MIRKA2: SMALL RE-ENTRY DEMONSTRATOR FOR ADVANCED MINIATURIZED SENSORS.


1 Institute of Space Systems, Raumschiffzentrum Baden-Württemberg, University of Stuttgart, Pfaffenwaldring 29, 70569 Stuttgart, Germany, herdrich@irs.uni-stuttgart.de
2 Keltec GmbH, Keltec, Jägerweg 2, 82139 Starnberg, Germany.
3 German Aerospace Academy (ASA), Steinbeis-Hochschule Berlin GmbH (SHB), Forum 1, Konrad-Zuse-Platz 1, 71034 Böblingen, Germany.
4 Jaime Esper, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

Introduction: The following abstract is based on a feasibility study for a micro return capsule (Mikro-Rückkehrkapsel, or MIRKA2) carried out in April of 2012 at the Institute of Space Systems (IRS) of the University of Stuttgart, in Germany [1]. This study proved the feasibility of a worst case scenario for a small spherical capsule for atmospheric re-entry research. In addition, a second design based on the Cubesat form-factor was developed for the Cubesat Application for Planetary Entry (CAPE) mission’s proposal to the NASA Office of Chief Technology Edison announcement.

The research focus of IRS includes, among others, the qualification of heat-shield materials and the development of flight instrumentation. In the past, the IRS has participated in the following re-entry missions: X38[5], EXPRESS [8], EXPERT [2], SHEFEX II [5] and the first MIRKA [3]. Furthermore, the institute took part in the airborne observation missions of the re-entries of STARDUST [4], ATV “Jules Verne” [4] and HAYABUSA [5]. Building on this experience, the current mission has been designed to test and verify the new Resin Impregnated Carbon Ablator (RICA) material [6], developed by NASA Goddard and the IRS, and to validate a new miniaturized entry vehicle.

Motivation: One of the main objectives of the re-entry mission is the flight qualification of a new Thermal Protection System (TPS) material developed by NASA Goddard Space Flight Center (GSFC) and the IRS in Germany. The Resin Impregnated Carbon Ablator (RICA) is a high-temperature ablator tested for hyperbolic entry into Saturn’s moon Titan and other planetary atmospheres, including Earth’s re-entry. By far, this TPS also supports the application of CubeSats as entry vehicles for atmospheric research, a significant objective that brings planetary entry exploration within the reach of University-financed research projects. Other objectives are the validation of existing numerical atmospheric re-entry models; technology demonstration of commercial off-the-shelf (COTS) products exposed to extreme environments; and utilization of Analog Resistance Ablation Detector (ARAD) sensors for the RICA material.

Mission Description: MIRKA2 is expected to slowly spiral down from a 400 km circular orbit, and re-enter Earth’s atmosphere on a shallow flight path angle. It will communicate via a relay (carrier) spacecraft from which it separates prior to re-entry. In order to determine the possible mission trajectories, simulations were performed with the IRS’ in-house simulation tool REENT [7], which uses the atmospheric model NRLMSISE-00 with F107, F107A, and AP set to 150, 150 and 4, respectively, a gravitational model including J2 to J4 perturbations, and using Earth centered coordinates for the integration of the equations of motion.

The assumptions made for the calculation are as follows:

- Launch in September 2014, at 40º inclination.
- Propulsive deorbiting with 1 mN thrust and an $I_d$ of 850 s, with an on-off duty cycle of 50% over an 85 minute orbit.
- $C_D$ of the joint system during deorbit is 2.3.
- $C_D$ of both the re-entry capsule and carrier spacecraft after separation is 1.5.
- $\Delta v$ at separation is 5 m/s.

The variation of the vehicle’s drag coefficient over altitude is modeled by adjusting the atmospheric density from its nominal value, +/-80%.

Figure 1 depicts the mission duration for various densities of the atmosphere. The difference between the worst case and best case assumptions with respect to mission duration is approximately 3.5 days, 17.5 days being the longest mission and 14 days the shortest.
The separation from the carrier spacecraft is defined to occur at an altitude of 110 km, whereas the entry phase ends at an altitude of 20 km. The maximum deceleration in the worst case for a variation of the atmosphere density of -80% is approximately 12 g for an entry velocity of approximately 7.3 km/s.

Figure 2 shows that variations of atmospheric density do not lead to significant changes in the peak convective heat flux (approximately 1.8 MW/m²). However, the phasing of the peak does change significantly.

