A Small Re-entry Capsule - BREM-SAT 2

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Abstract

Following the successful end of the first BREM-SAT mission, BREM-SAT 2 will return back to Earth with a deployable heat-shield and a small solid rocket motor after its mission. A parachute and a small radio beacon are then used to find the satellite with the scientific data of its re-entry and the material samples of a microgravity solidification experiment.

Most subsystems are taken from the flight-proven first BREM-SAT mission with minor adaptations to the new mission profile. Attitude control, power supply and onboard data handling will essentially remain unchanged, whereas the structural design incorporates most of the changes.

The results given in this paper focus on the heat-shield design, the flight dynamics, and the thermal loads associated with the re-entry. The heat-shield used for BREM-SAT 2 is a so-called parashield which resembles a reinforced umbrella and increases the satellites front area by a factor of 12. The initial diameter of 0.65 m during launch and orbital flight changes to 2.24 m when deployed. This shifts the peak of the deceleration loads to an altitude of 70 km; in contrast, the peak-load altitude of a standard re-entry capsule is about 40 km. Part of the heat flux is absorbed by the flow due to the blunt cone design, and the temperature is significantly lowered by the large emission area on the front and the back of the heat-shield. Lower temperatures allow the use of conventional, off-the-shelf available materials, like the silicon fabric of the heat-shield originally used for high temperature insulation in terrestrial applications.

In additional to the advantages in thermal design, a deployable heat-shield allows the integration of a solar array on the back side of the stowed shield. The shield offers additional safety to the design, because the satellite will not survive the re-entry temperatures when it is not deployed. Alternatively, it may be used to lower the orbit until the retro impulse will guide the satellite into a pre-determined landing area. The free-fall speed in the lower atmosphere is low enough to use a conventional parachute.

The mechanical design of the deployable heat-shield is necessarily more complex, and the materials used are pushed to their limits by both mechanical stresses and thermal loads. Finite analysis shows that the design is capable to carry the static loads, and where struts must be strengthened to provide a larger margin of safety. The mechanical design is in fact limited to small (and light-weight) satellites due to the mechanical loads.

A successful flight experiment will expand the applications of small and low-cost satellites.

Mass	86 kg
Dimensions	Height 600mm, Diameter 650 - 2240mm
Power	25W avg., 50W peak
Telemetry	Uplink 401 MHz, Downlink 1.4 GHz
Attitude Control	3-Axis controlled, momentum biased
Recovery System	Parachute, 61m^2, v < 3 m/s
Launch	1999
Estimated Costs	$ 7M
Status	Feasability study, pending

Table 1: BREM-SAT 2 Technical Summary

Introduction

During the last decade, small satellites had been developed for almost every type of mission, and been launched and operated with increasing successes. Among the small satellite concepts, only a few re-entry capsules can be found, primarily because a de-orbit engine and a conventional heat-shield use up most of the payload volume and mass. To reduce the mass of the heat-shield, it is important to lower the heat loads during re-entry. Two main methods can be applied, lift and a lower ballistic coefficient. Lift requires stable aerodynamic conditions over a wide range of flow conditions and a complex attitude control system. A low ballistic coefficient, on the other hand, requires either low mass or a large area.
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has a desire to design and use a small re-entry capsule for several reasons. It would allow retrieval of material samples after a long period under microgravity, and it would be possible to measure flow parameters during re-entry. Both objectives are a logical extension of a science program which started with the BREM-SAT mission, launched in 1994 (Königsmann, 1994 and 1996). Among other experiments, this satellite carried a microgravity experiment and temperature and pressure sensors for the initial phase of the re-entry, but it was not a re-entry capsule and did burn up during re-entry.

To convert BREM-SAT into a re-entry capsule, lift had been ruled out very early, because it would complicate the design and add more costs to the small satellite program than was intended. The use of low ballistic coefficient re-entry looks more promising, and a study had been performed to determine the technical and economical feasibility of the concept.

The Parashield Concept

An alternate design to the Mercury capsule developed by the AVCO-Everett Research Laboratories in 1957 (Detra, 1959) used metal plates to build a large area. Appropriate lightweight materials were not available at that time, and Mercury used a different heat-shield. In 1989, the University of Maryland (Akin, 1990) developed a capsule called Skidbladnir, which used an umbrella-like heat-shield made of silicon fabric, the parashield. Unfortunately, the launcher failed and destroyed the vehicle.

