STRUCTURAL MATERIALS

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The weapon systems of the future represent both the cause and the effect of structural materials research efforts. On one hand, we must obtain the improved materials capability required for these systems, and on the other hand, the feasibility of solving the materials problems in some manner, as indicated by our research efforts, to provide the basis for presenting these increased capabilities with some expectation of attainment.

Thus, in this broad scope, we are concerned with two questions:

a. The changing requirements for structural materials associated with future systems

b. The potential of structural materials for meeting these needs.

At this point we must define ''structural materials'' so that the broader aspect of this discussion may be kept in mind. Structural materials are those which provide the physical embodiment of the component, device, or vehicle, and which carry the loads or maintain the juxtaposition of the component parts. We include materials for wing structures carrying aerodynamic loads, materials for structures that contain or resist the forces of propulsion, or power, materials used to maintain the shape or orientation of the solar collector, the radiator, or the avionic component. The diversity of application of our advanced structural materials validates this definition.

It is apparent that our first question—the changing needs for structural materials—is essentially, how is the sum total of future vehicles and subsystems, performance, characteristics and configuration, different from that which has been done before—as translated into materials terms? Although the first part of the question is difficult, it is straightforward and directly amenable to analysis. The second part, the translation, is most complex because it involves the process of design.

Although the designer molds his article from material, his probable selection and demand on material reflects the compromise of many forces, type and magnitude of loads, volume to be enclosed, minimum weight, temperature and other environmental factors, as well as fabricability, producibility, reparability, cost, etc. Thus exact materials selections for specific structural needs are inextricably intermixed in the compromises of design. This aspect is in itself the subject of a separate presentation. Nevertheless, careful examination of the demands on the designer and his response in past and present problems, we can, and do translate these future systems into requirement trends for structural materials.

Environment, natural and induced, is one of the main factors in design and material selection. It is a useful parameter in the examination and summation of future system requirements. The induced environment reflects the trajectory or path as well as the shape of the vehicle, and the particular requirements for propulsion, power, and avionic subsystems.

With this in mind, we can visualize all aerospace missions divided into three major categories:

1. Suborbital—where we are interested in attaining hypersonic velocities that will permit the penetration of regions up to the lower fringe of space, with potentially rapid return through a carefully prescribed path.
2. Orbital—where we desire to establish our payload as a more or less permanent satellite for a specific mission.
3. Extraborbital—in which we desire to locate in the cislunar, lunar or interplanetary space.

Materials problems are common to all three categories, nevertheless each represents a significant difference in natural and induced environments.

In the sub orbital category, we can launch our vehicle vertically and bring it back through a ballistic trajectory, as for example Atlas, with great speed, for weapon delivery. Or we can build a high drag, smoothly decelerating body which may be manned. We can launch our vehicle horizontally, and bring it back in an aerodynamic trajectory as we now do with the X-15. By the use of aerodynamic lift, we reduce propulsion requirements, gain longer flight time and greater maneuverability.

Consider the next category: an orbital vehicle with a longer duration, useful mission, (figure 2) we still use 2 types of exit trajectories—horizontal with aerodynamic lift, or the brute force vertical take-off, in which the thrust would have to support and exceed vehicle weight. This puts our intrepid adventurer on the orbital highway, looking at the scenery and maybe dodging the traffic. It could also be the way station for a longer range mission, to provide refueling, changing the guard, or transfer of equipment, of a subsidiary vehicle, entering matching orbit in a similar manner, and would have several choices of returning to Earth. This re-entry could be a rapid, hot ballistic one, decelerated in the last minutes in the atmosphere for soft landing, or an aerodynamic maneuverable re-entry to a specific landing field. The specific path chosen would be determined by the ability of the payload to withstand the duration and amount of deceleration, and the ability of the vehicle structure and material to resist the induced environment.

We may consider single or multiple steps to accumulate the extra orbital velocity (figure 3). We could use vertical or horizontal aerodynamic take-off to orbital velocity and then accelerate to extra orbital velocities with optimum propulsion method and trajectory to suit the mission. As indicated previously, we could start our extra orbital mission from an existing way station satellite, or even a handy piece of real estate only 238,000 miles away from us. The extra orbital mission requires the greatest accumulation of energy and potentially the longest exposure to galactic environment.

In each category, we are interested in progressively increased payload capacity, increased versatility and effectiveness of military operation, and lower cost. This connotes such other considerations as reliability, durability, and maintainability.

We can now deduce by inspection that all of our systems will be concerned with the natural environment, and that the extent and duration of penetration of the reaches of aerospace reflect increasing concern with the behavior of structural materials in the less familiar environment.

However, further analysis reveals two more important problems derived from the induced environments:

1. light weight construction
2. extreme temperature resistance

In our analysis we will also see that in many cases, the problems are concurrent, and assume progressively increasing importance in future military weapon systems. Airborne vehicles favor lightweight construction; other things being equal, the lighter the better. The less dead weight we haul aloft the greater the payload. In the aerodynamic lift machine, the conventional aeroplane, the propulsion force needed to overcome drag and deliver payload is only a fraction of the total lift produced. For long range, fuel may be 50 percent of the gross weight, and structure may be 25 to 30 percent, (figure 4). In the vertical lift, propulsion force directly produces lift capacity and overcomes the drag involved in delivering the payload. For sub orbital devices, fuel is 85 percent or more of gross weight and the remaining 15 percent covers payload, which includes structures, guidance and control equipment. Increasing the velocity requirement to orbital and extra orbital values increases the energy requirements by the familiar velocity squared relationship, and therefore the fuel requirements. So, for the expanding scope and payload of future military operation and concurrent with tremendous efforts to increase the efficiency of our propulsion systems, we can see demands for more and more fuel per pound of payload and less and less pounds available for structure.

The temperature problem in our vehicle is closely associated with the projected mission. The great source of heat input to the vehicle occurs during passage through the atmosphere at very high speed, and in the generation of the original thrust.

We remember the shape of the aerodynamic heating curve which indicates the temperatures experienced with increasing vehicle velocity (figure 5). Moving at 3 to 4 times the speed of sound, some areas will be exposed to temperatures of 500 to 1200°F. In the lower altitudes, for this operating regime, propulsion is usually provided by airbreathing engines. Using fossil fuels, the propulsion agglomeration of structural materials encounters temperatures of about 3000°F in the combustion process, and extracting energy from the gas stream at somewhat over 2000°F, under severe vibratory and steady loading.

Velocities to Mach 5 and higher expose vehicle areas to temperatures in the range of 1500° to 2000°F. Concurrently our propulsion system needs higher energy fuels, and process temperatures enter the 3000° to 5500°F range. In addition, we introduce problems of containment of quantities of low density cryogenic fuel requiring relatively large volume containers with insulation to control heat flow into the liquid. If an exotic fuel is used, the increased volume and insulation problem may be traded for compatibility problems. Here we have increased the propulsion energy required, increased the volume contained, both increased and decreased from prior norms the temperature and temperature gradients. Concurrent normally desired increase in range, fuel, and payload,increases burden on the structure.

