The ParaShield Entry Vehicle Concept: Basic Theory and Flight Test Development

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Abstract:

With the emergence of microsatellite launch vehicle technology and the development of interest in space commercialization, there is a renewed need for entry vehicle technology to return mass from low earth orbit. This paper documents the ParaShield concept of the Space Systems Laboratory, which is an ultra-low ballistic coefficient (ULβ) entry vehicle. Trajectory simulations show that, as the ballistic coefficient is lowered into the range of 100-150 Pa (2-3 lb/ft^2), the total heat load and peak heating flux drop markedly, due to primary deceleration in regions of extremely low dynamic pressure. In this range, any of a number of ceramic or glass-based fabrics can withstand the entry dynamic pressures and heat loads. Incorporating an offset of the center of gravity from the symmetrical axis of the shield allows L/D, and thus peak deceleration loads, to be controlled. By using a titanium support truss and deployment mechanism, a very large heat shield can be deployed from an entry capsule prior to deorbit; since the shield survives entry, the same rib-braced fabric structure results in aerodynamic deceleration to a nominal landing velocity of 10-15 m/sec. Thus, the same structure that provides heating protection for hypersonic entry is also the terminal decelerator in the subsonic regime, and either water splashdown or a mechanical decelerator is used for landing impact attenuation. Since the same structure acts as both the heat shield and the landing parachute, the term "ParaShield" has been adopted to describe this concept. Results presented show the application of the ParaShield concept to a variety of entry capsules, including advanced manned spacecraft. A test vehicle was prepared to take data on ULβ entry from a suborbital trajectory. This paper also summarizes the experience gained from the design, construction, and integration of the Space Systems Laboratory ParaShield test vehicle on the American Rocket Company launch vehicle. With the failure of the launch vehicle, no flight test data was obtained; the test vehicle survived the launch incident, and is flight-capable for future suborbital missions. The development experience summarized in this paper has resulted in a sufficient knowledge base to allow the design and development of orbital ParaShield vehicles.

Theory:

In traditional entry vehicle design, the ballistic coefficient (β, or mass per unit area) has not been an independent variable in the systems design. The mass of an entry vehicle, such as a Gemini capsule, was fixed by the capacity of the launch vehicle; the diameter of the heat shield was similarly fixed by the diameter of the launch vehicle at the spacecraft interface. Thus, ballistic coefficients for these early vehicles tended to be in the area of 50-200 lb/ft^2.

The ParaShield concept, in summary, involves decoupling the ballistic coefficient from the launch vehicle parameters, to pick a value of β which optimizes the desired entry vehicle characteristics. As will be shown below, the use of very low values of β results in benign entry conditions, allowing the use of deployable heat shields with reusable ceramic cloth coverings. These same low values of β also result in a very low (~30–40 ft/sec) terminal velocity, allowing the use of simple impact attenuation to provide a soft landing on water or

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dry land. Since the same deployable fabric framework serves the functions of both heat shield and parachute, it is referred to as a *ParaShield*. Initial development of this concept was performed by Russell Howard, Jud Hedgecock, and Richard Patten while students of David Akin in an advanced space systems design class at MIT in the Fall of 1988.

Viewed parametrically, the ballistic coefficient significantly affects the nature of the entry profile, in terms of heating and trajectory. Figures 1–4 show the effect of ballistic coefficient on maximum heating rate, maximum dynamic pressure, maximum deceleration, and peak heat shield temperature. As can be seen, the peak heating rate drops markedly as β decreases below 1000 Pa (20 lb/ft^2). Maximum dynamic pressure is linear with β, with a slope fixed by the spacecraft L/D. L/D is also critical to the maximum deceleration force, as β has little effect on this parameter except at unreasonably low values. Conversely, β is the only significant parameter governing peak heat shield temperature. In summary, these graphs show a substantially more benign entry environment if the ballistic coefficient of the spacecraft can be reduced below 250 Pa (5 lb/ft^2).

By way of illustration, it is worthwhile to compare the entry performance of a conventional spacecraft (such as Gemini) with that of an ideal ParaShield. As Figure 5 shows, with identical L/D (=0.15) and entry conditions, the lighter ParaShield lofts higher and decelerates sooner than the Gemini spacecraft. This effect may be more clearly seen in Figure 6. While the heat shield temperatures are initially identical, the ParaShield temperature peaks at 1800°F about 275 seconds after entry interface, and then starts to cool as the vehicle slowly drops into the denser atmosphere. By comparison, the Gemini heat shield temperature continues to rise for an additional 100 seconds, reaching a peak temperature of over 3100°F before starting to drop. Figure 7 shows the cumulative effect: the total heat input to the ParaShield spacecraft (per unit area) is less than 20% of that of the Gemini spacecraft for an equivalent entry trajectory.

