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TITLE:

Mini-Irene Flight Experiment (MIFE) - Executive Summary Report

ABSTRACT:

AUTHORS: Vernillo Paolo

Gardi Roberto

APPROVAL REVIEWERS:

APPROVER:

Gardi Roberto

AUTHORIZATION REVIEWERS:

AUTHORIZER:

Vernillo Paolo

DISTRIBUTION RECORD:

Borrelli Salvatore; De Stavola Phyllis

Luca Ferracina (ESA)

MINI-IRENE FLIGHT EXPERIMENT (MIFE)

MINI-IRENE EXECUTIVE SUMMARY REPORT

REVISION LIST

REV.	DESCRIPTION	DATE	EDITOR
0	**First Issue**	07/04/2023	P. Vernillo (CIRA) R. Gardi (CIRA)
1	**Second Revision** Implemented comments of ESA	20/04/2023	P. Vernillo (CIRA) R. Gardi (CIRA)
2			

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FIGURE INDEX

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LIST OF ACRONYMS

ARD	Atmospheric Re-entry Demonstrator
CFD	Computational Fluid Dynamics
CMC	Ceramic Matrix Composite
COTS	Commercial Off The Shelf
ECSS	European Cooperation for Space Standardization
EGS	External Gas Spring (architecture)
ESA	European Space Agency
GNC	Guidance Navigation and Control
GSE	Ground Support Equipment
IGS	Internal Gas Spring (architecture)

NGS	Nose Gas Spring
OML	Outer Mold Line
PWT	Plasma Wind Tunnel
RFQ	Request for Quotation
TBD	To Be Defined
TBC	To Be Confirmed
UGS	Umbrella Gas Spring
VMI	Vehicle Model Identification
WP	Work Package

1 DOCUMENTATION

1.1 Applicable documents

[AD1]

- Mini-Irene Flight Experiment (MIFE) Statement of Work, ESA RfQ 3-14416/15/NL/KML/fg Issue 1, rev.0.

[AD2]

- CIRA CIRA-CF-16-0031, Financial and Contractual Proposal Mini-Irene Flight Experiment (MIFE) and updated proposal dated 4th April 2016, ref. CIRA-POO-16-0369.

[AD3]

- Mini- Irene Flight Experiment (MIFE) ESA Contract with CIRA N. 4000117718/16/NL/KML/fg

[AD4]

- Mini-Irene Flight Experiment (MIFE) ESA CCN.02 to the Contract N. 4000117718/16/NL/KML/fg (Procurement of the Flight Opportunity of Mini-Irene), dated 20 January 2021.

[AD5]

- Mini-Irene Flight Experiment (MIFE) - TN215 - FD Mission and System Requirements Definition (MRSD), Issue 1 Rev.0, dated 12 January 2017.

[AD6]

- Mini-Irene Flight Experiment (MIFE) - TN001 - Interface Control Document with the LV (ICD), Issue 3 Rev.2, dated 1 June 2018.

1.2 Reference documents

[RD1]

- Esrange Safety Manual, REA00-E60, Rev. 5.

[RD2]

- Proposal for MIFE Flight Ticket on S1X3-M15 - SCIENCE-51-20967, ver. 1.0, Swedish Space Corporation, dated 29 January 2021

[RD3]

- SubOrbital Express User Guide, ver. 1.2 dated October 2019, Swedish Space Corporation.

[RD4]

- Maser 15 Pre-Flight Report, DLR MORABA, 21.11.2022, Issue 1.0

[RD5]

- S1X-3 M15 Quick look data (S1XM-384989335-2400), 23 November 2022

2 INTRODUCTION

2.1 Scope and Purpose of the document

This document represents the Executive Summary Report of the Mini-Irene Flight Experiment (MIFE) as required by the Contract [AD3].

It summarized the findings achieved under the Contract [AD3] and the main achievements for a potential sharing to a wider scientific community.

3 MINI-IRENE FLIGHT EXPERIMENT OVERVIEW

The report is focused on the activities relevant to the technology so called 'IRENE' (Italian Re-Entry NacellE). The program still on-going started in 2010 and it was funded by the Italian Space Agency (ASI) and the European Space Agency (ESA). The program is aimed at realizing an innovative, deployable heat shield concept developed by a private aerospace enterprise, ALI SCARL, the Italian Aerospace Research Center, CIRA, and the University of Naples, Federico II, for allowing a payload to descent safely from low Earth orbit to ground. The innovative characteristics of the IRENE lander is the heat-shield deployment mechanism (an umbrella-like configuration based on off-the-shelf materials for the thermal protection. An additional benefit of the umbrella shaped heatshield is the very low ballistic coefficient that after the entrance in the atmosphere reduces the descent and landing velocity thus limiting the need for additional deceleration system or parachutes.

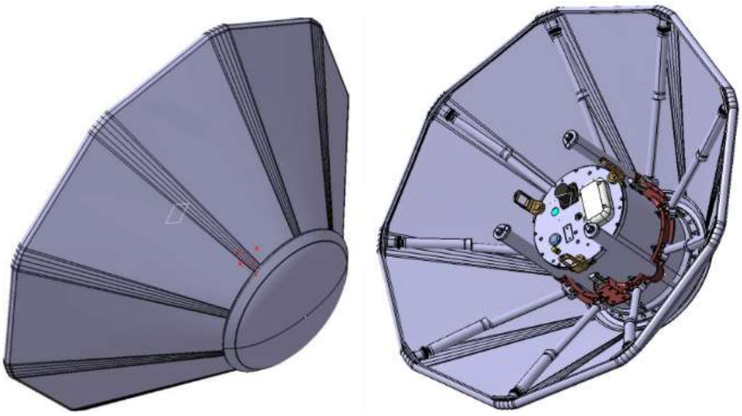

Figure 3. Mini-Irene Flight Demonstrator (front and back view)

The current phase of the program, funded in the framework of the ESA GSTP program [AD2], is called MIFE: "MINI-IRENE Flight Experiment". Its objective is to design and manufacture two test equipment to verify stepwise the functionality of the deployable heat shield, shield, namely the thermal-structural qualification and the mechanical qualification against the heat and pressure loads experienced during the atmospheric re-entry. The first objective has been achieved with a Plasma Wind Tunnel with a first equipment called Ground Demonstrator, the second required a Flight Demonstrator (FD) to be qualified with a suborbital flight. The final objective of the project was to bring the IRENE technology up to the TRL 6.

3.1 DESIGN OF THE GD AND THERMAL-STRUCTURAL QUALIFICATION

A Ground Demonstrator (GD), fully representative for what concerns the effects of thermal loads during the descent phase are concerned, was designed and built in order to be tested in the SCIROCCO PWT facility of CIRA. The GD was a simplified structure w.r.t. the FD but fully representative of the Deployable Mechanism and of the Flexible heatshield of an orbital re-entry mission. Its Deployment Mechanism as the one of the FD was designed around some commercial off-the-shelf (COTS) elements, some oil gas springs.

The PWT test conditions were based on numerical simulation carried out on the GD geometry. Main objective was to realize a test representative of the flight environment, that will not overstress the flexible TPS.

Figure 9. The GD installed in SCIROCCO before the test

Test conditions heat flux has been derived from the nominal orbital reentry trajectory, used for the design, by means of CFD computation in PWT environment.

The reference orbital reentry trajectory peak heat flux was 219kW/m2 in non-catalytic hot wall condition.

The PWT testing criteria were the following:

- At least internal fabric layers of the flexible heat shield not directly exposed to the plasma remains integer.
- All of the mounted Gas Springs remain locked or unlocked depending on the own role inside the two-steps deployment mechanism;

The test was successfully performed on the 28th June 2018 in the Scirocco PWT of the CIRA.

The GD was tested under the before mentioned conditions and for an approx. 3 minutes duration. The following figures shows the Test Article under the plasma flow during the 180 seconds test campaign and suddenly after the test completion.

Figure 10. The GD in the SCIROCCO plasma flow

Figure 11. Details of the TPS parts after the SCIROCCO test completion

Fabric made TPS is the most challenging technology of Mini-Irene. The test was performed at the expected temperature and at the expected settings of SCIROCCO, peak heat flux, Enthalpy and Pressure. The following pictures show the Infrared Camera temperature measurement taken in many spots of the outer TPS surface. It is worth to be remarked that the measured temperature fully comply with the presented thermal model and temperature distribution.

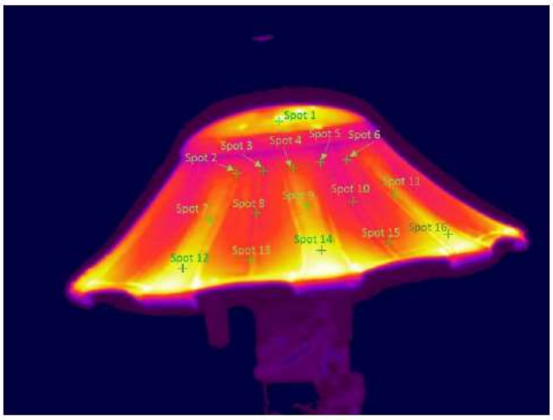

Figure 12. IR image of the GD

The main results of the test shown that the Nextel fabrics reacted to the plasma heat load as expected. The first evident fact was that the three-layer Skirt was still taut all along its surface after the SCIROCCO test. As per one of the main success test criteria, to have the internal layers (playing a structural role in the next atmospheric flight of a re-entry mission) intact and undamaged, the most important finding was that the inner layer reached a temperature in the range of 650°C – 950°C much lower than the maximum allowed by the material. This would constitute a margin of approx. 200% in a future orbital mission Also the Deployment Mechanism based on COTS component, oil gas springs, reacted very well to the test and **demonstrated the suitability of the overall flexible heat shield including a deployment mechanism to the thermal-structural solicitations of an orbital re-entry mission**.

3.2 DESIGN OF THE FD AND QUALIFICATION TO THE ATMOSPHERIC PRESSURE LOAD. THE MINI-IRENE FLIGHT MISSION.

The Flight Demonstrator of Mini-Irene, based on the same heat shield of the GD, same Deployment Mechanism and same COTS oil gas springs, was designed to withstand the Dynamic Pressure load during the atmospheric re-entry. The other objective of the flight was the verification by test of the stability in all the flight regime, especially the transonic one;

according to the literature, capsules open in back side might show unstable behaviour in transonic or subsonic regimes.

Mini-Irene was one of the 12 payloads embarked on the S1X3-M15 mission (with a VSB30 Sounding Rocket) launched from Swedish Launch Base of Kiruna on the 23th November 2022. Mini-Irene was the piggy bag of the payloads stack of the S1X3-M15 launched in Esrange from the Launch Base of SSC. It was attached at the bottom of the payload bay just on top of the first (S30) and second (S31) motors. At an altitude of appx 80 km, after motor separation, it has been release.

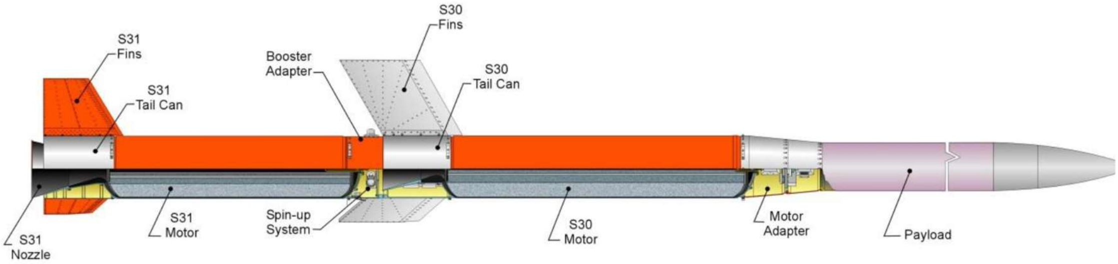

Figure 1 - VSB30 Sounding Rocket

The Flight Demonstrator assumed three configurations during the mission:

- Launch phase with the capsule in Stowed configuration, connected inside the launcher locking and release mechanism;
- Flight after the launcher release and before the heat shield deployment (Stowed Configuration);
- Re-entry phase (Deployed 'umbrella' Configuration), as shown for example Figure 4.

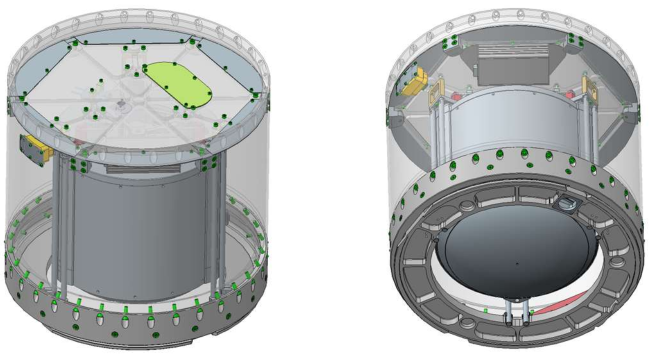

Figure 2 - MIFE Capsule 'Stowed' configuration during the Launch

The Launch of the S1X3-M15 was executed by SSC from the Tower Launch Pad on the 23th November 2022 at the 8.30 CET. The mission consisted of two main phases, the ascent phase,

where Mini-Irene along with the other 11 payloads was stowed in the payload bay and also Mini-Irene is not active for the data collection; the flight phase occurring after the release from the rocket and until the ground landing.
The launch and the next ascent phase of the Launch Vehicle were performed in the nominal way and also a nominal ejection from it was noticed.