Let us examine the orbital and extraorbital regimes. Both imply attainment of operating velocities beyond the upper end of our velocity curve. Depending on the velocity, (attitude route used to exit, to orbit, or beyond) our induced environmental temperature may range up to about 2000°F. In this operating regime, we anticipate propulsion systems that will integrate the features of the airbreathing rocket, and possibly nuclear and electric devices, with high energy and exotic propellants, which will involve process temperatures as high as 8000°F; problems of compatibility of materials with propellant, exhaust, and internal and external environment will be multiplied.

The desire to increase payloads, and the greater energy needed to attain the desired velocities, can only result in added demands on the designer to reduce the structural weight fraction, which will consequently make greater demands on structural materials.

The job of absorbing or dissipating energy during re-entry deceleration of obital and extra orbital vehicles, is another facet of the induced environment problem. The path that we chose for re-entry has strong influence on the induced environment, the vehicle configuration and the magnitude of the temperature problem. The quickest return with the greatest deceleration is the ballistic type path which results in the highest peak heat flux. Since the duration is short, the total heat accumulated will be less than for other re-entry paths. Typical heat flux, and temperature levels are shown in figure 6. In cases where more moderate decelerations are required for manned vehicles in which increased maneuverability and fly-back are desired, lifting bodies, figure 7, or glider shapes, figure 8, are used.

The lifting body must operate at fairly high velocity to sustain itself in a controlled path, and enters at a fairly rapid rate in relatively short time. The addition of the "wing" gives increased aerodynamic lift, allows slower re-entry velocities and requires longer re-entry time. For the glider, the peak heat pulse may be lowest, but because of the long time period, accumulates the greatest total heat. Typical values are shown in figure 9, together with representative design configurations.

We must consider at this point that the examination of other subsystems indicate similar concern with light weight construction and extreme temperatures. Thus, high levels of flight vehicle power with more kilowatt output per pound weight for increasingly longer periods of reliable operation, results in higher operating temperatures and structural loading, together with problems of containing the reactive energy transfer fluids.

Our efforts thus have been to indicate the changing and increasingly severe requirements for structural materials in future systems. Before we throw up our hands in despair, let me say that changes in design techniques and significant improvements over a period of time in the capability of structural materials are providing initial solutions to these problems. Nevertheless, we will examine our capability for using present materials to solve these problems. And now, the second problem, the potential of structural materials for meeting the need.

As indicated, the selection of structural material is inextricably intermixed in the compromises of design. It is well nigh impossible to identify one overriding parameter that controls design selection. Strength, weight, and temperature are important factors, therefore these have been used to convey the general capabilities of materials, for comparison with the trends of potential needs.

In this formula chart, figure 10, of tensile strength to weight ratio vs. temperature, we see no overriding trend toward high strength with temperature. Quite the contrary is true. We find that as temperature increases, attention moves from aluminum and magnesium, overshadowed by the tremendous potential of filaments, beryllium and titanium, chrome nickel steels, super alloys, refractory metals and graphite material. Beyond 3000°F we are limited to graphite, tungsten, ceramics, and other still not defined combinations of squares in the periodic table. All manner of combinations of the materials shown may be contemplated also, if optimization of a specific performance parameter is desired.

The trend indicated is significant in another aspect—the increasing difficulty to form and fabricate special environmental protection needs, leading up to the designers nightmare—the brittle materials and the loss of the cushion of ductility.

The contribution of present materials to the solution of our problems, is as follows:

1. There are materials that offer some load carrying ability at high temperature with low strength to weight ratio.
2. There are materials that can sustain exposure to very high temperatures.
3. There are no structural materials that can withstand the very highest temperatures projected.
4. We must look to design alternatives in the use of materials wherever possible, to obtain the future light weight structures.

Where temperature is not a significant problem and our emphasis is on light weight structures, we have many materials and design techniques available. For some of our applications with extreme emphasis on light structure, the inflatable expandable materials may be the answer, figure 11. In outer space, gravity and air density are greatly reduced, and also weight and drag effects. So, we have less need for heavy construction. All that may be needed in our space structure is sufficient strength to hang together in spite of the minor induced loads from equipment operation of crew movements. Thus, for permanent type satellites, way stations, or moon lodges, we can consider some sort of foldable, suitably coated, fabric bag. Lofted into orbit by a booster, it would inflate itself for an active function, possibly carrying only electronic equipment. It may be one of several similar packages to be assembled into something more complex on the site. There are several variants that are being explored in terms of materials for inflatable structures, depending on the function that the structure is expected to carry out. There is the simple, inflatable balloon, such as the Echo experiment, or a functionally configured structure of double wall construction inflated with air, a gas, or a cellular material. We visualize that once in orbit the foaming process to obtain the cellular material would both produce the inflation as well as permanently rigidize the structure.

Configuring materials that could be collapsed, and subsequently expanded to the desired shape,and honeycomb panels are also a possibility. When we refer to fabric, we include: cotton, rayon, nylon, etc.; as well as filaments, or even very fine metallic wire of high strength steel or superalloys, as well as new inorganic fibers such as graphite and metallic oxides.

Alumina, silica, beryllia, zirconia, choria, essentially single crystal fibers, and so we have a potential solution to the requirement for a low strength exceedingly light weight structure, with resistance to increasing temperature levels.

Where load bearing is an important factor, and local temperatures are getting uncomfortably high, we compare the brute force approach using the higher temperature material with other approaches, such as local cooling with ambient air, (this has been done in subsonic aircraft nacelles) or with air or fuel in an active cooling arrangement in airbreathing and rocket engines. Passive cooling arrangements of ceramic insulative coatings may be used to retard heat flow and protect against oxidation.

As the problem becomes more acute in higher heat flux, limited space, materials compatibility duration, and durability, the solution will be that one which results in the least compromise to the weapon system. Where varying degrees of active and passive cooling are considered in conjunction with varied levels of operating temperature, a complex design evolves.

A small amount of cooling may reduce the operating temperature to the point that a new material selection can offer a significant increase in operating stress level. Of course, the effect of the permanent weight of the cooling arrangement must not offset the benefits obtained by operating the new material at a higher stress level. For short durations and modest heating conditions, the materials may be able to absorb the heat input with only a moderate temperature. The extreme of this approach of course involves selecting material specifically for its high specific heat, and hopefully at the same time use it as a structural element.

As the temperature and duration of exposure of structure increases, the alternative is to permit modest increases of structure temperature level. Under severe conditions it may be necessary to operate prime structure at relatively high temperatures 1500 °F and also isolate this structure from the peak heat input with insulations. This also requires that all components, ducts, wiring, controls, etc., in the prime structure area must also operate at this high temperature. Design decisions must also consider the effect of this situation on the overall weapon system. For the short duration peak heating conditions non-reusable ablation cooling has proved very successful, maintaining the prime structure at modest temperatures.

In any case, there will be a very definite and unavoidable price paid for the privilege of operating in these increasingly severe natural and induced environments. Therefore continued pressure will be placed on the researcher to find improved materials. We sense the designer's hope for multipurpose materials—load bearing insulation. There is increasing recognition that ingenious solutions will come from a closer partnership of designers and materials people, gained by the knowledge and experience from all other technologies.