**Capsule design:** The aeroshell design presented here is driven by the Cubesat form-factor constraints, whereas the subsystem arrangement is defined by the requirement to situate the Center of Gravity (CG) as much forward of the Center of Pressure (CP) as possible to ensure a stable flight.

**TPS Heat Shield:** The main objective of the Thermal protection system (TPS) is to withstand the thermal loads during re-entry. The TPS heat shield consists of three different layers: an outer layer 5 mm thick made of the RICA ablator material, a variable thickness low-density insulator (DLR), and the “cold” aluminum structure with a thickness of 3 mm. Properties of the insulator materials are given in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>RICA (Low-density insulator)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>1360</td>
</tr>
<tr>
<td>Thermal conductivity [W/(Km)]</td>
<td>5.2 – 8.1 (Max 17)</td>
</tr>
<tr>
<td>Specific Heat [J/(kgK)]</td>
<td>1400</td>
</tr>
<tr>
<td>Heat of ablation [MJ/kg]</td>
<td>77 - 178</td>
</tr>
</tbody>
</table>

**Thermal Analysis:** For the thermal analysis a convective heat flux of the trajectory with 0% variation of the assumed atmospheric density is used. Since the distribution of the convective heat flux is not known, the peak heat flux is imposed to the surface at the stagnation point over 25% of MIRKA2’s spherical nose, and half is imposed on the rest (consistent with analysis from the European reentry capsule EXPERT). Based on these boundary conditions, and assuming radiative cooling alone, the temperature distribution over the surface is shown in Figure 3 for the CAPE reentry capsule. Once ablation is entered into the model, the temperatures are expected to decrease considerably.

**Instrumentation:** During the spiral-down phase, a pair of Flux (Φ) Probe Experiment (FIPEX) sensors gathers information about the atomic oxygen and atmospheric density. Accurate measurements of tri-axial and rotational acceleration forces give the opportunity to describe the time profile of attitude and altitude, and to characterize high and low-altitude atmospheric properties. The probe enters the denser atmosphere at about 100 km where the second series of measurements begins. The heat load is recorded by five pairs of thermocouples. Ablation processes along the probe
body are traced by three ARAD sensors, which measure the regression of the ablator. Possible sublimation and ionization of the heat shield material is observed by a radiometer placed at the stagnation point. This measurement location is also used by a pressure gauge. The data is stored and transmitted by a small onboard computer, allowing communication with the host satellite via radio link. A global positioning System (GPS) tracker is used to trace the flight path and to update the Inertial Measurement System (IMU).

Instrumentation for main mission objective. Since qualification of the new RICA material is one of the main scientific objectives, it is essential to measure the distribution of temperature and heat flux over the probe. In addition, TPS material recession rate will be measured using direct and indirect methods. Sensor locations are shown in Figure 4.

To measure the temperature profile inside the TPS layer, ten thermocouples (Omega P30R, Type B, operational at temperatures of up to 1800 °C) are distributed within the material. The thermocouples are arranged in pairs in two different depths inside RICA. These pairs are distributed over the surface at five positions, allowing measurement of the temperature distribution over the surface and over time. The thermocouples are arranged in a spiral configuration to reduce the influence of unsymmetrical heat fluxes due to aerodynamic effects during re-entry. It is important that the exact position of each thermocouple be determined after integration via X-ray or Computed Tomography (CT), in order to minimize measurement errors.

A pressure transducer (Measurement Specialties EPIH, Range 0 bar to 0.35 bar) will be used to record the total pressure at the stagnation point area. In order to detect pressure oscillations, which might occur due to tumbling, a second pressure port is needed in an off-stagnation point location. By using static pressure values from atmospheric models, which are relatively well known for altitudes below 100 km, the dynamic pressure at each point of the re-entry trajectory can be extrapolated.

