Executive Summary Report

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Contents

Acronyms

AD	Applicable Document
COTS	Commercial Off-The-Shelf
D4D	Design for Demise
DeCAS	Debris Collision Alert System
ESA	European Space Agency
GPS	Global Positioning System
GSTP	General Support Technology Programme
IDEA-RAP.ID	Initial DE-risk for the Assessment of a Re-entry Analysis Platform for the Investigation of Debris
NDA	Non-Disclosure Agreement
PBS	Price Breakdown Structure
QARMAN	QubeSat for Aerothermodynamic Research and Measurements on Ablation
RAP.ID	Re-entry Analysis Platform for the Investigation of Debris
RAP.IFLEX	Re-entry Analysis Platform for In-FLight EXperiments
RD	Reference Document
TPS	Thermal Protection System
TRL	Technology Readiness Level
VKI	von Karman Institute for Fluid Dynamics
WP	Work Package

Applicable documents

[AD1] Assessments to Prepare and De-Risk Technology Developments Black Box Re-Entry Capsule for Satellites. Prepared by the von Karman Institute for Fluid Dynamics, 2019.

[AD2] IDEA-RAP.ID: Negotiation meeting minutes and attachments. April 2019.

[AD3] TN-1: IDEA-RAP.ID: Technical background and mission requirements, von Karman Institute for Fluid Dynamics, December 2019.

[AD4] TN-2: IDEA-RAP.ID: Preliminary Design, von Karman Institute for Fluid Dynamics, September 2020.

[AD5] TN-3: IDEA-RAP.ID: Business analysis and project implementation, von Karman Institute for Fluid Dynamics, November 2020.

[AD6] IDEA-RAP.ID: Detailed Development Plan, von Karman Institute for Fluid Dynamics, October 2020.

Reference documents

[RD1] Richard G. Stern. Re-entry Breakup and Survivability Characteristics of the Vehicle Atmospheric Survivability Project (VASP) Vehicles. Technical report, The Aerospace Corporation, 08 2008.

[RD2] William Ailor, Ian Dupzyk, John Shepard, and Mark Neweld. REBR: An Innovative, Cost-Effective System for Return of Re-entry Data. AIAA SPACE 2007 Conference & Exposition. DOI: 10.2514/6.2007-6222.

[RD3] William Ailor, Vinod Kapoor, Gary A Allen, Ethiraj Venkatapathy, James O Arnold, and Daniel Rasky. Pico re-entry probes: Affordable options for re-entry measurements and testing.

[RD4] The i-BALL experiment from JAXA.
http://iss.jaxa.jp/en/kiboexp/theme/iball/index.html. Accessed: 2019-06-17.

[RD4] Adam Sidor, Robert D. Braun, and Dominic DePasquale. Red-data2 commercial re-entry recorder: Size reduction and improved electronics design. In AIAA Atmospheric Flight Mechanics Conference, 2014.

[RD6] RED-Data2 thermal protections system testing. https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation. Accessed: 2019-06-18.

[RD7] RED-Data2 capsules. https://www.spaceworks.aero/flight/.

[RD8] Trevor G. Watts. Demise observation capsule (doc) development status, in 4th international space debris re-entry workshop. March 2018. URL: https://conference.sdo.esoc.esa.int/proceedings/isdrw04/paper/22/ISDRW04-paper22.pdf

[RD9] The EntrySat experiment. https://websites.isae-supaero.fr/entrysat. Accessed: 2019-08-07.

[RD10] Isil Sakraker, Ertan Umit, Thorsten Scholz, Paride Testani, Gilles Baillet, and Vincent Van der Haegen. Qarman: An atmospheric en- try experiment on cubesat platform. In 8th European Symposium on Aerothermodynamics for space vehicles, Lisbon, Portugal, March 2015.

[RD11] Piermarco Fattori Martegani. Re-entry broadcasting alert apparatus, system and method, November 23 2016. European Patent EP2880646.