Suborbital Test Flight Attempt:

In the Spring of 1989, the American Rocket Company (AMROC) contacted the Space Systems Laboratory (then at M.I.T.) about the availability of a flight opportunity on the first flight of their launch vehicle. The SSL responded with a design for a ParaShield vehicle optimized for the suborbital trajectory (110 mile apogee, impact 150 miles downrange) of the AMROC SET-1 launch vehicle. This flight test vehicle, designed and built over a period of five months, was named *Skidbladnir* after an ingenious folding boat of Norse mythology. Support for the construction of the suborbital test vehicle was provided by AMROC, as well as the NASA Office of Aeronautics, Exploration, and Technology. Total costs for the spacecraft came to slightly below $100,000.

The design concept for *Skidbladnir* was a conical pressure vessel, containing all of the vehicle systems, with the ParaShield folded around it for launch. The interior systems of the capsule can be seen in Figure 8. *Skidbladnir* was basically a complete spacecraft, incorporating control systems (redundant microprocessor-based controllers), propulsion system (cold-gas nitrogen thrusters for three-axis stabilization), flight control sensors (three-axis accelerometers and angular rate sensors), data collection system (microprocessor-based solid state data storage for an array of thermal, pressure, and strain gauge sensors), recovery systems (dual radio direction finding beacons, flotation collar, water dye marker, and a high intensity strobe), and payload (two film cameras and a video camera). Limitations of the vehicle, based on the suborbital flight, the constraints of the launch vehicle, and the limited budget and development time included:

- ballistic coefficient of 6.5 lb/ft^2, approximately twice that desirable for orbital entry;

- no inertial measurement unit or external sensors for vehicle attitude, requiring the vehicle to sense the deceleration direction at g onset and perform an attitude maneuver to reach the desired entry attitude;
- no in-flight communications capability.

The stowed and deployed configurations of *Skidbladnir* are shown in Figures 9 and 10, respectively. Figure 11 shows the spacecraft integrated onto the SET-1 launch vehicle. All spacecraft systems functioned nominally during the launch attempt of October 5, 1989, during which the launch vehicle developed insufficient thrust to lift off, was damaged by a fire in the flame deflector, and fell over and burned. Damage to *Skidbladnir* during this incident was limited to a large dent in the capsule and the destruction of the ParaShield ribs and fabric; the spacecraft is back in the Space Systems Laboratory at the University of Maryland, and is being refurbished and modified for an orbital flight test.

Potential Applications:

There are a number of potential applications of ParaShield technology in current and planned future space activities. As a lifting entry vehicle, it offers a benign ride (~3 g's maximum) to payloads coming back from orbit; it is thus applicable to missions such as the Assured Crew Return Vehicle, which would involve carrying wounded or ill crew back from orbit. The major effort of the Space Systems Engineering class which initially developed the ParaShield concept was to design an "Alternative Manned Vehicle"; that is, a spacecraft capable of carrying humans into orbit on any of the existing expendable launch vehicles (Titan, Atlas, or Delta) to supplement the limited number of Space Shuttle missions. The ParaShield concept allowed for a much more useful vehicle than the more traditional spacecraft design. The large shield area allowed a relaxation of volumetric and shape constraints. The spacecraft designed was cylindrical, with sufficient internal volume for eight crew and supplementary cargo for Titan launches, yet the same basic configuration with the removal of additional crew accommodations provided the capability for two-person missions capable of being launched on a Delta vehicle. (An abort rocket motor, similar to the Apollo system, provided crew safety in the event of a failure of these non-man-rated launch vehicles.) The same basic spacecraft was also shown to be applicable to an Earth-orbit-rendezvous Lunar mission, using the lifting capability of the ParaShield to perform a multi-pass aerobrake maneuver upon return to Earth.

Preliminary studies have indicated a variety of useful unmanned applications of ParaShield as well. Since the mission approach is inherently safe (all recovery devices are locked into place prior to deorbit), routine flights of a commercial sample return vehicle could be made over inhabited areas, resulting in targeted landings at ranges such as White Sands or Edwards Air Force Base. A thousand-pound vehicle should have a payload capability on the order of three hundred pounds; economies of scale yield larger payload fractions for larger vehicles. The low ballistic coefficient of the ParaShield makes it ideally suited for low-density aerocaptures, such as at Mars. The system is not susceptible to pressurization failures, as is the ballute, nor is it particularly easy to damage, as are rigid thermal tiles.

Conclusions:

By making the ballistic coefficient an independent parameter in the spacecraft design process, the ParaShield concept has the potential to open a new regime of hypersonic aerodynamics: that of low ballistic coefficient, low dynamic pressure flight. Results to date indicate that the concept has unique promise over a wide range of spacecraft designs, from small recovery capsules for materials samples to manned spacecraft and interplanetary applications. Before widespread consideration of the concept can take place, it will be necessary to validate the concept by flight test experience. One ParaShield vehicle was built and damaged somewhat in a suborbital flight attempt: it is currently undergoing refurbishment and modification for a near-term orbital flight test under the sponsorship of NASA Goddard Space Flight Center. Designs are also well underway for the construction of a 1000 lb gross weight ParaShield vehicle with a 300 lb payload, to be constructed for subsequent flight test opportunities. Activities relating to ParaShield development in the Space Systems Laboratory for the near future will be focused on orbital flight tests, better understanding the subsonic aerodynamic parameters of these vehicles through wind tunnel testing, and pursuing in greater detail both hypersonic computational fluid dynamics models of the ParaShield, as well as the detailed designs for subsequent vehicles.

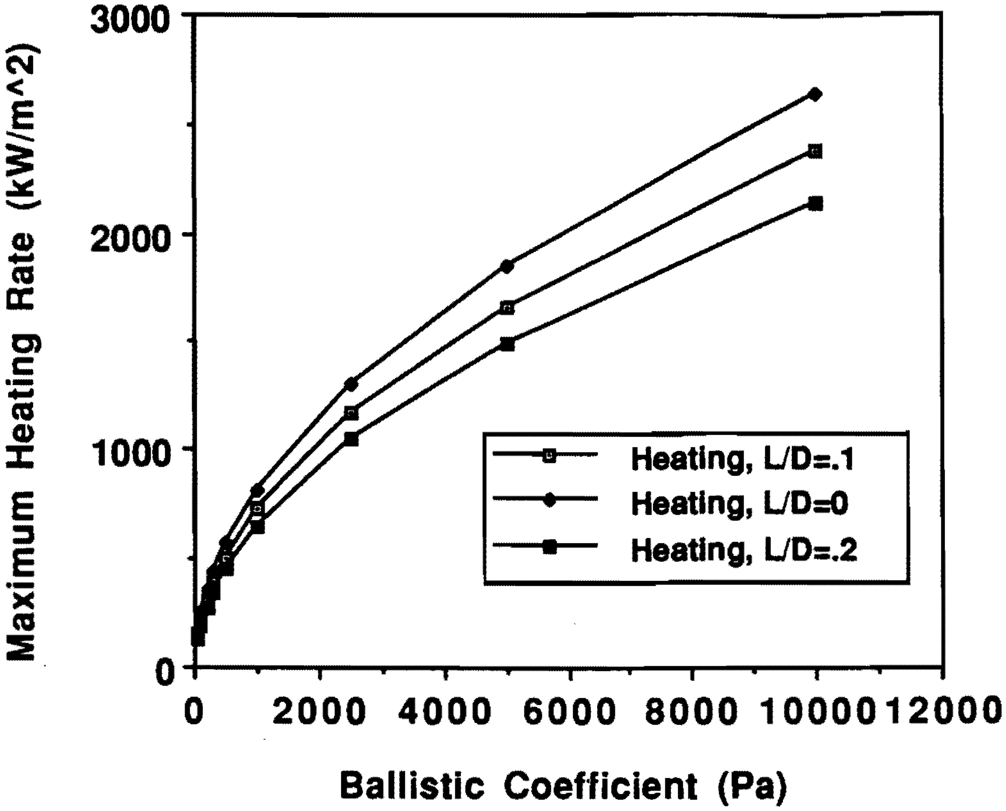
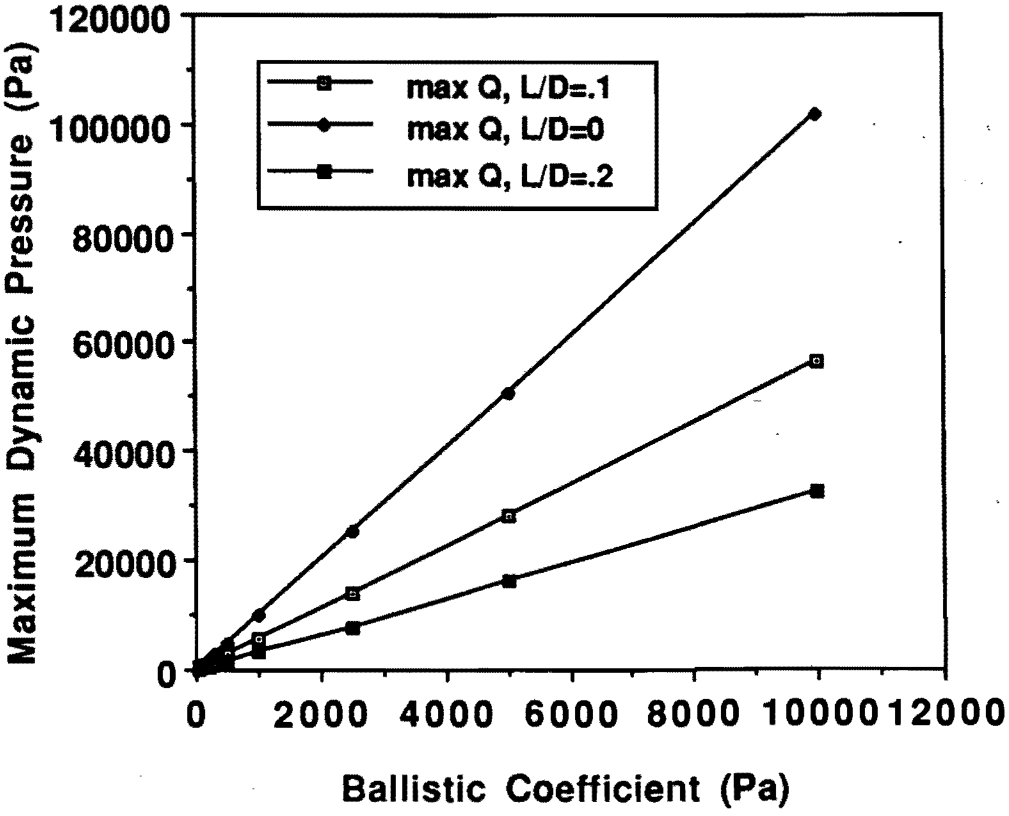