The parashield configuration used for BREM-SAT 2 uses a low ballistic coefficient and a large heat-shield radius, which yield to a heat flux maximum of 200 KW/m^2 for the BREM-SAT-2 configuration. A heat-shield with a larger area does not lower the maximum deceleration, as does lift, but the deceleration maximum occurs at a higher altitude. In addition, a lower ballistic coefficient causes the ground track to decrease and the time of flight at lower altitudes to increase.

Parashield Design

The parashield resembles an umbrella with heat-resistant silicon fabric and titanium arms. Twelve arms are attached to the satellite and increase the area by a factor of 12 to 3.9 m2 (2.2m diameter). When folded, BREM-SAT 2 looks almost like a conventional satellite with solar panels attached to the parashield arms (Figure 1). The parashield cover is stored between the arms and behind the solar panels.

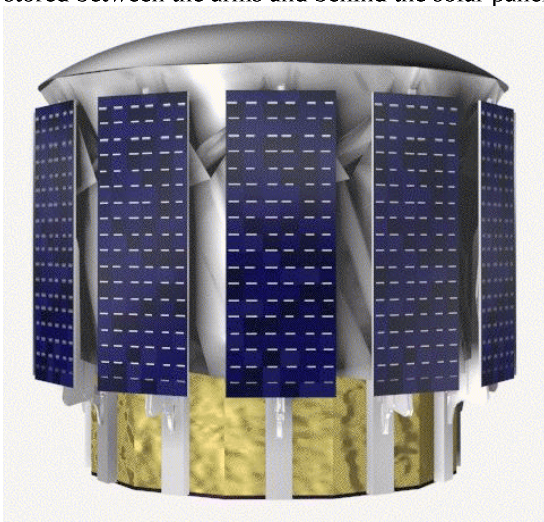

Figure 1: BREM-SAT 2 With Folded Parashield

The deployed parashield is shown in Figure 2 without the satellite and the solar panels for clarity. The solar panels remain attached on the back side of the shield.

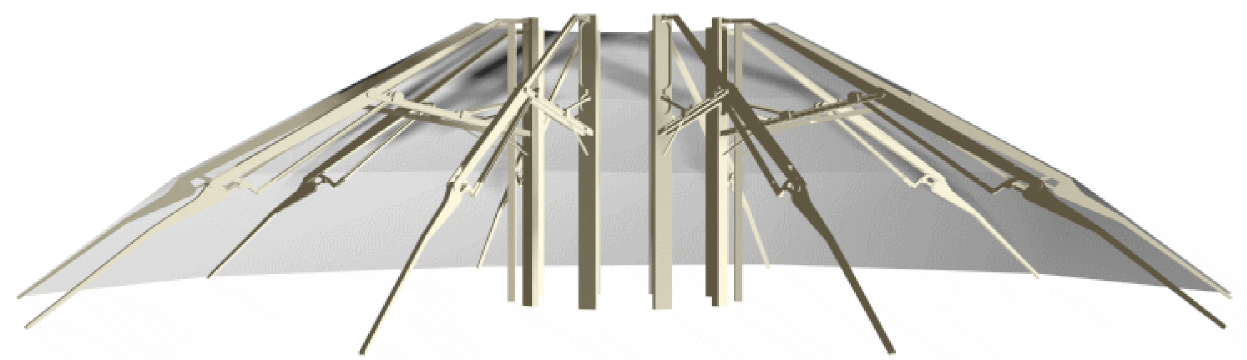

Figure 2: Deployed Parashield Without Satellite and Solar Panels

Each arm unfolds, pushed by two redundant springs, within 2 seconds. The more the arm unfolds, the more the remaining force pushes it, helping to stretch the silicon fabric. The deployment procedure is illustrated in Figure 3 to Figure 6.