1. Introduction

The present project, named "***I****nitial* ***DE****-risk for the* ***A****ssessment of a* ***R****e-entry* ***A****nalysis* ***P****latform for the* ***I****nvestigation of* ***D****ebris*" (IDEA-RAP.ID), aimed at defining the appropriate framework in which the complex thermo-mechanical environment of the demise phenomena could be accurately recorded during dedicated flight experiments (i.e., Re-entry Analysis Platform for the Investigation of Debris: RAP.ID). This capability, if available, could allow pushing significantly forward the understanding of the demise of the current spacecraft and their components. Furthermore, eventually, it will help the aerospace community to make the D4D real, enabling possible in-operation trade off of innovative concepts to mitigate the risk associated to the re-entry of man-made objects.

The declared purpose of IDEA-RAP.ID was to bring the concept idea of the in-flight experiment to a preliminary design ensuring that i) all the key technologies identified could be brought to the necessary maturity level in a reasonable amount of time and ii) that such a product could, once operational, allows to target an acceptable share of the market of interest for the VKI.

The project was structured following three keywords: **Awareness**, **Design** and **Planning**. The "Awareness Phase" [AD3] was dedicated to i) review the literature on present simulation and ground testing strategies and existing similar concepts of flight experiment; and ii) perform a preliminary survey among relevant space players (e.g., agencies, industries, etc.) to probe their possible interest as users of the in-flight experimental platform, also drafting a list of phenomena of interest to be investigated. Additionally, following the outcome of this analysis, the scientific requirements for the RAP.ID mission were identified.

The "Design Phase" [AD4] covered the preliminary design for the RAP.ID mission and the platform concept. Moreover, a plasma wind tunnel test in the VKI Plasmatron was conceived and executed to de-risk an identified critical component of the envisaged RAP.ID platform.

The "Planning Phase" [AD5] had two objectives i) the identification of potential stakeholder for the design and the operation of the RAP.ID platform and any possible identified connected concept/product/service; and ii) the definition of a business and development plan.

The present document is meant to briefly summarise the work performed describing the main outcomes of the different phases. Interested readers are referred to the relevant applicable documents listed in the bibliography for more details.

2. Awareness

This phase covered the literature review on, tools/models, on-ground experimental activities and in-flight experiments of relevance for the understanding of the demise process of re-entering space debris [AD3].
A clear understanding and an expert knowledge of the numerical efforts being currently done to simulate the re-entry of space debris was considered of importance to conceive and design the in-flight experimental platform. The performed review highlighted several aspects that justifies the development and the evolution of current re-entry analysis tools.
Whether "object oriented" or "spacecraft oriented", deterministic tools for spacecraft re-entry analysis are generally composed by a set of modules that are dedicated to specific aspects of the end-to-end re-entry analysis modelling: atmospheric model; flight dynamics and trajectory; aerodynamics; aerothermodynamics; geometry; structural analysis.n The review analysis performed focused on the aerothermodynamic modules of the most common re-entry analysis tools of each of the two categories. In particular the different treatments employed for the evaluation of the incoming heat flux (convective and radiative), the material conduction, and the material degradation/ablation were presented.
The parallel analysis on the different on-ground experimental strategies was meant to identify the effort made over the last years to provide input data for the numerical tools. Considering the prediction of the impact area of a debris as the ultimate goal, and assuming ideally that the numerical tools are error-free from the modelling point of view (actually the modelling limitations of the conventional tools are numerous), we reviewed the necessary input/properties and the experimental effort undertaken to make them available. The identified categories were: spacecraft geometry and features; spacecraft entry conditions, attitude and aerodynamics; and material properties. Our analysis remarked that testing activities specifically related to investigate the re-entry of space debris are limited by the actual capabilities of the facilities and, at bottom, there is no facility that can reproduce the actual re-entry in all its aspects. The disintegration of uncontrolled man-made space objects is indeed driven by a complex interplay of the several phenomena that could be reproduced only uncoupled and partially in the labs. The performed review revealed that a very limited number of experimental test campaigns was conceived and run to specifically investigate some phenomena of interest for the debris' re-entry problem. The list of identified experimental approached includes: wind-tunnel testing for primitive-shape and vehicle aerodynamics; wind-tunnel testing for aeroheating; re-entry chambers and plasma wind tunnels for thermo-mechanical characterisation of materials; space-debris material testing in plasma wind tunnel; and spacecraft-component testing. In conclusion, the performed literature review highlighted

several limitations of the numerical and experimental approaches. These limitations are often related to the inability to completely reproduce the typical environment, and consequently, fail in simulating accurately the phenomena of a destructive space debris re-entry.

Flight experiments are considered the answer to the above-identified limitations and were the subject of another review. This survey revealed that observations of space debris entering the atmosphere have been carried out since the 1970's. The identified dedicated flight-experiments include: Vehicle Atmospheric Survivability Project (VASP) [RD1]; Re-Entry Breakup Recorder (REBR) [RD2, RD3]; The i-BALL [RD4]; RED-Data2 [RD4, RD6, RD7]; Break-Up Camera (BUC) Demise Observation Capsule (DOC) [RD8]; EntrySat [RD9]. Moreover, additional flight data that, although not directly dedicated to space debris testing, brought some conclusions on the destruction of the flying vehicle were also identified: Automated Transfer Vehicle – 1 (Jules Verne); QARMAN [RD10].

Relevant patents were also screened and the following list was drafted:

- Spacecraft Re-entry Breakup Recorder; US 2004/0254697 A1; W. H. Ailor (2004).
- Spacecraft Hardware Tracker; US 7,557,753 B2, W. H. Ailor (2009).
- Re-entry Broadcasting Alert Apparatus, System and Method; WO2014/045078Al; Tommaso Sgobba (2014).
- Re-entry broadcasting alert apparatus, system and method; European Patent EP2880646; Piermarco Fattori Martegani (2016).
- Crash Survivable Enclosure for Flight Recorder; US 4,944,401; J. B. Groenewegen (1990).

The last step of the “Awareness phase” tried to collect, from research institutions and space industries, the needs and the requirements for possible in-flight experiments related to space debris. A series of interviews was conducted with the main actors of the European space sector. Focus was given to the issue of the space debris demise, but the interviews also covered the aerospace scenario in general and the definition of an adapted flight mission experiment. The actors showed interests in flight experiments and in particular on a space debris demise demonstration mission. Few revealed to be more concerned with the space debris generated from access-to-space operations. Some others considered mainly the end of life of satellites and their ability to demise as the critical scenario. A last group remarked its interest in the design of entry vehicles and defence activities. It appeared clearly that space debris demise is considered by the space industry, in a first instance, as a legal aspect that they have to satisfy as they need to satisfy a customer. They recognize the effort to be made, but they do not have a clear view on any competitive advantage that it could bring. In this context the investment does not appear as a natural step. However, as anticipated, they also clearly see the benefit of a well-organized flight demonstration to consolidate their design tools.

Scientific requirements for a possible mission for investigation on debris

The survey revealed that three main aspects shall be covered/addressed when defining a potential demonstration mission for an in-flight experiment related to space debris. This mission shall be:

1. Relevant, i.e., address all the important physical phenomena of space debris demise.
2. Manageable, i.e., do not involve excessively complex measurements but rather target robust measurement techniques to access all the quantities of interest.
3. Affordable, i.e., remain in the low-cost category for flight experiments.

In view of this analysis, multiple business cases appeared, and it seemed limitative to target a final product "specialized" to study a specific phenomenon (e.g., the breakup), exactly as it would be impractical to design a wind tunnel targeting a single possible experiment to perform. Consequently, the modularity of the system to be designed was confirmed as the key to ensure providing a versatile enough infrastructure able to address a variety of requests from different customers.

3. Design

This phase of the study included three WPs [AD4]: the first one related to the definition of the in-flight experiment mission; the second one devoted to a conceptual preliminary design of the platform to perform this experiment; and the third one dedicated to the experimental de-risking of an identified key component of the platform.

The Design Phase began with the definition of the following mission statement for the foreseen flight experiment:

> In the context of CleanSpace, Clean Sat initiatives and D4D framework, there is a need for better knowledge of the re-entry demise process and associated phenomena. Aerothermodynamic effects and fragmentation are of particular interest. Moreover, attitude and temperature data are needed to validate the existing codes and models. In the short-/mid-term scenario, the RAP.ID system will demonstrate the feasibility and added value of a small-scale, flexible, and cost-effective flight recorder for investigation of debris. In the long term, the system (RAP) could also be used as a standardized "black box" for space systems, or as a platform (RAP.IFLEX) to perform hypersonic flight testing, evaluate thermal protection materials in a re-entry environment, study the rarefied flow regime, or deliver down to Earth small samples from in-space stations/platforms.

Data will ultimately be used by engineers and scientists from space agencies and companies, for codes and models validation and update, debris reduction programs, design of new spacecraft, etc. **The system shall be affordable and versatile (to permit multiple flights). It should be possible to include it in missions of interest without interacting with the primary mission.**

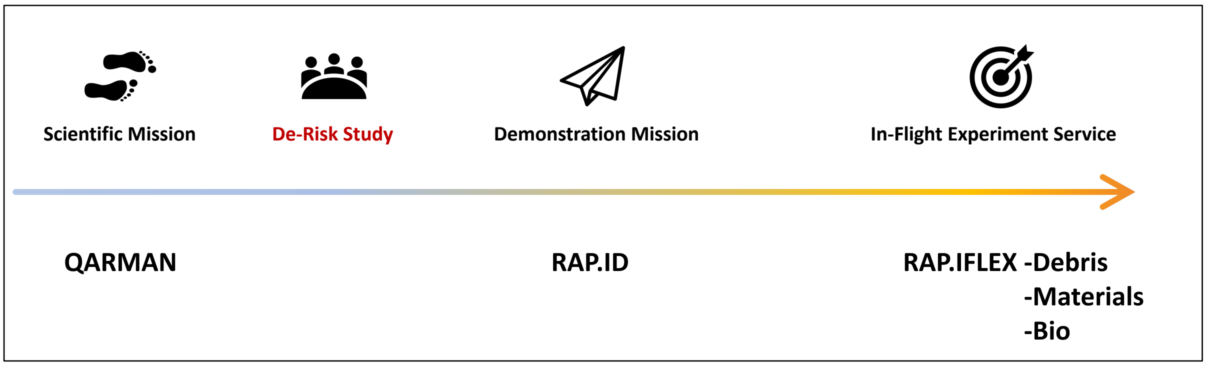


Figure 1: Conceptual path from QARMAN to RAP.IFLEX. The RAP.ID mission is meant to bridge the QARMAN to RAP.IFLEX, demonstrating the feasibility of valuable in-flight analyses maximizing the usage of COTS components to reduce the costs.

With reference to the above statement, primary and secondary mission objectives were put forth:

Primary objective—Provide quantitative intrusive measurements relative to the phenomena and processes occurring during the re-entry of space debris, at low-cost and in a versatile way, no interfering with the primary mission of the object of interest.

Secondary objectives—i) be a first step towards a versatile platform for missions and researches related to re-entry; and ii) leverage the expertise acquired with QARMAN project.

A concept of operations, consisting of 7 steps, was elaborated to meet these objectives: 1) mission of parent spacecraft; 2) detection of re-entry phase; 3) data acquisition and storage; 4) end of phase of interest; 5) detach from parent spacecraft (optional); 6) data transmission; 7) splashdown or crash (end of mission).

Based on this concept of operations, the possible mission scenarios were analysed and compared. The decision to pursue the development of RAP.ID through the conception of a possible multi-purpose CubeSat was taken. The CubeSat scenario appeared to promote more synergies with possible partners/customers within the European aerospace industry. Considering that CubeSats are accessible to many companies and institutions, one can imagine to embark the black box on a different, third-party, CubeSat with limited modifications.

At this stage, a possible collaboration with Aviosonic Space Tech, an Italian company proprietary of an industrial patent [RD11] for a system (the DeCAS) that appeared to have functionalities needed/advisable in/for RAP.ID was identified. A discussion was started with the aforementioned company to analyse the possible commonalities between the different technologies and identify any mutual interests. This discussion brought eventually to establish a fruitful collaboration which, within the present project, practically resulted in i) the tentative to incorporate the system designed by Aviosonic in the RAP.ID platform; and ii) the joint definition and execution of the de-risking experiment.

The preliminary design for the RAP.ID platform started drafting a functional architecture which allowed defining the different phases of the mission and identifying the subsystem necessary to perform it. It was decided that the demonstration mission should consist of three main systems: a **Carrier** (CubeSat), a re-entry **Capsule**, and the **Carrier-Capsule interface**. For the demonstration mission, it was considered to limit to the minimum necessary the payload inside the Carrier, as the main objective is the validation of the platform.

Then, the Product Breakdown Structure (PBS) (see Figure 2) was defined accordingly, and the preliminary selections for the mechanical and the avionics systems followed. The work was then concluded with a preliminary system budget. Product breakdown structure and system/subsystem selection

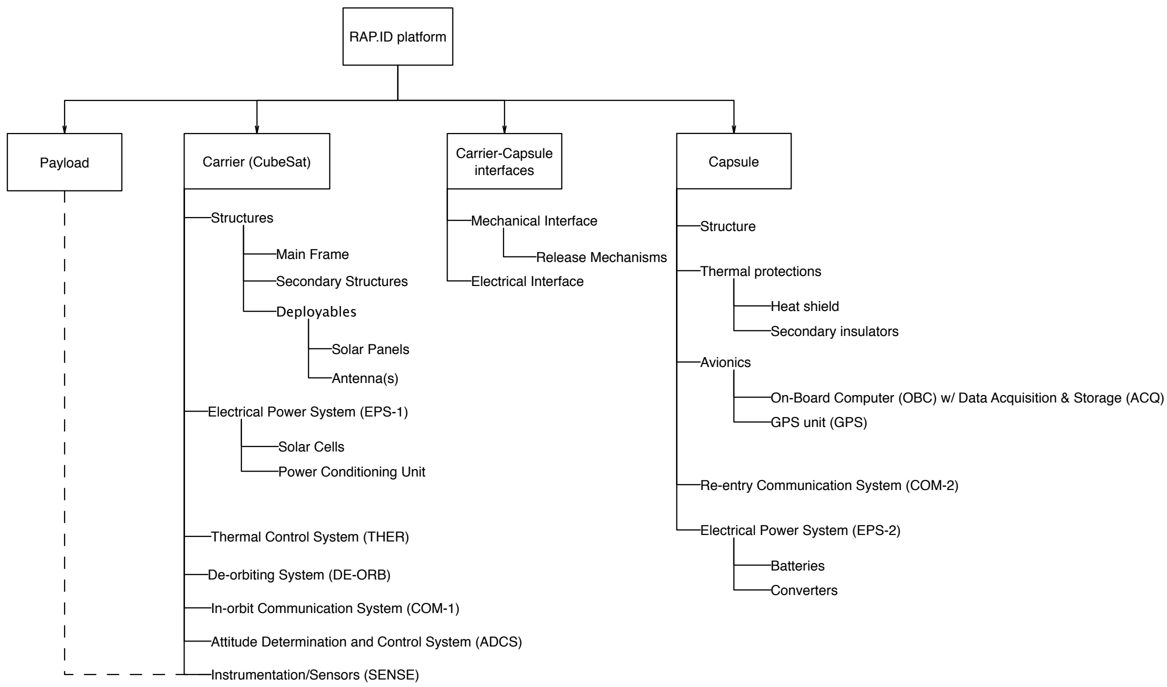


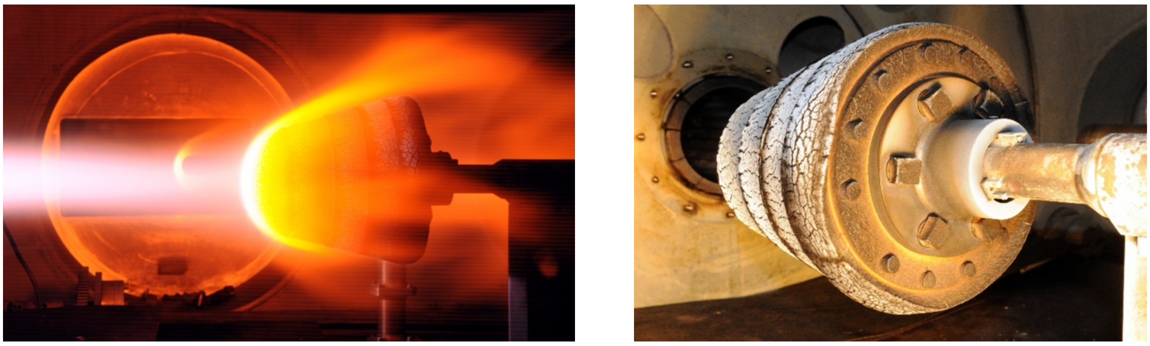
Figure 2: RAP.ID Platform Product Breakdown Structure (PBS).

Following the draft of the Product Breakdown Structure (PBS) given in Figure 2, the work covered in detail a preliminary selection of components suitable for the mechanical configuration and the avionics architecture of the platform. The mechanical-configuration analysis identified solutions for the structure, the deployable appendages, and the thermal protections for either the Carrier or the Capsule. The avionics architecture preliminary design for the Carrier included the electrical power system; the in-orbit communication system; the attitude determination and control system; the instrumentations and sensors; and the de-orbiting system. Similarly, the parallel analysis performed for the Capsule suggested solutions for the electrical power system; the on-board computer; the re-entry communication system; and the GNSS receiver and antenna.

The conclusion of the performed analysis was that, for what concerns the Carrier, the RAP.ID platform should be designed maximizing the usage of COTS components based on QARMAN [RD10] heritage. Differently, for the Capsule, the technical analysis—supported also by the market analysis performed within the present project—suggested that the most effective strategy should be to envisage collaborative efforts to add specific re-entry functionalities, e.g., transferring them from QARMAN technologies, to existing similar concepts already under development (e.g., the DeCAS system of Aviosonic). To this end, de-risking the compatibility of some relevant functionalities has been the subject of the experimental activity performed under WP230 [AD4] and summarised in the following.

De-risking experiment

As anticipated, the experimental activity was carried out in collaboration with Aviosonic Space Tech., and its consortium. The main goal of the experiment proposed within this activity was to test the possibility to employ a revised DeCAS board to allow processing and transmitting data from intrusive measurements (e.g., thermocouples), alongside the main task of computing the impact footprint based on simulated entry data, while immersed in a plasma flow. Although the focus was on temperature measurements for this specific project, the concept could be extended to other relevant quantities of interest for the break-up of space debris, such as pressure, accelerations or mechanical/thermal deformations. The experiment performed on the modified DeCAS board proved the possible co-existence of the alert system and "health monitoring sensors".



(a) During test (b) Post-test rear view

Figure 3: Test and Post-test pictures of the modified DeCAS prototype tested in the VKI Plasmatron as potential black box for the RAP.ID platform

4. Planning

The analysis performed under this last phase set the ground for the implementation of the possible follow-on project/s: the development of the RAP.ID platform and its demonstration mission [AD5]. Moreover, the study conducted and the actions taken under the present activity revealed the possibility to set up collaborations/partnerships that may allow to go beyond the possible follow on, enabling the development and the commercialization of one or more service products. This target service products may represent a possible business for the Belgian aerospace industry. The identification of these service products was achieved thanks to the input provided by the different tasks performed, which analysed both the technical and the commercial viability of the foreseen services.

The identified long-term activity is a recurrent re-entry service to provide an in-flight experimental framework for aerospace industries, agencies and research centres. The general idea is to put in place a standard mission/measurement capability (e.g., material testing similar to Plasmatron, component structural/demise testing). Nevertheless, it was also considered relevant to give to the developed framework enough modularity such that it can be adapted to possible specific needs/requests of the customers.

The RAP.ID mission constitutes the first attempt and was seen as a minimum valuable product for the system that will allow to reach the presented long-term objective. The project life cycle for the RAP.ID development and its demonstration mission was drawn. The present de-risking project was considered part of this development, and its integration into the RAP.ID project was detailed. The possible fully-fledged follow-on activity was identified as a key step in this development.

The proposed phasing is shown in Table 1. The suggested duration of the development part of the project (Phases 0–D) was set to 2.5 years, which should allow Phase E to be completed within 3 years. Particularly, the duration of Phases 0–B for the RAP.ID platform (Carrier, Payload, Capsule and Interface) shall be covered within one year. Note that for the sake of completeness Table 1 indicates a generic phase 0–B that covers the development of both the Carrier and the Capsule. However, the market analysis of the present De-risk suggested that there is a limited financial justification / too high strategical risk (e.g., because of international competitors) to carry on the development of the Capsule within RAP.ID (at least in the early phase). Therefore, it was proposed that the fully-fledged follow-on focuses exclusively on the development of the Carrier, with the Capsule development pursued within a similar time frame but through an independent, parallel project leveraging the converging interests on this technology (i.e., black box) whose usage may go beyond what is foreseen into RAP.ID.

Table 1: Phases for the RAP.ID demonstration mission.

Phase 0	Phase A	Phase B	Phase C	Phase D	Phase E	Phase F
T0 T0+3	T0+3 T0+6	T0+6 T0+12	T0+12 T0+24	T0+24 T0+30	T0+30 T0+36	T0+36 T0+38
MDR	PRR	SRR PDR	CDR	QR AR OPR	FRR LRR FDR	MDR

5. Conclusions

The objective of the present activity was to perform a preliminary analysis on the possibility to exploit commercially the need for in-flight data on the demise of satellites and/or their components/subcomponents and materials.

The performed de-risk study revealed that space players are aware of the D4D constraints that one day may be standard rules for Space Agencies. The need to acquire in-flight data is considered of primary importance. However, costs and benefits of in-flight experiments shall be compared. From the analysis conducted by VKI it emerged that recurrent low-cost experiments could be a winning strategy considering i) the intrinsic stochastic nature of the space-debris phenomenon; ii) the reduced measurement capabilities compared to ground experiments; iii) the high risk of a big single experiment. VKI performed therefore a preliminary conceptual design of a modular CubeSat platform (RAP.ID) that should allow to achieve the aforementioned objective at a relatively low-cost. The modularity of the platform is also guaranteed by the black-box recorder, which is in charge of acquiring, storing and transmitting the data. The market analysis suggested that there are existing technologies being already developed that could serve this scope. A customized version of a promising technology, the

DeCAS capsule (patent of Aviosonic Space Tech), has been tested in the VKI Plasmatron to this end.

Obviously RAP.ID cannot be considered completely representative to study the demise process of a full-scale satellite. However, its modularity would allow recurrent low-cost missions that will be appealing for space players seeking for relevant data on the demisability of components/parts/materials that need to be re-designed following the D4D paradigm. VKI firmly believes that there is no alternative to a modular platform capable of recurrent "cheap" flights to exploit the commercial benefits of the space-debris emerging market.

The final application is a commercial service platform: RAP.IFLEX. The roadmap to reach this goal envisages the preparation of a demonstrator (RAP.ID) and its mission under an ESA GSTP project. With the goal of reaching a TRL 9 by Q1 2024, the next suggested step is a Phase 0-B study for the proposed platform.