3000
2000
1000
0
Maximum Heating Rate (kW/m^2)
0
2000
4000
6000
8000
10000
12000
Ballistic Coefficient (Pa)
Heating, L/D=.1
Heating, L/D=0
Heating, L/D=.2

Figure 1


120000
100000
80000
60000
40000
20000
0
Maximum Dynamic Pressure (Pa)
0
2000
4000
6000
8000
10000
12000
Ballistic Coefficient (Pa)
max Q, L/D=.1
max Q, L/D=0
max Q, L/D=.2

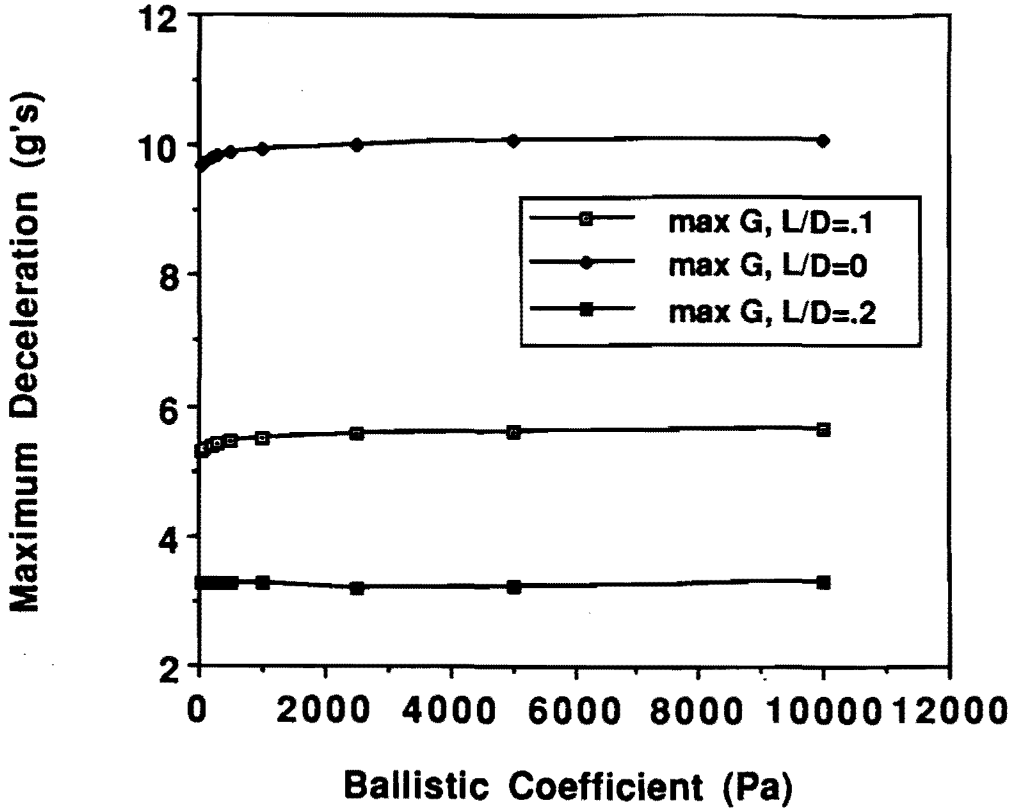
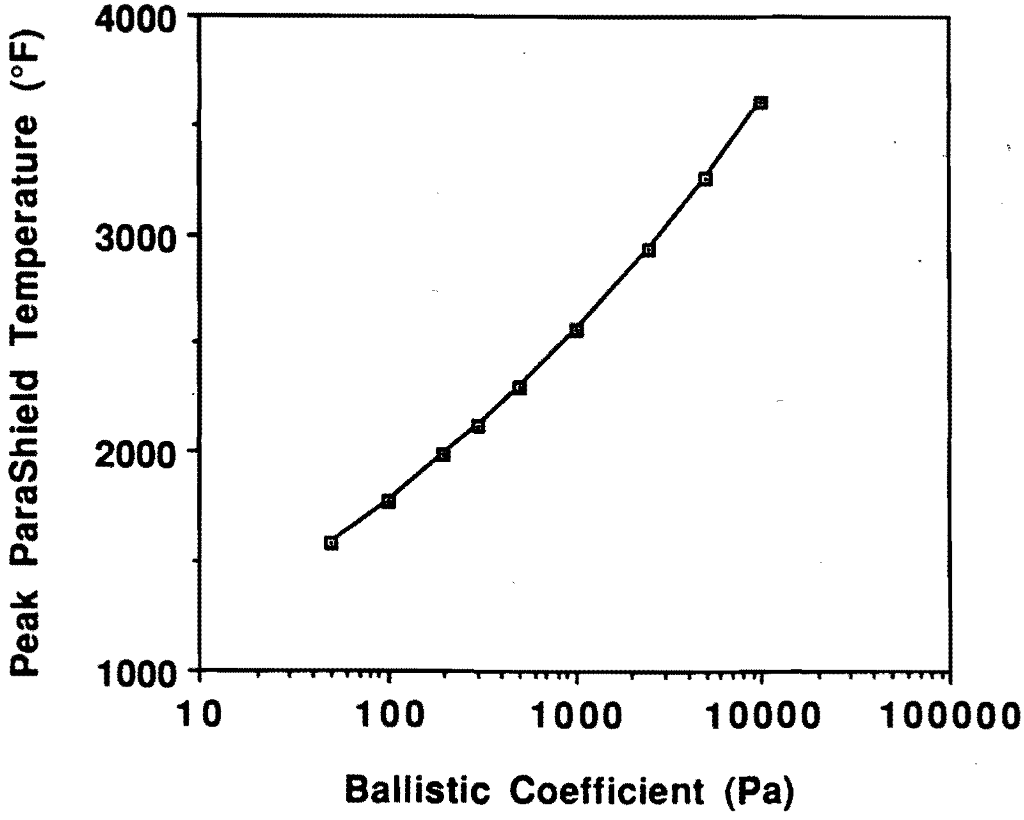