Certainly for the most severe requirements for load bearing and temperature resistance, the designer will have to use ceramics; this multipurpose material, he will use with some design limitations, no doubt. The timing of this occurrence will be influenced by the importance of the need, the alternatives available, and the confidence in the materials developed by thorough knowledge of the capabilities and limitations of the materials that must be used. It thus rests with our materials community to provide the ultimate capability for our future weapon systems.

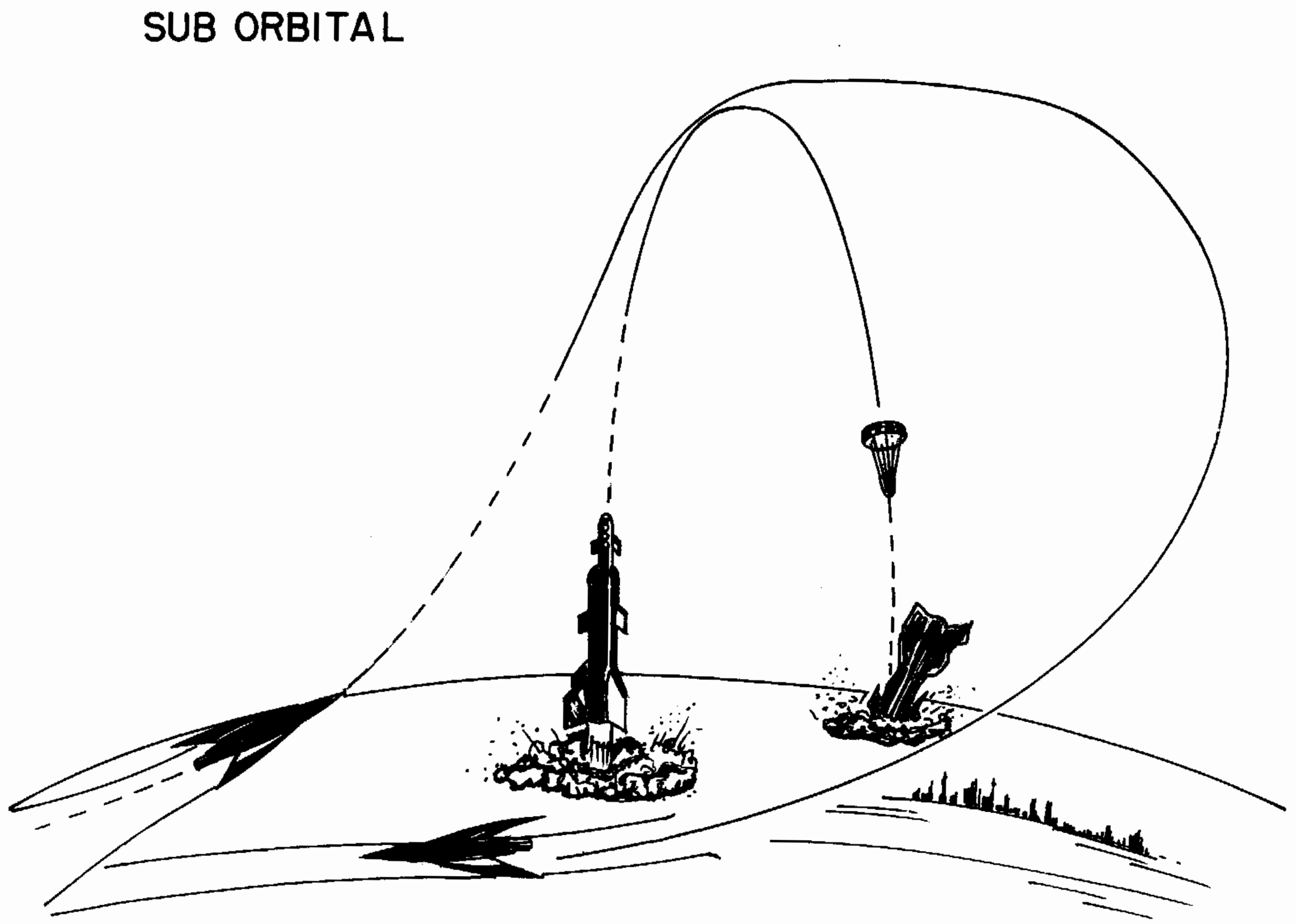


Figure 1.