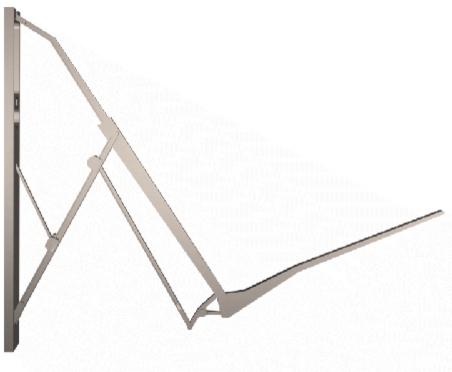

Figure 3, Figure 4, Figure 5: Parashield Arm Deployment

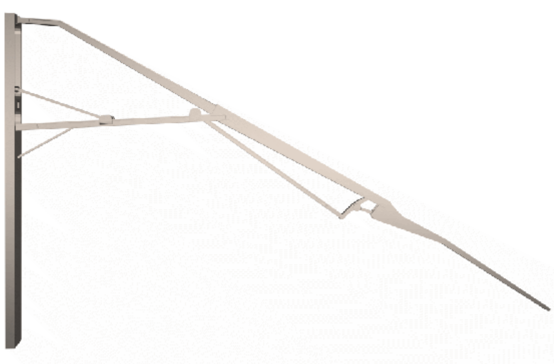

Figure 6: Deployed Arm

The large area emits the heat and lowers effectively the temperature during re-entry. A major concern is the part of the heat-shield on the satellite body itself, which is heavily insulated to mitigate the heat flux into the satellite structure. If the payload would heat up more than 100°C, experiment results would have been lost and the radio beacon might fail.

This part of the heat-shield is designed as a sandwich consisting of a 5 mm titanium cover, a 20 mm insulation and 2 mm stainless steel inside cover. The temperature of the titanium cover, which protects also the parashield hinges, is expected to be 850°C at the stagnation point. The thermal insulation is a commercially available, flexible ceramic material with a short term maximum temperature of 1400°C and an extremely low thermal conductance. With the short term exposure, the temperature at the inner steel plate does not exceed 100°C.

The mechanical strength of the parashield had been verified with an FEM analysis, which shows that the arms would bend 42 mm at their tips during maximum deceleration. For this analysis, an nickel-alloy used in gas turbine engines had been selected, because it is easier to manufacture than titanium. It provides a minimum safety margin of only 1.13, which makes it desirable to either reinforce the critical points or use a stronger material.

The parashield cover consists of several layers of a silicon-oxide fabric. The maximum continuous temperature is specified between 1000° and 1200°C, depending on the manufacturer. However, initial tests showed that high temperatures lower the mechanical strength. The thermal and mechanical margin, although existent, is not as high as given by the specifications. The main parameter is the thermal emission coefficient, which has to be determined by tests.

Experiments

A material science experiment developed by the Hungarian University of Miscolc had been selected as prime experiment. It requires that material samples are returned to Earth for investigation in a laboratory. An aluminum alloy (Al-Al_3-Ni) is melted and, within 48 hours, slowly solidified in a gradient temperature field. The structures of the sample is then used to compare the results of two (contradictory) theoretical models. A similar oven design had been used for experiments in the Bremen Drop Tower where valuable experience has been gathered during the past years.

The experiment requires 40 Watts for heating, delivered by the solar generator and a rechargeable silver-zinc battery[1] with 30 Ah capacity. To mitigate high temperatures within the satellite during the operation of the experiment, use of a so-called Active Radiator Tile provided by the European Space Agency ESTEC is anticipated. It allows variation of the heat flux between the satellite's interior and space by an electrostatic signal and is a new application of micromechanics on a spacecraft.

Pressure transducers and temperature sensors will record the flow characteristics on various locations of

[1] The cycle number of the battery is limited to approximately 500 cycles, compatible with the short mission time.

the satellite during re-entry. These data will be stored in EEPROM to be analyzed after recovery. In addition, a set of accelerometers and gyros will be used to determine the flight dynamics.

While all the experiments had been defined during the feasibility study, the most effort was spent on the design and analysis of the parashield itself.

Flight Dynamics

The parashield can efficiently be used to lower the orbit of a satellite without fuel. Although this might be a useful application to remove satellites from LEO, it involves risks with regard to the landing area of a re-entry capsule. For BREM-SAT 2, a solid rocket engine providing a delta velocity of 70-120 m/s has been assumed. Solid rocket engines require a stable attitude during firing with a minimum spin rate to avoid thrust vector divergence caused by irregular burn rate. The angular momentum of the satellite interferes with its aerodynamic stability, which will be described below.