Maximum Deceleration (g's)
12
10
8
6
4
2
0
2000
4000
6000
8000
10000
12000
Ballistic Coefficient (Pa)
max G, L/D=.1
max G, L/D=0
max G, L/D=.2

Figure 3


Peak ParaShield Temperature (°F)
4000
3000
2000
1000
10
100
1000
10000
100000
Ballistic Coefficient (Pa)

F- //

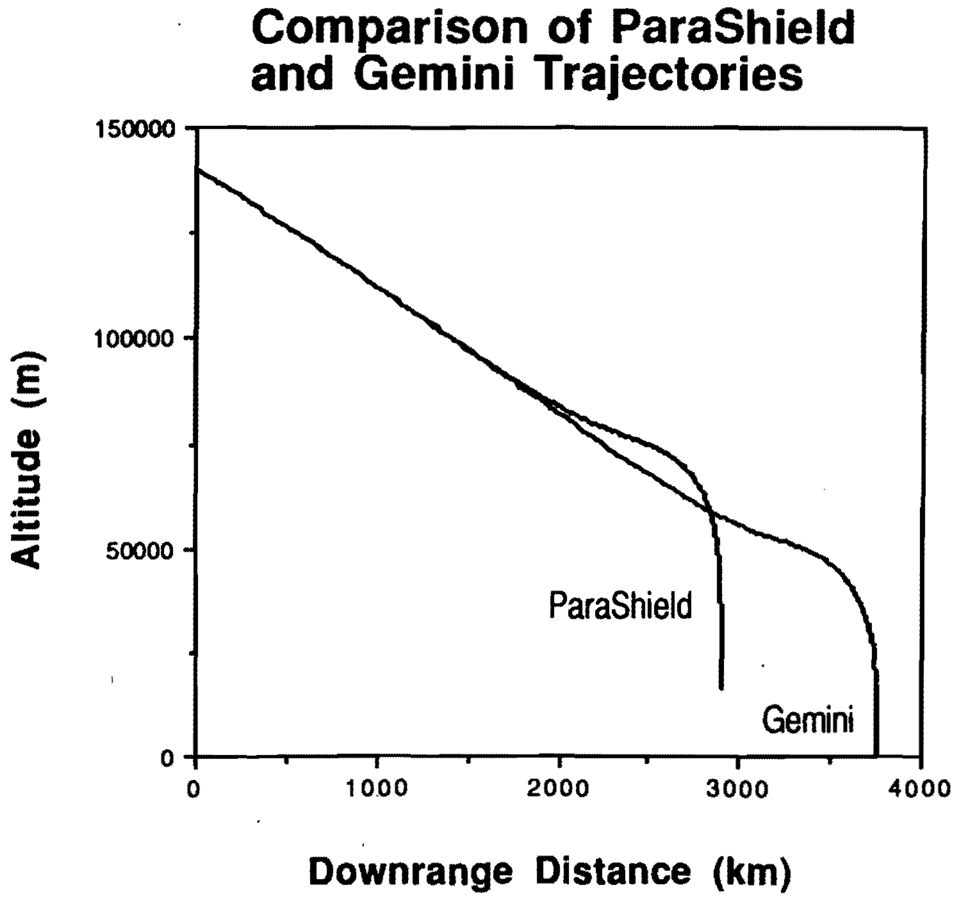

Comparison of ParaShield and Gemini Trajectories
150000
100000
50000
0
Altitude (m)
0
1000
2000
3000
4000
Downrange Distance (km)
ParaShield
Gemini