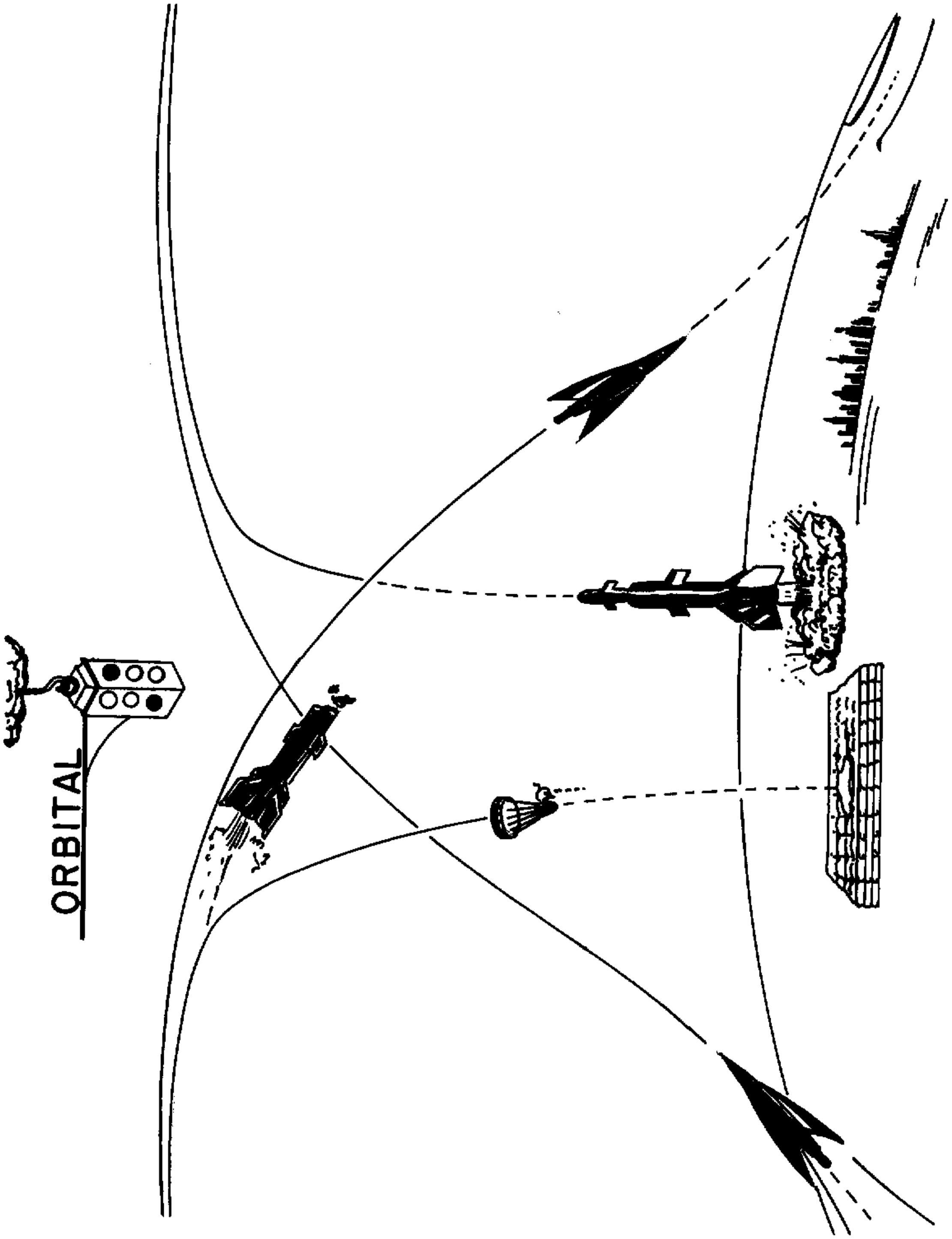


Figure 2.

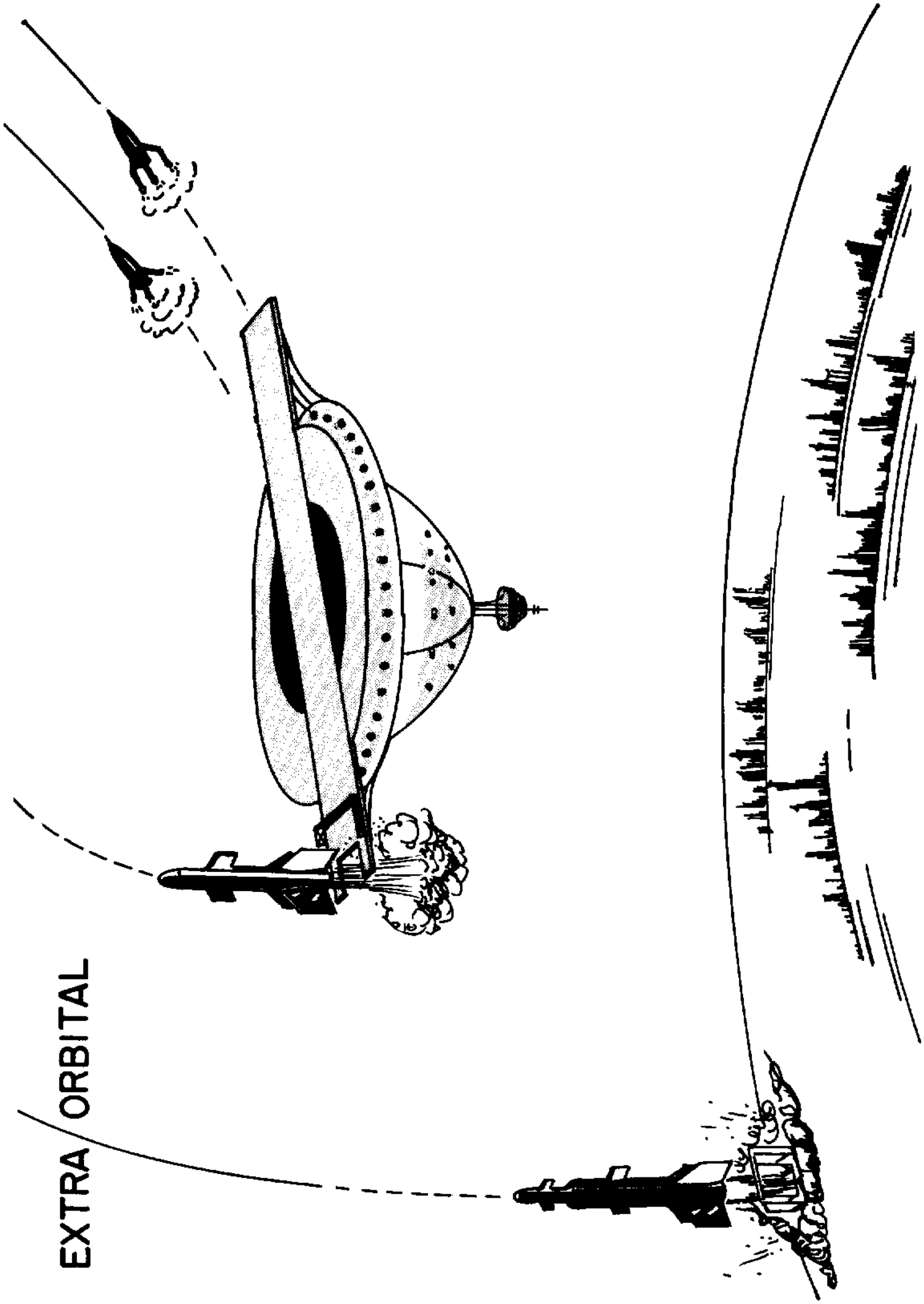


Figure 3.