For what concerns the main results of the flight phase of the Capsule since the ejection:

- The Launch vehicle brought the Capsule up to the nominal apogee of 257 km allowing, hence, in the next flight in the atmosphere the reaching of 1980Pa of Dynamic Pressure, target of the qualification.

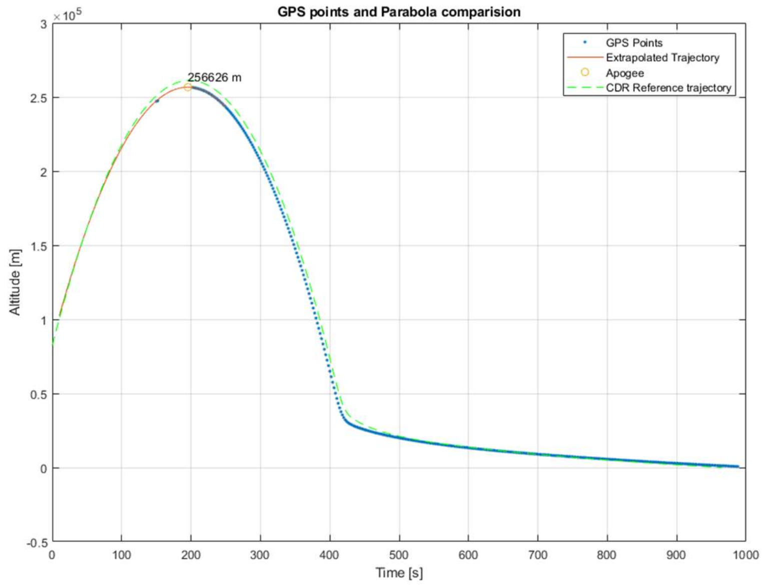

Figure 3 Altitude vs time. GPS data, extrapolated trajectory, apogee and reference trajectory.

- The Capsule deployed the heat shield properly and with the expected delay after the ejection from the Launch Vehicle.

Figure 4 Excerpt of the Footage of the deployment sequence.

- The Telemetry including the GPS coordinates for the localization after the Landing was transmitted nominally since a bit before the Atmosphere Interface and until the Landing. With more details 17 Telemetry messages were transmitted during the flight by the on-board telemetry and collected in real-time from the Ground Station. Before the Atmosphere Interface at higher altitude because of the poor visibility of the antenna toward the Iridium Satellites, no telemetry was received from the Ground Station. The data collected from the telemetry allowed a preliminary post flight analysis, aimed to characterize the flight.
- **The Capsule withstand the aerodynamic loads occurred during the complete trajectory, this was the main objective of the mission.** The next Figure reports the measured load factor compared with the expected one, showing that the capsule sustained an aerodynamic load close to 12g.