Due to the changing flow conditions, the aerodynamic drag coefficient and the ballistic coefficient change during re-entry. Under subsonic conditions, the ballistic coefficient is about three times higher than during hypersonic or transitional flow, as shown in Figure 7. The deceleration, also given in this figure, reaches a maximum value of slightly more than 8g.

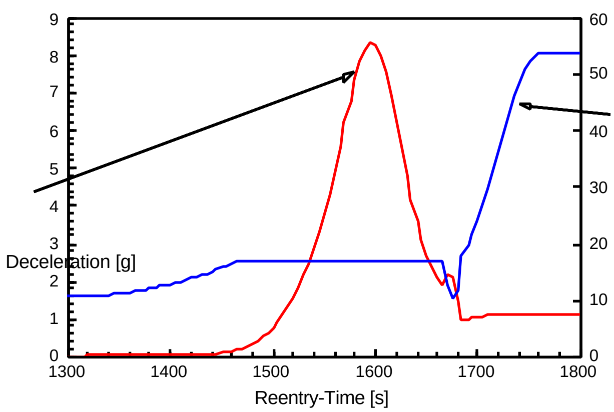

Figure 7: Ballistic Coefficient and Acceleration During Re-entry

The ground track after firing the retro engine is about 10,000 km long (Figure 8). Under nominal conditions, the ground track of a re-entry capsule with a low ballistic coefficient is shorter compared to a ground track of a vehicle with higher ballistic coefficient. If BREM-SAT 2 would survive the re-entry without deploying the parashield (which, of course, is not the case), the ground track would be 400 km longer, mainly because the satellite would be decelerated in lower altitudes. The time between retro burn and landing would be shorter (~2 minutes) with a higher ballistic coefficient. The parashield concept is slightly more sensitive with respect to landing site dispersion than a conventional re-entry capsule.

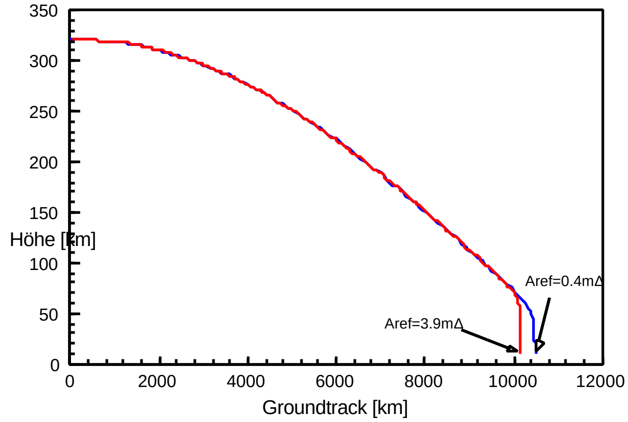

Figure 8: Ground After Re-entry Burn (-100m/s)

Similar to BREM-SAT 1, the attitude control uses a momentum wheel and magnetic torquers in orbit. A similar deploy mechanism of the momentum wheel (Königsmann, 1996) had been considered to improve aerodynamic stabilization, but simulation results show that due to the high stability in the hypersonic flow regime the wheel could remain on-board. The flight angle (angle between velocity vector and the satellite's symmetry axis) is shown in Figure 9 for an angular momentum of 0.5 Nms. After the retro burn, the satellite's attitude remains inertially fixed for a short period of time, until the increasing aerodynamic torques force the satellite into aerodynamic stabilization. With a higher angular momentum, this period will become too long. For the important part of the re-entry, below 100 km, the flight angle has been effectively reduced below 2°. The peak aerodynamic torques apparently occur between 80 and 60 km when the flight angle is below 1°.

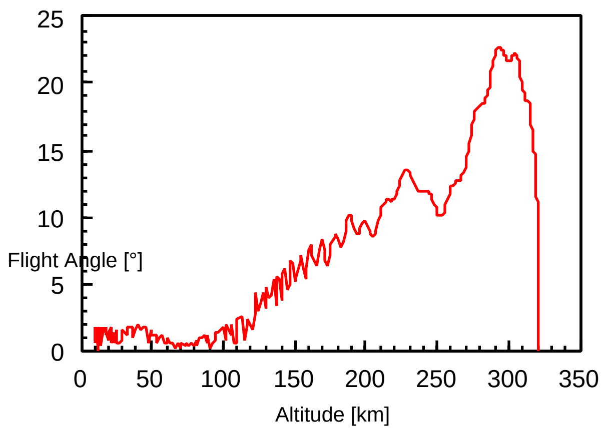

Figure 9: Flight Angle vs. Altitude, Angular Momentum 0.5 Nms

The simulation shown in Figure 9 assumes no offset between the center of mass and the center of pressure, seen from the velocity vector. Clearly, any offset will affect the attitude during re-entry, a worst-case analysis assuming an offset of 0.1 m is shown in Figure 10.

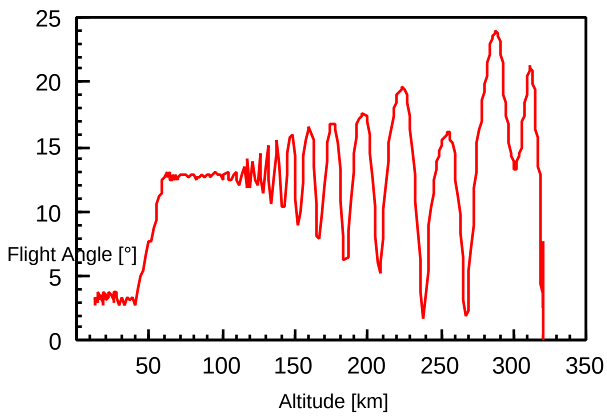

Figure 10: Flight Angle vs. Altitude, Angular Momentum 0.5 Nms (Offset of 0.1 m between center of pressure and center of mass, perpendicular to symmetry axis)

With a diameter of 0.65 m (resp. 2.2 m), an offset of 0.1 m is certainly a high value. This value will also simulate the effect of a partial deploy of the parashield. During re-entry, the satellite has a constant flight angle of 13°, which causes lift and increases the ground track. Around 60 km altitude, the transition between the flow conditions cause the aerodynamic parameters (drag and lift coefficients) to change, thereby decreasing the flight angle.

Thermal Analysis

To determine the temperatures of the satellite during re-entry, a thermal model consisting of 190 nodes had been constructed[2], taking into account the different materials, emission factors and view angles. The heat flux at the stagnation point, shown in Figure 11, has been computed using the Stanton number (St) of a sphere, as given by

$$St = 1.13\ C_{Shape}\sqrt{Kn_{\infty}} \quad \text{with}$$

$C_{Shape} = 1$, Kn_{∞} : Knudsen Number (Wiegand, 1994).

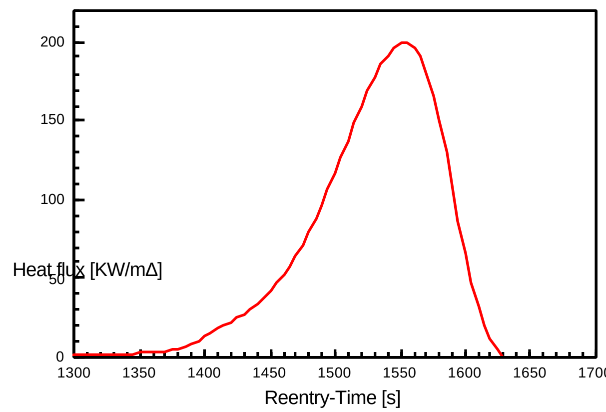

Figure 11: Heat Flux at Stagnation Point

This heat flux has been used with a distribution function in a thermal analysis. A 10% safety margin had been added to take into account the coupling between heat flux and temperature[3]. The silicon fabric has a negligible heat capacity, but its emission coefficient has a major influence on the temperature. Figure 12 shows the temperature at various satellite locations during re-entry with the highest temperature at the outer diameter of the heat-shield. The comparably thick titanium part absorbs the heat flux and require a longer time to cool down again.