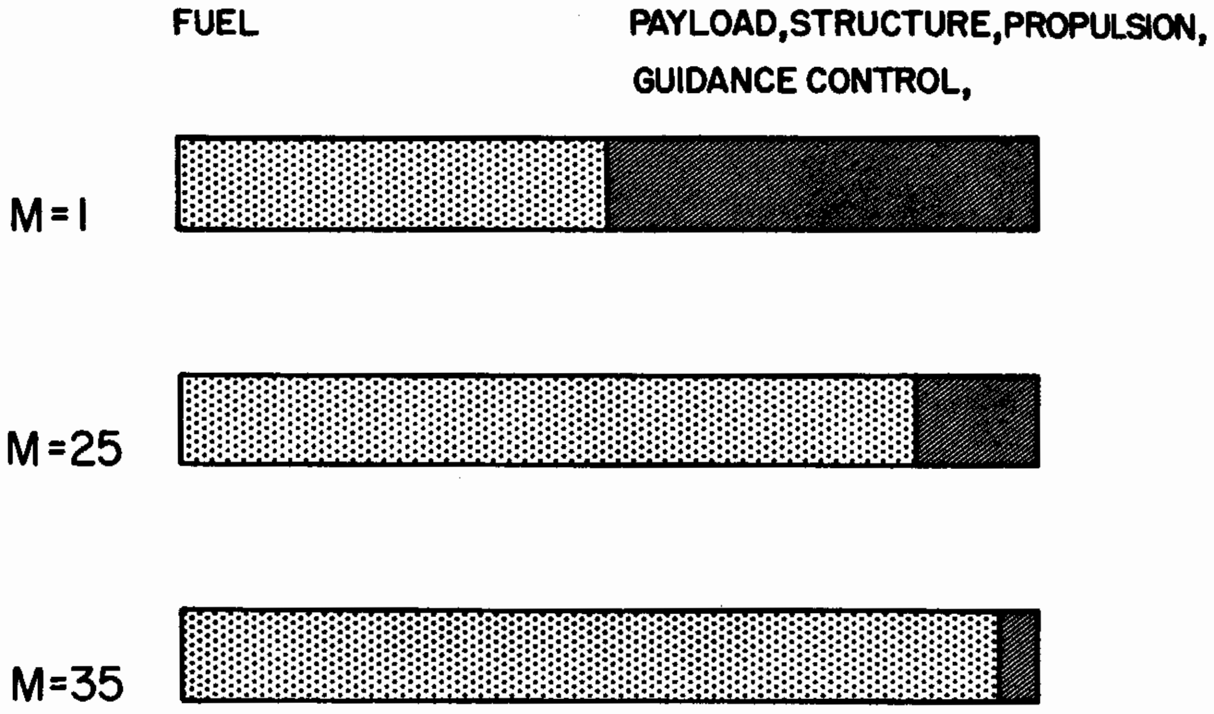
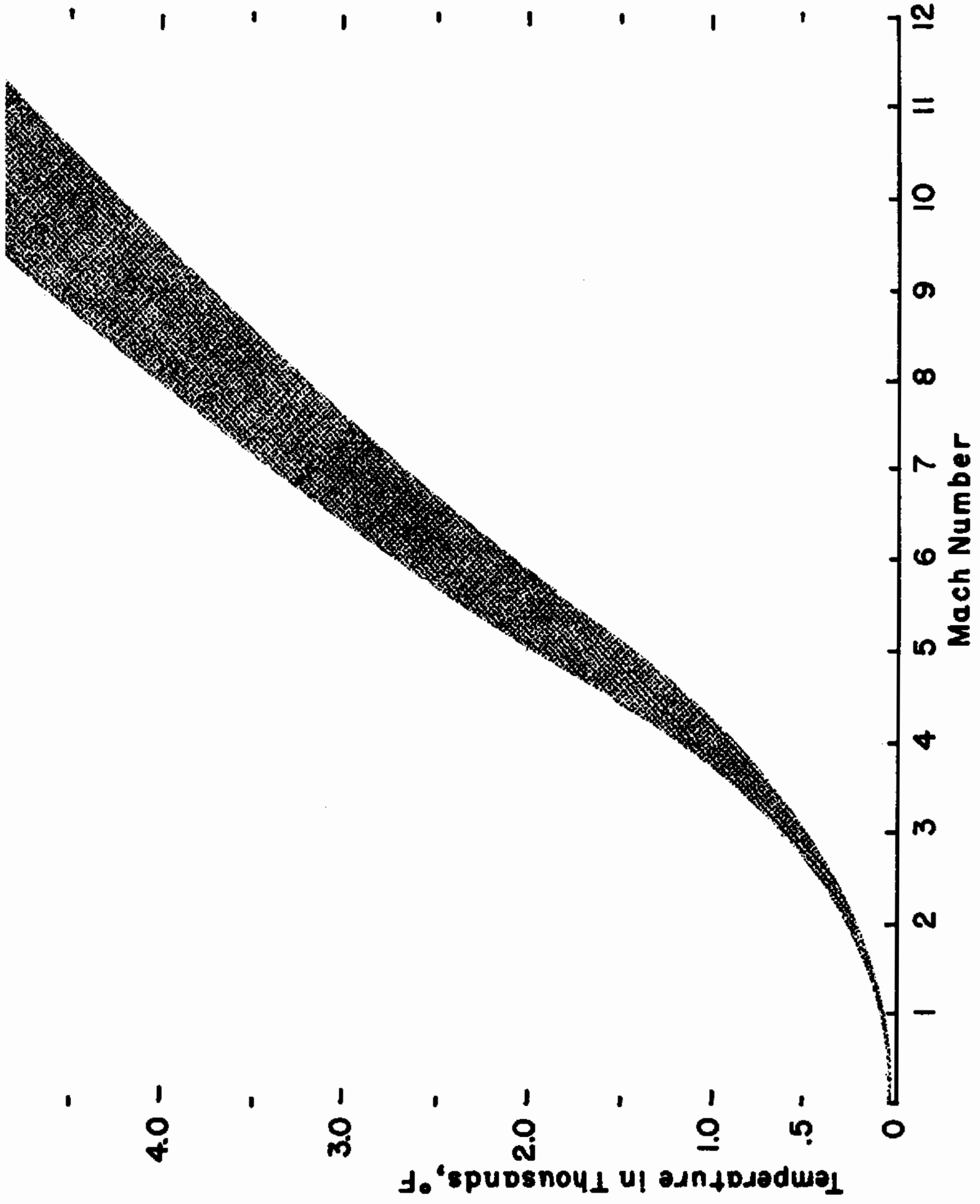

FUEL
PAYLOAD,STRUCTURE,PROPULSION,
GUIDANCE CONTROL,
M=1
M=25
M=35

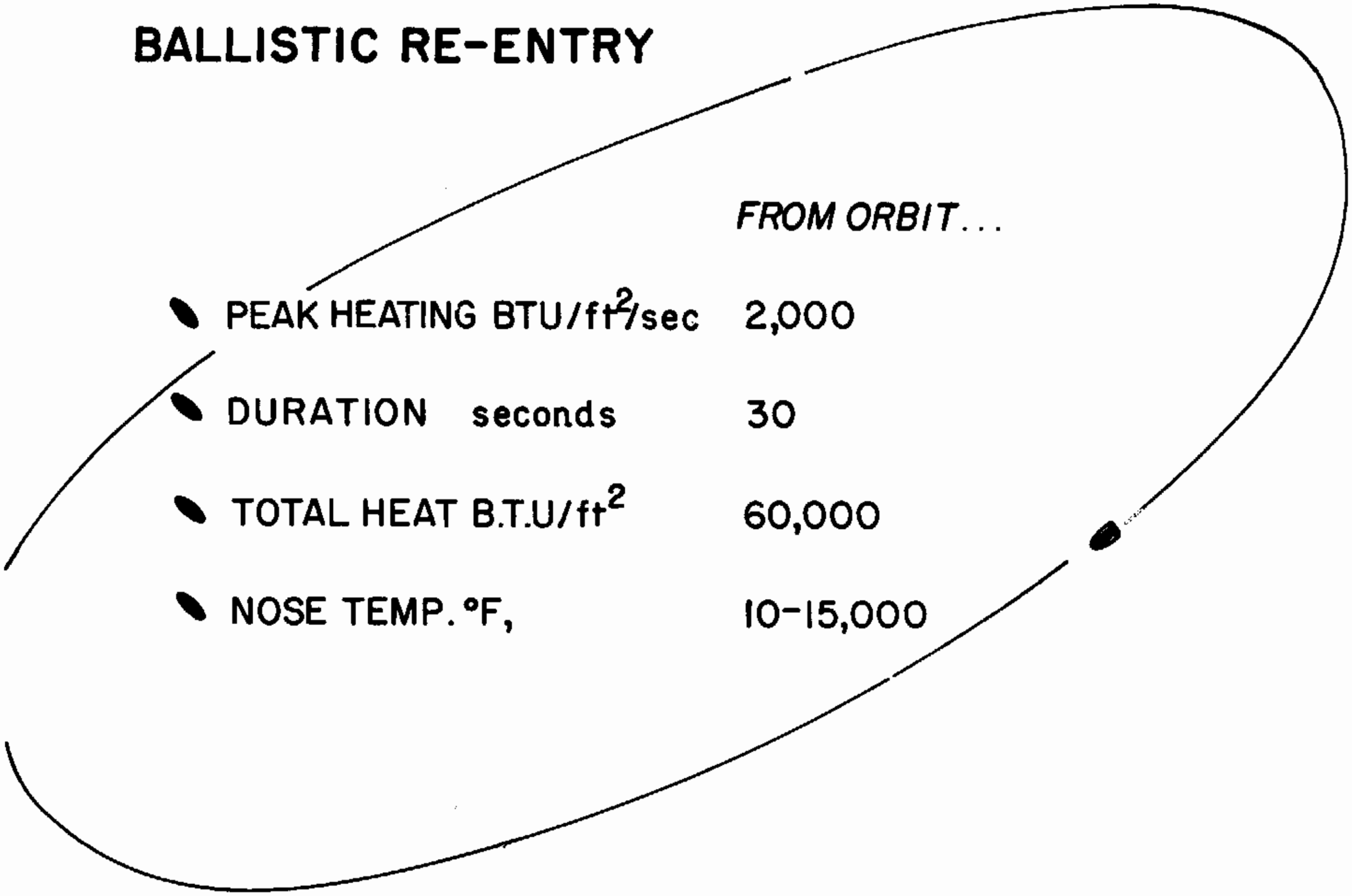
Figure 4.



