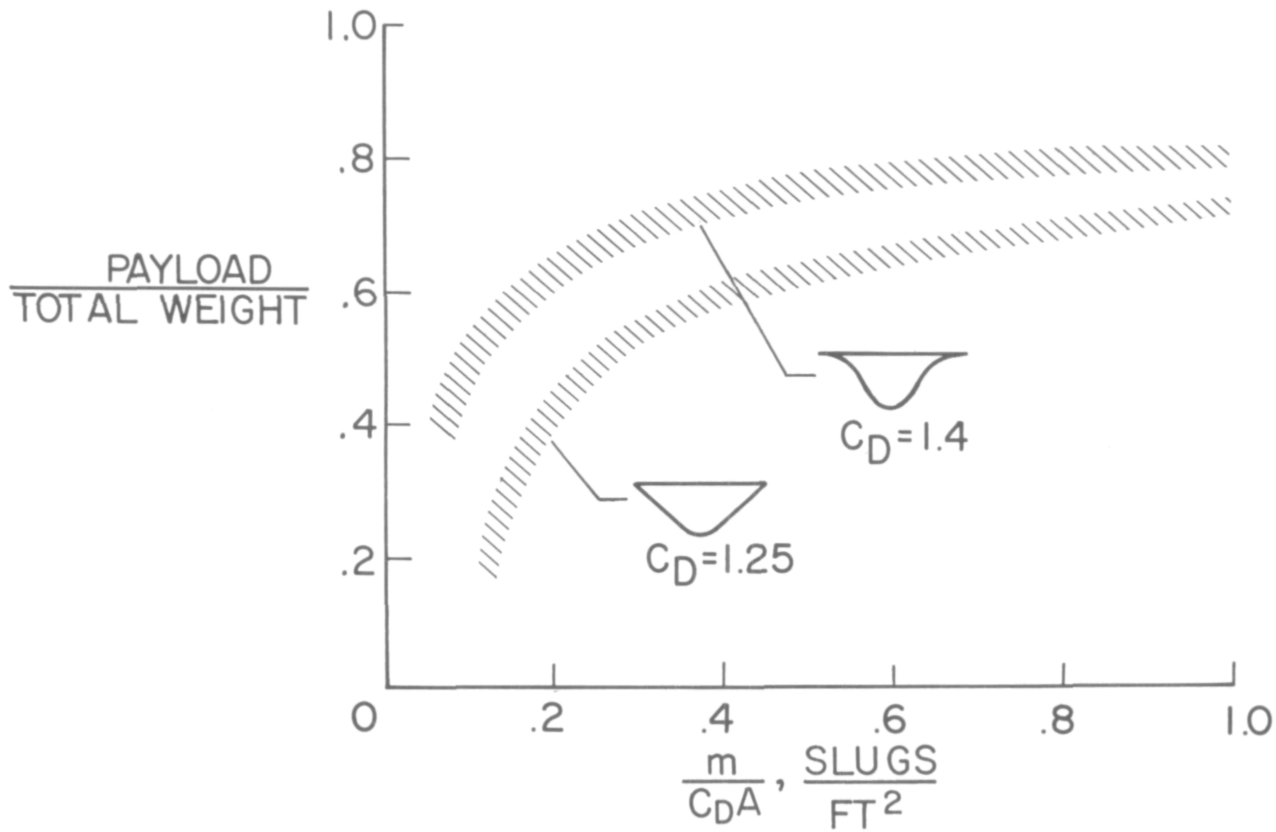

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Figure 15.- Payload weight comparison for entry bodies of low ballistic coefficient.

NASA-Langley, 1964