[2] This task has been performed by OHB-System
[3] Higher Temperatures decrease the heat flux

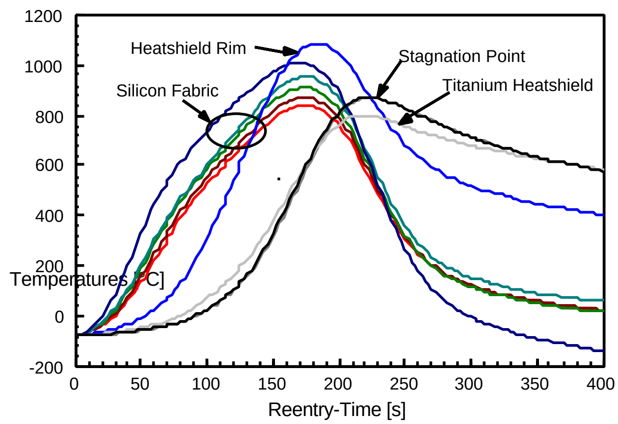

Figure 12: Temperature During Re-entry (ε = 0.6)

As a result of the thermal analysis, the titanium heatshield had been enlarged to cover the parashield hinges, which are exposed to very high temperatures (see Figure 1). It should be mentioned, that the emission coefficient used for the silicon fabric is a conservative number, assuming a higher material degradation than specified.

Re-entry Scenario

The primary mission goal, set by the German Space Agency DARA, called for a safe landing at the predetermined place with absolutely no risk that BREM-SAT 2 causes damage or injury to people. BREM-SAT 2 has constantly been compared with other conventional re-entry capsules, although it differs significantly from these. Conventional capsules, mostly converted from military programs, had been designed with a high ballistic coefficient, which causes a high impact velocity in case of a parachute failure. In addition, these vehicles will always return to Earth, whereas BREM-SAT 2 will be destroyed during re-entry if the heat-shield does not open correctly. The parashield design adds significant safety to a re-entry mission.

Due to the safety concerns, it was decided to deploy the parashield only after the correct firing of the retro motor occurred, as recorded by accelerometers. A mobile ground station will ultimately decide if the heat-shield can be deployed or not. After re-entry, the comparably low free-fall velocity allows to use a conventional parachute, deployed by a timer or a baroswitch. At the same time, a radio beacon at VHF frequency is activated to locate BREM-SAT 2. The large battery required by the material science experiment supports a long transmission time of up to five days.

Conclusions

The preliminary design study to determine the feasibility of a parashield re-entry vehicle based on the BREM-SAT design has given us confidence in a successful mission. The parashield design allows use of a small satellite for material science research and re-entry measurement, new applications for small and low-cost satellites. Due to the re-use of BREM-SAT 1 components, costs can be saved for the standard subsystems, e.g. attitude control, onboard data handling and power.

We like to acknowledge the financial support by the German space agency DARA. The cooperation of the University of Maryland is highly appreciated, as is the cooperation of OHB-System and HTG Göttingen. Finally, Figure 13 depicts our vision of BREM-SAT 2 after its re-entry.

Figure 13: BREM-SAT 2, Landing After Re-entry

References

Barczy, Paul: "Fibrous Eutectic Solidification", Department of Nonmetallic Materials, University of Miscolc, Hungary

Königsmann, Hans J., Oelze, Holger, Rath, Hans J.: "BREM-SAT - First Flight Results", *Proceedings of the 8th USU Conference on Small Satellites*, Logan, 1994

Detra, R.W. et al.: "The Drake Brake Manned Satellite System", Research Report # 64, AVCO-Everett Research Laboratories, Everett, MA, Aug. 1959

Akin, David L.: "The Parashield Entry Vehicle Concept: Basic Theory and Flight Test Development", USU Conference on Small Satellites, Logan, 1990 (not included in the proceedings)

Königsmann, Hans J.: "The Case Study BREM-SAT", in Wertz, J. (ed): *Reducing Space Mission Cost*, Kluwer Academic Publishers, 1996

Wiegand, M: "Auslegung und konstruktiver Entwurf eines entfaltbaren Hitzeschutzschildes" (Design of an Deployable Heat-shield) , TU Braunschweig/ Universität Bremen, 1994

Magazu, H. K.: "Aerothermodynamic Calculations on the Parashield Re-entry Vehicle", Master Thesis, University of Maryland, 1995