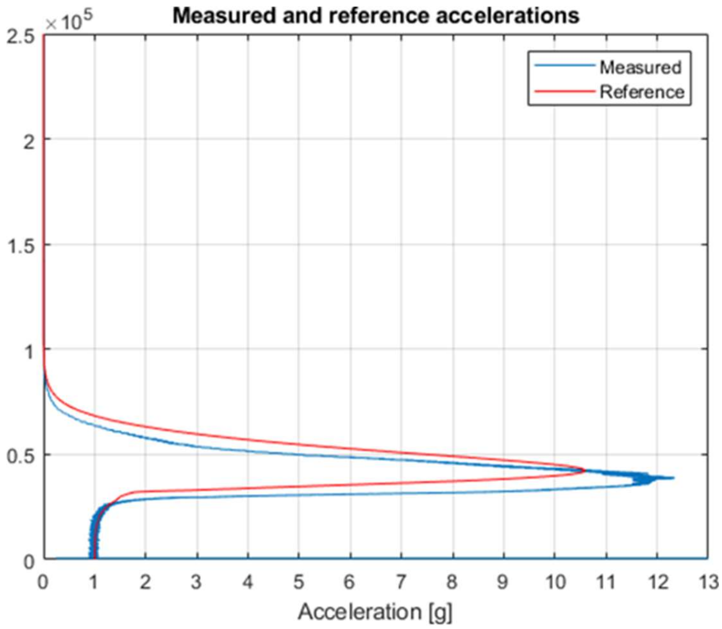

Figure 5 Comparison of flight and predicted load factor during the re-entry

- **Mini-Irene didn't lose the stability and didn't tumbled in every flight regime, the other main objective of the flight**, showing rather from both the camera footages and the data (accelerometers, magnetometers) a very stable attitude and very limited oscillations, especially in the most critical regime, **the transonic**. In the following Figure are shown the trends of the Magnetometers and the Angle of Attract of the Capsule calculated with the accelerometer measures (N.B. the negative values shown are not reliable because are due to the a neglectable value of z-accelerometer, lower than the accuracy of the sensor).

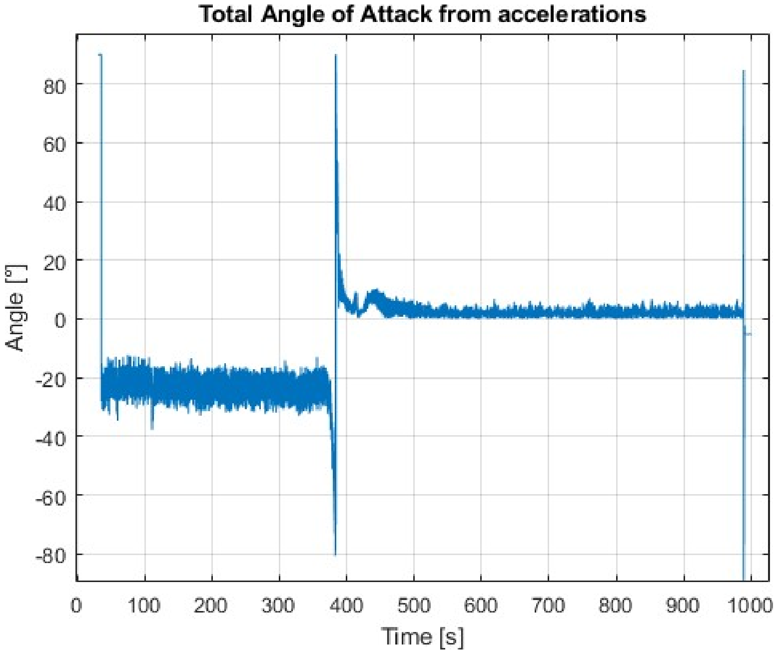

Figure 6 – Angle of Attack of the Capsule calculated from the accelerations

- The landing speed was comparable with the prediction of 20 m/s, confirming the excellent intrinsic capability of aerobrake of the umbrella shaped Mini-Irene. Because of the impact **the Nose** made in ceramic composite and silica foam as expected (all the TPS of Mini-Irene is not conceived to be reusable)broke in the silica foam layer but nevertheless shown ad additional feature of the silica foam to be **a shock absorber, preventing the structure and the payload bay from severe damages**, as confirmed by the next positive post-inspection of the Capsule.

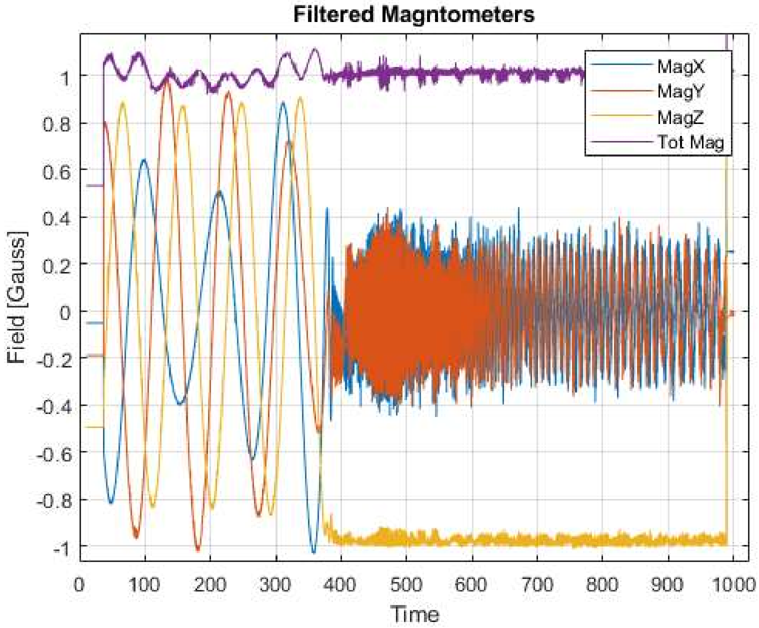

Figure 7 – Magnetometer of Z axis showing stable attitude across the re-entry

- After the recovery and dismounting of the Avionics the **Flight Recorder and Flight Data were recovered** and allowed the detailed post flight analysis.