Figure 5

Comparison of ParaShield and Gemini Heat Shield Temperatures

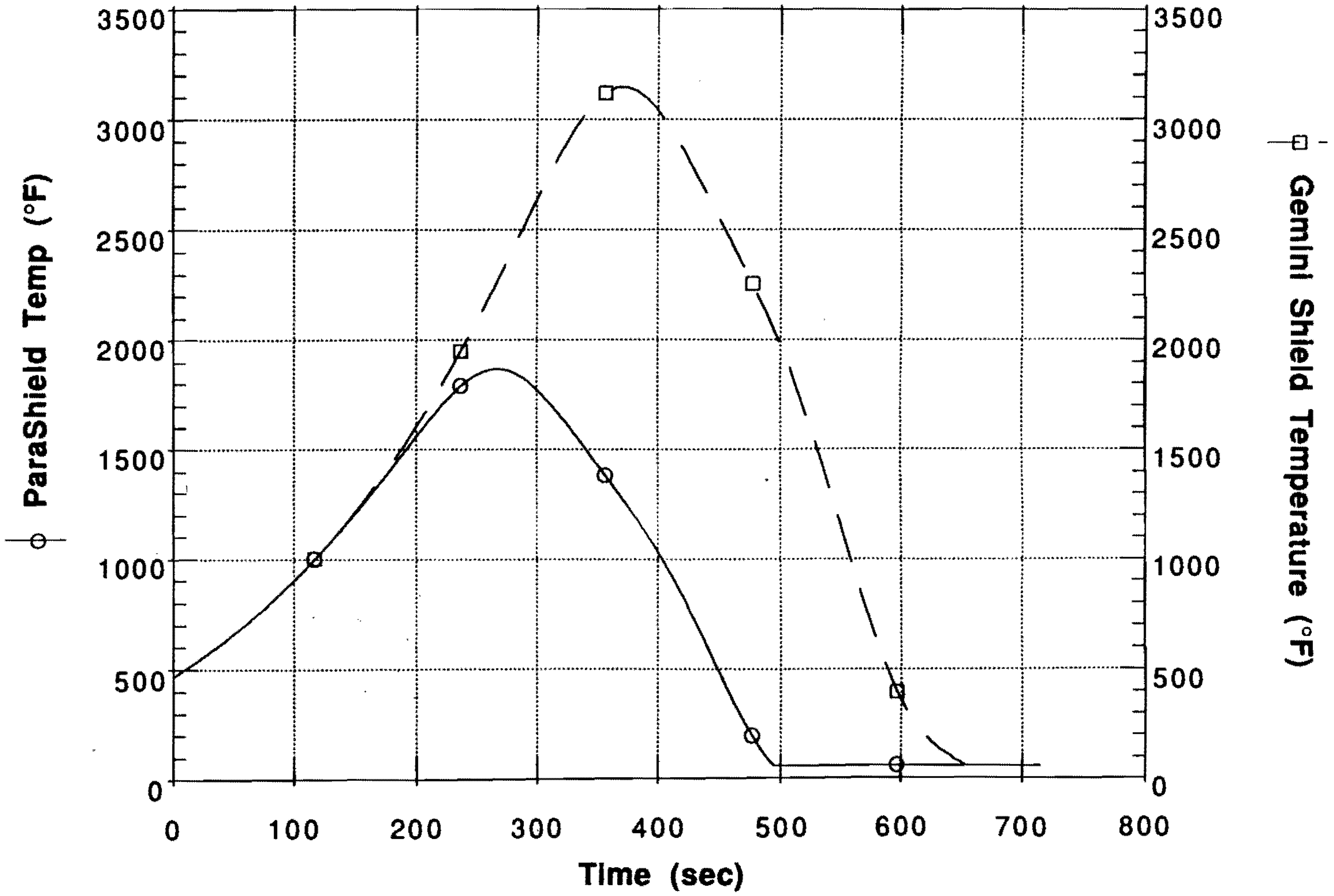


Figure 6

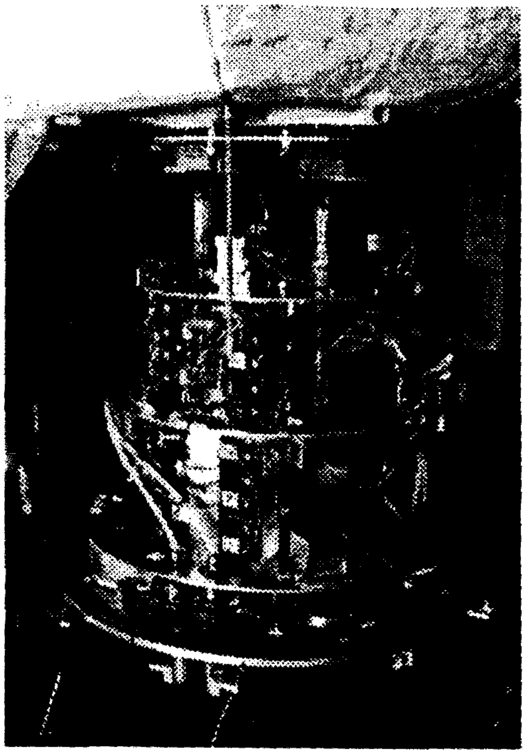


Figure 8