Temperature in Thousands, °F
0
.5
1.0
2.0
3.0
4.0
Mach Number
1
2
3
4
5
6
7
8
9
10
11
12

Figure 5.

BALLISTIC RE-ENTRY



	FROM ORBIT...
PEAK HEATING BTU/ft^2/sec	2,000
DURATION seconds	30
TOTAL HEAT B.T.U/ft^2	60,000
NOSE TEMP. °F,	10-15,000

Figure 6.

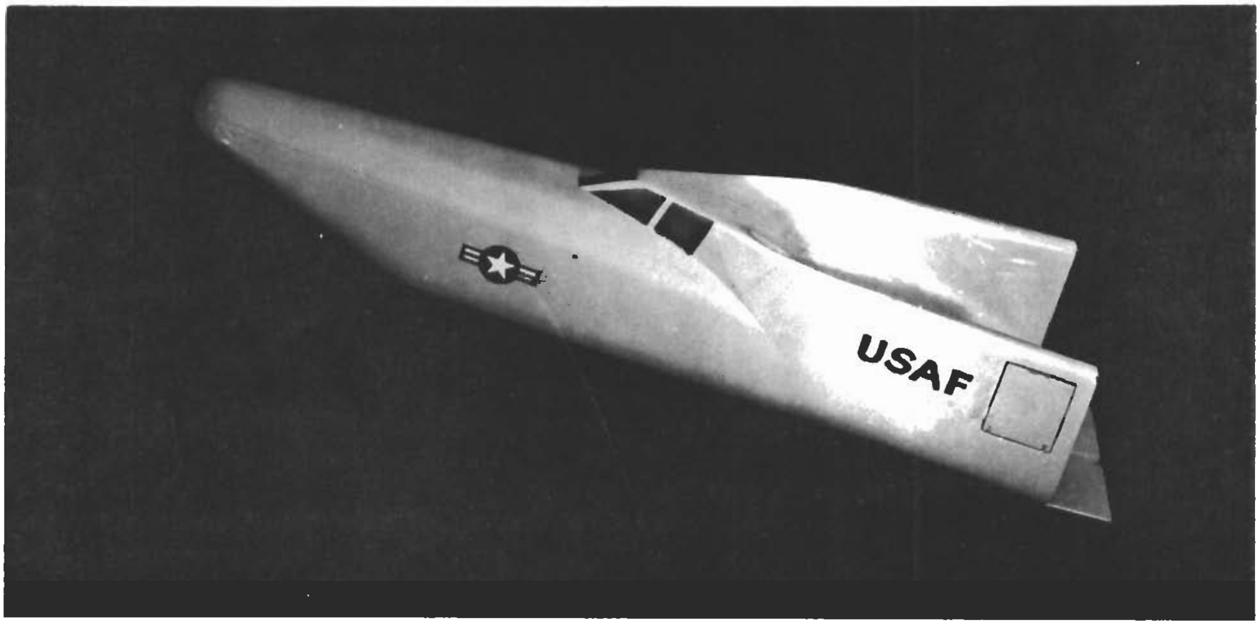


Figure 7.

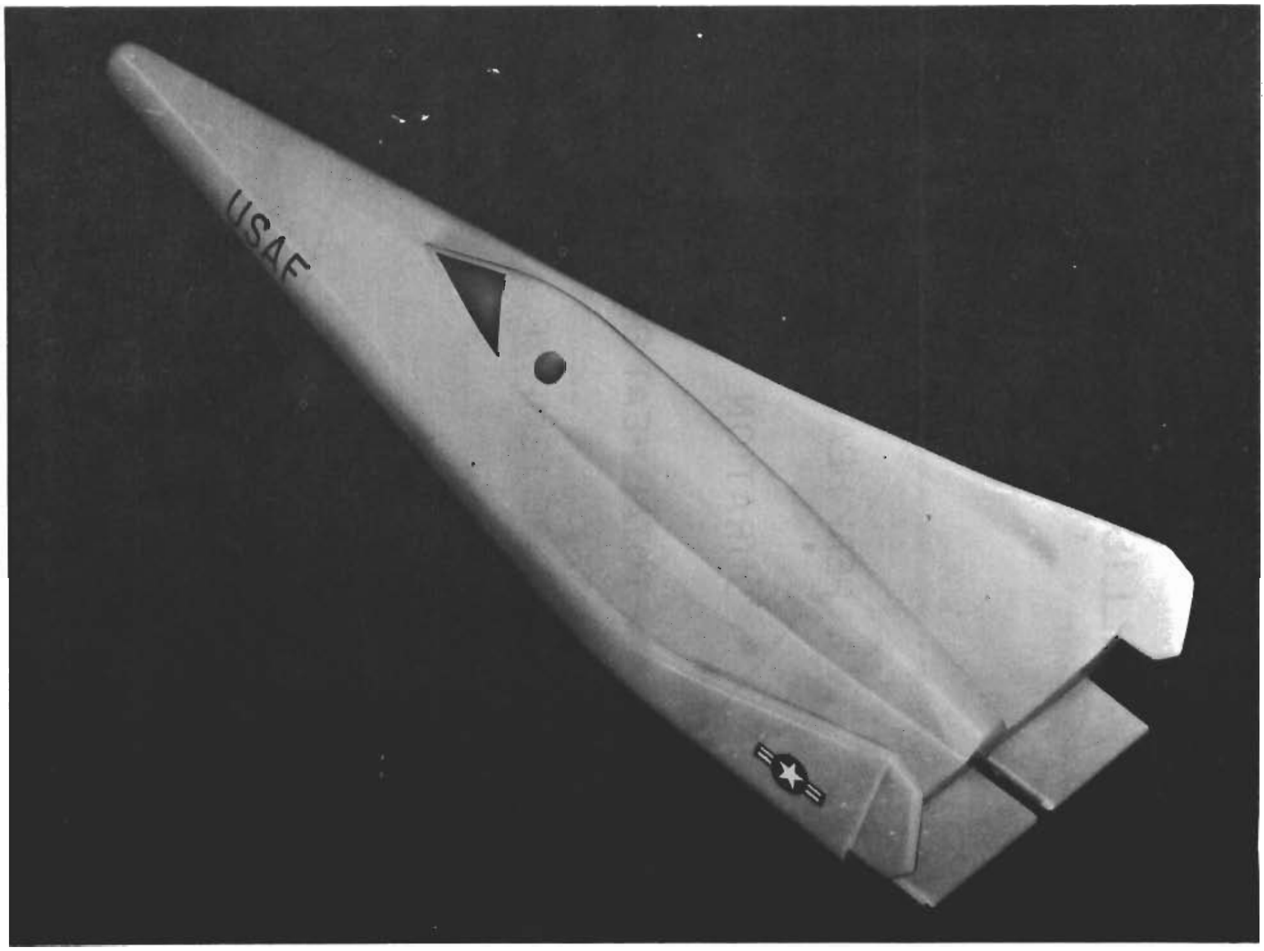
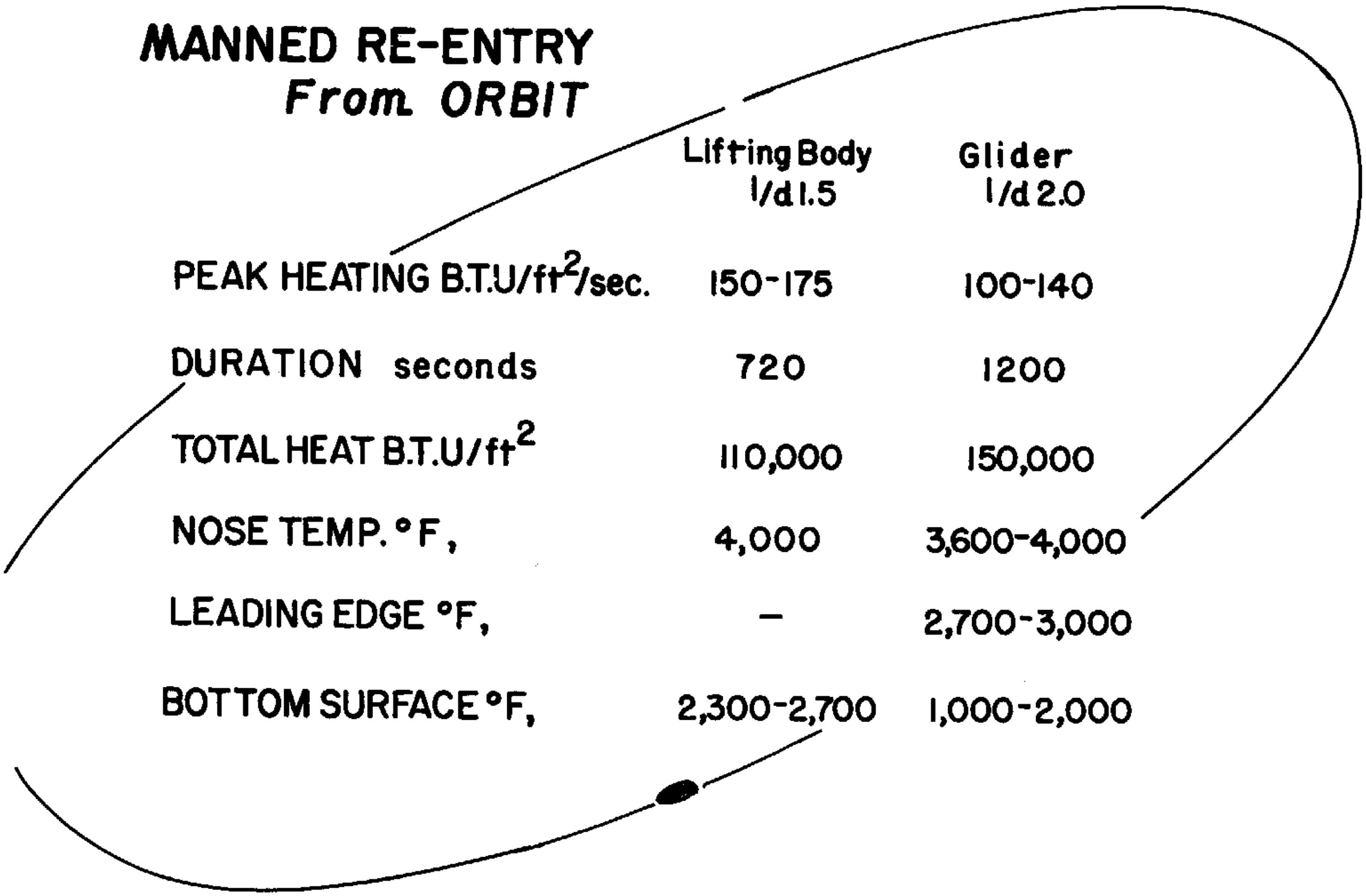


Figure 8.



MANNED RE-ENTRY
From ORBIT

	Lifting Body l/d 1.5	Glider l/d 2.0
PEAK HEATING B.T.U/ft^2/sec.	150-175	100-140
DURATION seconds	720	1200
TOTAL HEAT B.T.U/ft^2	110,000	150,000
NOSE TEMP. °F,	4,000	3,600-4,000
LEADING EDGE °F,	—	2,700-3,000
BOTTOM SURFACE °F,	2,300-2,700	1,000-2,000

Figure 9.

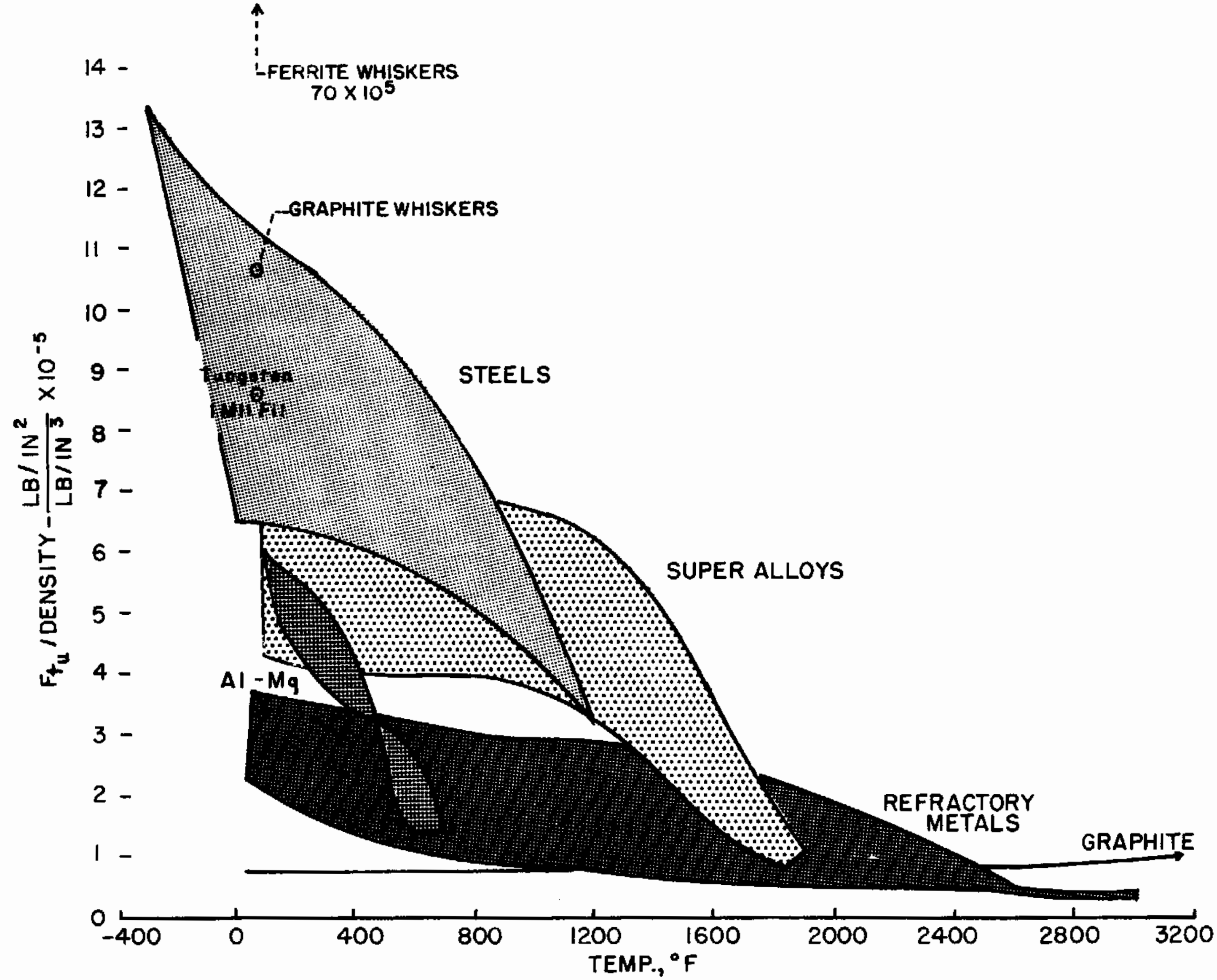

FERRITE WHISKERS
70 X 10^5
GRAPHITE WHISKERS
Tungsten
STEELS
SUPER ALLOYS
Al - Mg
REFRACTORY METALS
GRAPHITE
F_{tu} /DENSITY - $\frac{LB/IN^2}{LB/IN^3}$ X 10^{-5}
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
-400
0
400
800
1200
1600
2000
2400
2800
3200
TEMP., °F

Figure 10.

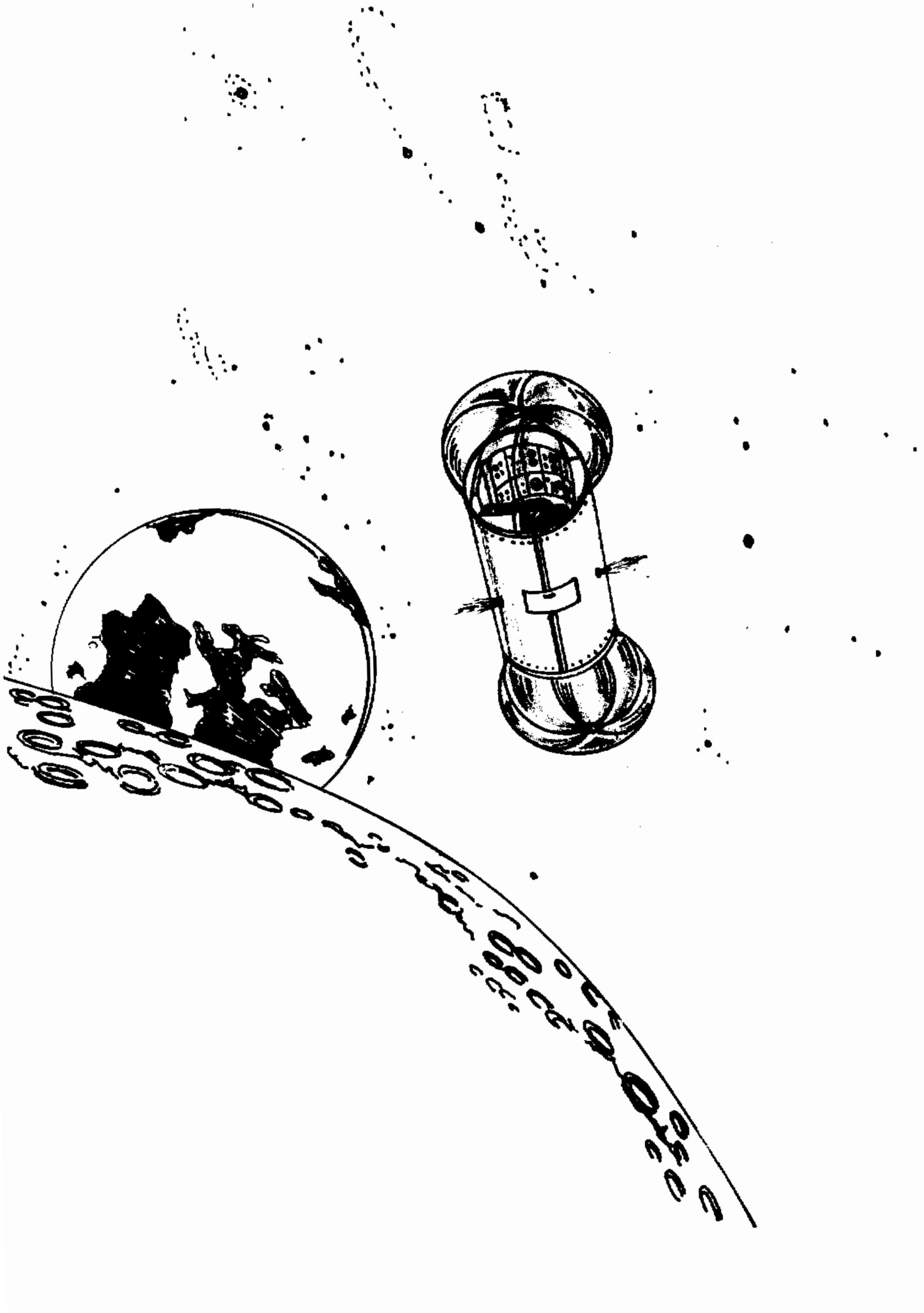


Figure 11.