5 MAIN OUTCOMES AND FINDINGS

The heritage gained from the partners involved along the six years of lifetime of this project and the results of the Ground and Flight Demonstrators testing resulted in some very important findings for the Space Community about the potential usage of the IRENE technology (or other equipment included in its product tree) in future re-entry or even interplanetary missions. In this section these findings are summarized sorted in single chapters. In the first subsection will be summarized the outcomes relevant to the original main objectives of the project whilst in the second one some other also important findings retrieved along with the testing activities developed in the lifecycle of this Study.

5.1 ASSESSMENT BY TESTING OF THE MAIN OBJECTIVES OF THE PROJECT

As summarized in the introductions of this document in addition to the achievement of the TRL 6 of the IRENE technology also some relevant outcomes were expected by the testing of the two demonstrators. Deferring the reader to the more detailed documentation of Mini-Irene for a deeper analysis of the topic, in this subsection will only be provided a synthetic description of that achievement along with the reference to the relevant objective.

Distribution of the re-entry heat load over a larger surface

The Test Campaign in Scirocco and the relevant measurement of the temperature distribution over the flexible TPS has highlighted that the current temperatures were as expected by the numerical simulation and also lower than the maximum allowable of the Nextel. A deployable heatshield result in a very effective distribution of the heat load of the re-entry.

Pressure and G-Load Peaks occurring in less critical air rarefied condition

Both the mechanical stresses for the flexible heatshield occur, in the present geometry and design of the re-entrant payload, at altitude in the range of 45 km where the air density is very low, resulting in a safer re-entry.

Low Ballistic Coefficient resulting in relevant deceleration and limited impact velocity at the landing

The aerobrake shape of the umbrella-like heatshield results in a limited velocity at the impact, in the range of 20 m/s. Future exploitations of this technology have the benefit of limiting the need for deceleration systems, e.g. parachutes, or even nulling it (the post inspection of the

Flight Demonstrator after the flight showed an intact internal structure and still functioning Avionics).

Ergonomics and Cost-effectiveness of the stowed payload to be embarked on the Launch Vehicle

The Flight Demonstrator in the 'stowed' configuration was embarked in the narrower 17" payload bay of a Sounding Rocket, usually suitable only for the small-width of the micro-gravity experiment. An Ergonomic configuration of the payload Mini-Irene at the launch also resulted in an affordable and cost limited way of accessing the space environment.

5.2 AFFORDABLE COTS HEAT SHIELD FOR FUTURE RE-ENTRY OR INTERPLANETARY MISSIONS

The most important achievement of the project was the possibility of setting-up at very low cost a complete process of manufacturing of an alternative, effective and affordable heat shield for re-entry application. Even the procurement of each single raw material used for the manufacturing of the macro-system of the heat shield, namely the OCMC and the Rescor for Nose, the Skirt fabric sheets and the Oil Gas Springs (UGS and NGS) resulted in a very short lead time, e.g. few weeks in every case, being every part Commercial off the Shelf. And the lead time was always the same in the three cases when these same items were purchased, for the manufacturing of the two Demonstrators and the ITE (Integrated Test Equipment, engineering model of Mini-Irene). Also the process of assembling of all the three macro-systems, the Nose, the Skirt and assembly UGS/NGS, run flawless once designed and exploited the proper Jigs or consolidated a proper procedure, especially at the time of the ITE testing for the Bread Board Test Readiness Review. With more detail, the processes of moulding the OCMC of the Nose and of milling the Rescor still of the Nose, both performed by one manufacturer, was very simple and effective. The process of manufacturing the flexible TPS out of the Nextel sheets and of adding the longitudinal and transversal reinforcement bands also was very quick and issueless. For this purpose it was very useful to have a detailed assembling procedure also envisaging the usage of some Jigs, like the Sewing Frame (shown in the following Figures) and the consolidation of the design also achieved with some engineering models.

Figure 8 - The Sewing frame and the process of manufacturing the flexible TPS

The cost of the raw materials and of the manufacturing were in all the cases in line with those of standard process for industrial applications.

In conclusion, having, as explained in the previous sections, properly qualified in the relevant environments the overall heat shield, a future procurement of another heat shield like Mini-Irene or even a series production of heat shields, will require limited assembling time and noticeably lower costs (for the materials and the manufacturing) than the other conventional thermal protection systems for space applications.

5.3 ADDITIONAL FEATURE OF THE NOSE IN ABSORBING THE SHOCK AT THE LANDING

The other main key-advantage of an umbrella-shaped heat shield results obviously in having without any effort already a decelerator for the flight phase in the atmosphere next to the re-entry. Specifically, in case of the Mini-Irene geometry and mass properties the impact landing velocity, as also detected by the flight mission of the Flight Demonstrator, was approx. 20 m/s, certainly a very limited amount of a re-entrant system with no additional decelerators. This limited value probably is not sufficient for a full safe landing in case of more fragile payloads but in this case only an aiding system for the further deceleration will be needed and not the overall decelerator and consequent more weight and allocated volume. The deceleration of course is effective where is present a consistent atmosphere, for instance the entrance in the Martian atmosphere of the IRENE umbrella based technology would be not a very good option.

Another advantage of the technology discovered after the launch of the Flight Demonstrator was the intrinsic shock absorbing property of the Rescor one of the two materials of the rigid

Nose and the main as the thickness to absorb the energy at the landing impact and play the role of shock absorber.

Figure 9 The Capsule (and on the right the trace of the impact) as found after the landing

In case of the FD flight mission, the impact resulted in detaching the rigid Nose from the Capsule and also a capsizing of the Capsule but only once the Nose actually absorbed most of the impact energy, as long as no significant damaged were noticed in the structure, other internal parts and last but not least the Avionic was still functional. Also the intrinsic quality of the technology provides benefit in reducing or limiting the need for shock absorbers or further subsystem and the consequent weight and volume. With reference to the previous finding and chapter, finally, it is very worth to be mentioned that the whole thermal protection system and so forth the Nose of Mini-Irene are low cost and expandable parts, therefore there is really a non-disadvantage in the damage of the Nose or of the heatshield after one re-entry mission.

5.4 AFFORDABLE DATA LINK WITH NO GROUND STATION

Another very important discover of the Flight Demonstrator flight was the proper and flawless of the Iridium on-board transmitter that transmitted to the LEO satellite constellation an amount of approx. 2kb/s of telemetry data including partly the GPS coordinates (used for localizing and recovering the capsule) and with the remaining part of the band the experimental data. Even though a very limited band and the possibility of transmitting lower sampling frequency data, this feature is an important option in those space applications where design constrains prevent the embarking of data links, normally power and volume (heat exchanger is normally needed) demanding or where the need of telemetry arises in a second moment after the freezing of the design. The small and less power consuming Modem used in the Mini-Irene flight mission resulted in a very effective way of retrieving some flight data at very limited effort and also less costs. Since these Modem are suitable for terrestrial or low altitude application, in order to use in the spatial (vacuum and without atmosphere for the heat exchange convection) Mini-Irene application, some not drastic modification of its electronic board, mostly consisting in replacing the electrolytic capacitor, were necessary. These modifications are not trick and fully repeatable in case of other space missions.

5.5 COMMERCIAL AVIONIC EQUIPMENT WITH LIMITED QUALIFICATION EFFORT FOR USAGE IN SPACE APPS

Last discoveries found along with the excellent result of the Mini-Irene flight was the proper functioning of other COTS and for terrestrial applications, once they were subjected in advance to a delta qualification in a relevant environment, e.g. Space Qualification Lab, or subjected to specific testing. These components are the Radio Beacon, second quantity other than Iridium used for the Capsule localization, and the on-board Cameras, normally used in Drone and lower altitude application. In both cases the very limited cost of the procurement, quite neglectable, the limited need of delta qualification (these components were qualified in the already planned Space Qualification campaign for the Capsule) or limited additional specific testing (for assessing the landing impact) resulted in a very effective and low cost possibility to add to Mini-Irene as well as potentially to other avionics for Space Applications some very useful functions, if not planned in the original design or in case of design constrains.

END OF THE DOCUMENT