Skidbladnir Spacecraft Interior

Figure 9
Skidbladnir Spacecraft in Retracted Configuration

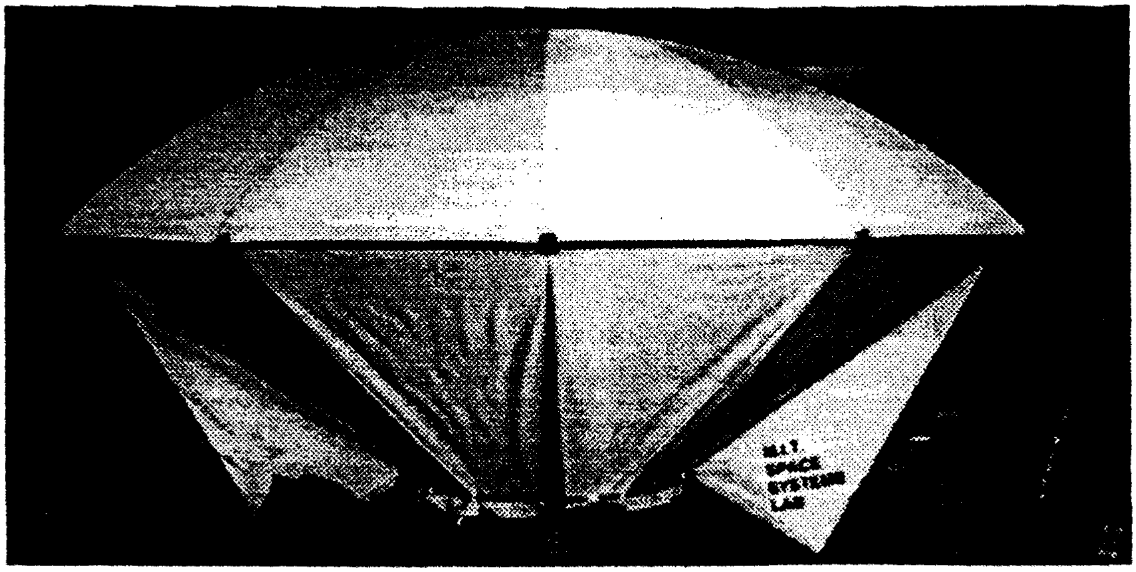
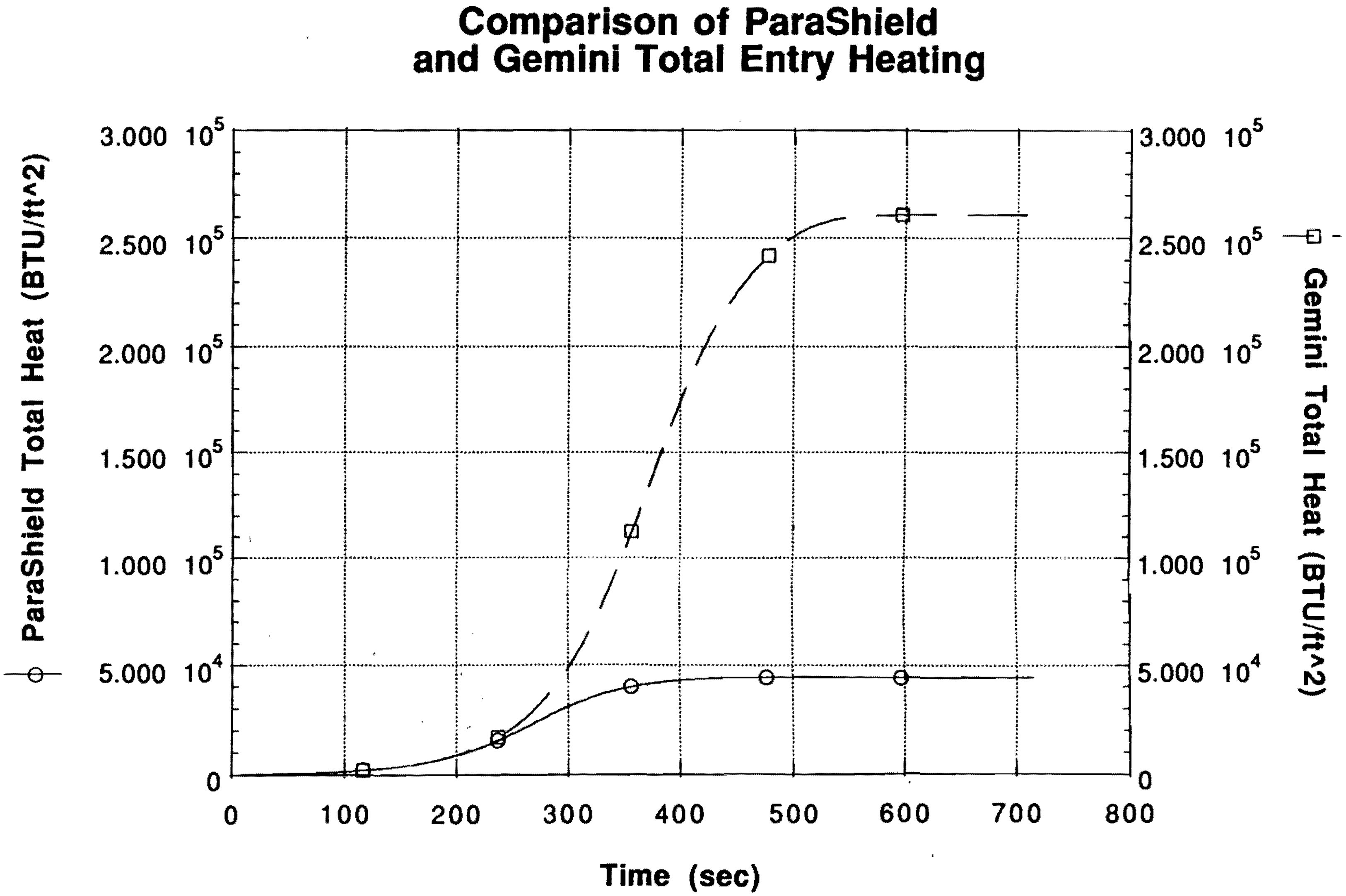


Figure 10
Skidbladnir Spacecraft in Deployed Configuration



Comparison of ParaShield and Gemini Total Entry Heating

Figure 7

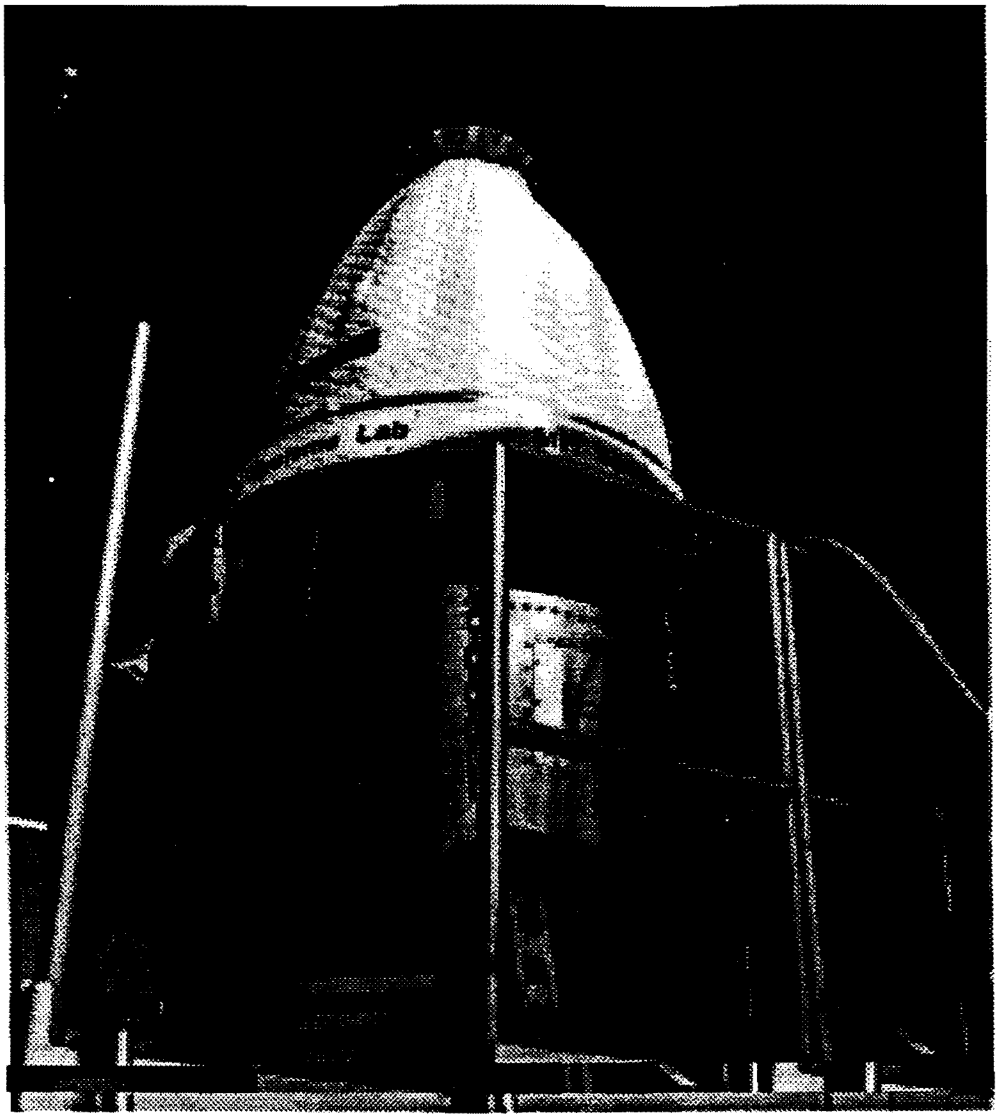


Figure 11
Skidbladnir Integrated to
AMROC SET-1 Launch Vehicle