The recession rate of the RICA material will be measured by three ARAD sensors. Each ARAD device consists of a narrow rod made of the ablating material itself (carbon fiber phenolic) wrapped with alternating layers of insulating tape (Kapton), Platinum-Tungsten wire, another Kapton layer, and Nickel ribbon (Figure 5). The measurement methodology is based on the fact that char produced by ablated Kapton is electrically conductive. Excited by a constant current the Platinum-Tungsten wire and the Kapton char complete the circuit. With the ablator thickness decreasing in time, the Platinum-Tungsten wire shorts and therefore its resistance decreases. By measuring the voltage across the Nickel sensing wire and the Platinum-Tungsten wire, the recession rate of the RICA material can be determined [9]. The working principle of ARAD sensors is illustrated in Figures 6 and 7. ARAD sensors have flown on the Galileo Space probe [10]. Before using existing ARAD hardware on MIRKA2 however, it is necessary to ascertain whether the sensor shows recession characteristics similar to RICA. Otherwise the core material would need to be modified from the original carbon fiber phenolic to RICA or a material with compatible thermal behavior. Qualification of the ARAD sensor for mid-density ablator materials up to TRL 6 has already been performed by NASA Ames Research Center [10]. In MIRKA2, one ARAD sensor is installed at the stagnation point and two at different positions within the TPS in order to acquire data on the ablation rate distribution (Fig. 4).
One of the reaction byproducts of the ablation process is CN, which radiates strongly in the wavelength range from 320 nm to 440 nm. The radiation intensity at the stagnation point is hence measured by a thermopile sensor (Dexter 2M thin film), with a filter tuned to these frequencies. This measurement enables a comparative decomposition between carbon recession, and the overall recession of the ablator.

Additional Measurement instrumentation. Due to the relatively long duration of the de-orbit phase, the capsule will spend most of the mission time in the upper regions of Earth’s atmosphere. The atmospheric models for these regions are not as well developed as those for lower altitudes. This fact, combined with a very conservative capsule design in terms of available electrical energy, provides an opportunity for studying the upper regions of the atmosphere using solid electrolyte gas sensors, called FIPEx. These sensors are capable of measuring the concentration of either atomic or molecular oxygen. By using two sensors it is possible to gather information about the gas composition of the upper atmosphere at different altitudes, which adds value to the scientific objectives of the mission.

Position and Attitude Determination. A GPS receiver will be used to record the capsule trajectory during re-entry. This is required in order to precisely correlate sensor data to a specific point in the trajectory. Other tasks for the GPS receiver are to correct the Inertial Measurement Unit (IMU) drift errors, and to trigger all remaining sensors once the capsule is below 110 km. The GPS-receiver is flight-qualified and built by DLR Oberpfaffenhofen [12].

Common IMUs are relatively large and heavy. Advances in the field of solid-state technology allow for small, laser-based gyroscopes and accelerometers. Current devices have reached high accuracy and their commercial use in modern game controllers has led to cheaper prices. The state of the art ST Microelectronics STM32L141 combines the function of gyroscopes and accelerometers in one small unit. This leads to a drastic reduction in size and power requirements. The IMU allows high accurate measurements along all three translational and rotational degrees of freedom, and will be used to record MIRKA2’s attitude and deceleration at all times in the trajectory and during radio blackout. When the GPS signal is lost during blackout, the IMU is also used to determine the position and to estimate the trajectory by dead reckoning.

Auxiliary Subsystems. Miniaturized bus subsystems are essential in enabling the measurement objectives of MIRKA2.

Electrical power is supplied by two Li-SOCl2 batteries (SAFT LSH 20) with high nominal power output as well as a high capacity. A DC/DC converter (Aeroflex VRG8662) will ensure that all electronic systems are supplied with the proper voltage, whereas an amplifier (Aeroflex RHD5900) will boost the current or voltage outputs of the analog sensors.
The onboard computer (OBC) is a small microcontroller (ST Microelectronics STL32L152xx). In addition to handling and processing digital data, this device features integrated Analog-to-Digital converters (ADC), and is used to process all analog sensor data.

The transmitter constitutes the only means of retrieving sensor data as a recovery of the capsule after impact is not planned (would obviously be the case for a planetary entry mission as well). For the data transmission to the carrier spacecraft a Cadet Nanosat Radio manufactured by L3 Communication Systems-West is used as a baseline. A backup transmitter from European manufacturers, e.g. Clyde-Space, may be used if there are ITAR concerns. Although the Clyde transmitter has a lower mass and power need, it can only broadcast about half the data rate of the Cadet Nanosat Radio. Nevertheless, due to a comparably small amount of data, the transmission can be completed in a short time period and this is a viable alternative.

Finally, a heating unit has to be used to ensure the probe’s internal components remain within safe operating limits. Heating units are available in small sizes, and a candidate is the Polyimide Thermofoil™ heater model HK5160R157L12 from Minco, with dimensions of 12.7 mm x 2.4 mm, a power draw of 1 W at 5 V, an effective area of 0.84 cm², and an electrical resistance of 25 ohms.

References: