**Deutsches Zentrum
für Luft- und Raumfahrt e.V.**

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**Activities of Member States:
Annual report on German space activities, here: reports on research on space debris, including information on practices that had proved effective in minimizing the creation of space debris**

International Activities

In 2008, Germany actively participated to the work of the UN-COPUOS, the UN-COPUOS-STSC, the IADC, the NoC-SDCG, the ECSS-SDWG, the ISO-ODCWG, and actively supported the French initiative on "Long Term Sustainability of Space Activities".

Activities on German Space Agency Level

The Quality Assurance and Product Safety Department of the German Space Agency DLR has tailored the National Space Debris Mitigation Guidelines from the European Code of Conduct of Space Debris Mitigation to German space projects needs. A consolidation process under inclusion of German industry is currently ongoing. It is foreseen to finalize relevant procedures by the end of 2008. The National Space Debris Mitigation Guidelines as part of the complete quality assurance and product safety requirements catalogue will be applicable to national space projects.

German Space Debris Mitigation Research Activities

Research activities in Germany related to Space Debris issues in general cover various aspects, such as space debris observation technology, space debris environmental modelling, investigation of impact physics to get a better understanding of the hypervelocity impact phenomena as well as technologies to protect space systems from space debris and to limit future generation of space debris.

Financing is ensured either via the German national space budget directly or via the European Space Agency ESA. German activities executed under ESA contracts are presented in the corresponding report of ESA.

In 2008, nationally funded research activities in Germany were initiated and carried out respectively as follows:

A. Re-entry Wind-Tunnel Tests and ORSAT/SCARAB Comparisons

This project was the continuation of a long cooperation between HTG (Hyperschall Technologie Göttingen) and NASA to compare both atmospheric re-entry simulation programs, the HTG program SCARAB (Space Craft Atmospheric Re-entry and Aero-thermal Break-up) with the NASA program ORSAT (Object Re-entry Survival Analysis Tool). This cooperation started in1998. Previous studies have confirmed that both tools provide almost identical results for the re-entry of simple shaped objects (i.e. spheres, boxes, cylinders). However, analyses of a complex satellite have shown large differences between the actually predicted ground risks.

The objective of this project was the improvement of a better knowledge of the material's behaviour during the space craft re-entry for more exact predictions of the fragmentation processes.

The project had its main focus on the following topics which had been identified as the most important uncertainty sources:

- Improvement for a more realistic modelling/analysis of the aerothermal destruction of CFRP elements during re-entry

  → Execution of tests in the DLR Arc Heated Wind Tunnel Facility LBK in Cologne
  to investigate material destruction under re-entry conditions

- Improvements for the aerothermodynamic of aerodynamically misshapen construction elements (hollow and/or box-shaped geometries at arbitrary flow directions)

  → Execution of tests in the DLR hypersonic vacuum wind tunnel facility in Göttingen to investigate the aerothermal heating under re-entry conditions

- Comparisons of the fragmentation processes in ORSAT and SCARAB for a simplified generic test satellite

  → New comparison of ORSAT and SCARAB.

<u>Wind-Tunnel Tests for Material Destruction</u>

The necessity for experimental material tests arose out of previous SCARAB re-entry analyses. The aerothermal destruction mechanism and the corresponding material data for refractory materials respectively alloys like Invar, copper, the glass ceramic ZERODUR, bulk CFRP etc. were unknown. Therefore, the arc-jet wind-tunnel LBK was used to conduct material destruction tests under re-entry conditions.

These tests revealed that CFRP does not burn up rapidly due to chemical reaction with the atomic oxygen of the flow, but is destroyed very slowly with very high surface temperatures (> 2000 K) ensuring an effective radiative cooling. Thus, CFRP acts as a quite resistant ablative heat protection for space craft components behind. These results were implemented in SCARAB, but only preliminarily based on the standard material destruction mechanism for metals. Chemical destruction mechanisms, e.g. oxidation, were not implemented.

Space industry is increasingly using honeycomb structures made of CFRP. Typical examples are the European scientific satellite missions GOCE and TerraSAR-X, but also large components of the Ariane-5 upper stages. In order to improve the destructive re-entry prediction for such construction elements, more material tests are necessary. Only based on the results of such tests, new destruction mechanisms can be implemented in SCARAB to reduce major uncertainties for re-entry ground risk prediction.

Material destruction tests have been conducted in the LBK. 14 Material samples and one heat flux probe have been tested under re-entry conditions. Comparison with SCARAB have shown that the used wind-tunnel conditions are similar to those in reality at 53.6 km altitude and with a velocity of 3.6 km/s. The corresponding cold-wall flux was about 1.4 MW/m².

7 Samples were Al-honeycomb sandwich with CFRP face sheets, which were representative samples of the Ariane-5 payload adapter Sylda provided by ESA.

Another 3 samples were from the GOCE project. One sample was again an Al-honeycomb sandwich with CFRP face sheets used for GOCE's solar panel. The other 2 samples were special carbon/carbon materials used within the gradiometer instrument of GOCE, provided by Alenia Spazio Torino.

The remaining 4 material samples were an Al-honeycomb core with glass fibre/epoxy resin face sheets, a plain Ti-alloy and the same alloy coated with CFRP to represent CFRP overwrapped titanium high pressure tanks used in Ariane-5 upper stages, and a 2-part copper model where one half was coated with nickel-chromiu8m for surface catalycity investigations.

The destruction behaviour of all Al-honeycomb models with CFRP or glass fibre face sheets was similar. The characteristic destruction event was the failure of the first face sheet. A wide span of failure has been observed. The carbon/carbon material proved to be very resistant. The plain titanium model was not destroyed; after testing, the model was only covered by a porous oxide layer. However, the same titanium alloy was destroyed, if coated by CFRP. The nickel-chromium coating of the copper model did not show any effect.

For comparisons of the measurement results with numerical simulations, SCARAB has been used in a new, experimental 'wind-tunnel mode'. The primary objective for these SCARAB simulations was to reproduce the wind tunnel conditions, especially the heat flux that were used for the LBK tests.

The general conclusions from these comparisons are:

- SCARAB results and LBK measurements show a good agreement for the general destruction prediction (no destruction for titanium, ablation rate of CFRP, destruction sequence of CFRP-Al-honeycomb sandwich structures), and some similarities w.r.t. temperature evolutions.
- There are large differences for details of the temperature evolution resulting from SCARAB analysis deficits, such as:
    - no chemical destruction processes (e.g. surface oxidation, ablation)
    - incorrect radiative surface for layered models
- The heat loss due to thermal conduction into the model holder should be quantified.

<u>Wind-Tunnel Tests for Aerothermal Heating</u>

Complete Satellites and most construction elements of space crafts are bodies without any usual aerodynamic shape. During re-entry, in principle any flight attitude is possible. In most cases, typical satellite components have the shapes of hollow cylinders (pipes) or boxes, struts with various cross-sections, thin-walled plates and shells.

For aerodynamically misshapen bodies like boxes, hollow cylinders etc. only a limited amount of experimental data is available that could be used for verification of the numerical analysis methods. Therefore, experimental testing of such misshapen bodies is necessary without limitation of the angle of attack.

These bodies are mostly blunt. Thus, aerodynamic force coefficients can be calculated with sufficient accuracy based on a modified Newtonian theory. However, the calculation of that heat flux distribution and the corresponding integral heat flux on the whole body still causes significant problems. Tumbling and open hollow bodies can be additionally flowed through the inside at certain attitudes, what is very difficult to be analysed numerically. But such bodies are very common as space craft components.

The heat transfer tests with 22 different geometric models provided a valuable database on the dependence of the integral heating rate on body shape and angle of attack.

For the tests, two model groups have been used, namely group A for angle of attacks between -90 and +90 deg, and group R for rotating models. In addition, each model group consisted of solid and hollow models.

It is of interest to compare the test results for solid and hollow bodies, which allow also internal flow and internal heating. If the hollow part is pointing in flow direction, one have large internal heating flow and the heating rate is strongly increased, when compared to a solid body with the same frontal are4a. With increasing angle of attack the internal flow and heating is reduced whereas the external heating increases due to larger flow exposed external area. The addition of these two opposing effects results in a smoothing of heating rate change with angle of attack.

Selected he4ating flux results on solid bodies have been compared with SCARAB analysis method. The normalised angle of attack dependence of the heating rates is reasonable predicted with SCARAB methods. A more detailed comparison with SCARAB's analysis method is foreseen within the verification procedure of the new SCARAB 3.1L version, which is at present under development.

Comparison of ORSAT and SCARAB

In order to achieve a better coordination and adaptation of the software systems ORSAT and SCARAB on real space craft re-entry conditions, a simplified generic test satellite has been used for comparisons of the results of the numerical simulation of the fragmentation processes and predictions. Such comparisons proved to be very difficult in the past for complex satellites.

The test satellite was a joint development between the NASA and HTG teams. It has a mass of about 400 kg and is not necessarily realistic as its main purpose is to identify different destruction processes during re-entry that lead to different results on ground.

The main difference between ORSAT and SCARAB is the treatment of fragmentation. ORSAT assumes a break-up altitude of 78 km. At this altitude, all modelled objects are 'released to the flow' and are analysed separately. SCARAB analyses the connectivity (touching) between the panelised volume grid in order to identify fragments which have lost their connection due to melting to other parts of the space craft. Loose fragments are analysed separately. The ORSAT approach leads to one instantaneous fragmentation event at 78 km altitude, whereas the SCARAB approach causes a more continuous fragmentation regime with its maximum between 80 and 60 km altitude.

ORSAT and SCARAB Analyses for the test satellite show a good agreement for the trajectory results. The ground impact footprints have similar shapes and are only shifted by about 70 km along track direction.

The comparison of the survivability shows that the agreement for the surviving mass is quite good. However, ORSAT predicted almost more surviving fragments than SCARAB, and a casualty area which was larger than the one predicted by SCARAB. This was a surprising result.

A detailed comparison of the surviving fragments revealed that the large ground risk differences are mainly caused by the different fragmentations of the battery box, where ORSAT fragmentation approach at 78 km altitude all internal components are released as separate fragments and survive re-entry. This results in more impactors. In SCARAB, these internal battery components remain attached together, surviving as one fragment. The higher number of ORSAT’s ground impact fragments strongly increases the resulting ground risk. In general, both scenarios are possible and none appears to be more likely.

It is not possible to decide yet, whether the ORSAT or the SCARAB results are more representative describing the real process of space craft fragmentation during re-entry. Further research is necessary, especially w.r.t. the validation or better the verification of the re-entry simulation programs by observation of real re-entry events.

B. Improvement of Hypervelocity Impact (HVI) Test Capability

Development of an Accelerator for the Laboratory Simulation of Impacts of Space Debris Particles in the Millimetre Regime at Velocities of 10 km/s

The objective of the project is the assessment and improvement of the performance of the test facilities at the Ernst-Mach-Institut (EMI) for simulation of space debris hypervelocity impacts (HVI) on space craft structures and components in the millimetre regime at velocities of about 10 km/s. For the experimental simulation of HVI, EMI is using the light gas gun (LGG) technique, which allows reproducible shots of particles without changing their physical properties. Another objective of the project is the reduction of the loads of the LGG to reduce experiment cost.

In begin of this project the limitations of the gun’s performances were assessed using analytical theories, and the possible performance gain through geometrical changes was identified by numerical simulations. To increase the theoretical performance limit, it was found that a higher light gas pressure is required. Focused on the calibre 4 mm two-stage light gas gun (so-called Baby LGG), the geometry modifications investigated, showed possibilities to optimise the acceleration cycle. The most significant action identified, was a re-design of the high pressure section, resulting in a longer section with a concave shape.

In the first half-year of the reporting period, the preparatory work on the launch tube has been finished. The procurement of the needed materials has been initiated. A new high pressure section part is in production. The sealing between the high pressure section and the launch tube has been modified. The function was demonstrated by numerical simulation of its installation.

TwinGun - Development of a New Accelerator Concept

In begin of 2008 a new project started with EMI on the development of a new accelerator concept for the experimental simulation of space debris HVI. In the above mentioned project, the feasibility of a new accelerator concept, the so-named TwinGun Concept was performed. A concept with the objective to realise the acceleration of millimetre size particles to higher velocities than the current LGG on a reproducible and wear reduced way. The concept is based on the LGG technique. But unlike the current used LGG, the acceleration of the particle in the TwinGun will be generated by two pistons in two parallel guided tubes, connected with the same powder chamber of explosives, and to lead in one launch tube.

By the suitable combination of operations parameters the pressure pulse at the launch tube entrance gets a wider shape in opposite to a conventional LGG. By this 'pressure pulse shaping' a projectile can be accelerated to higher velocities because of a more effective acceleration section. Also it can be avoided that critical pressure limits will be exceeded.

The principle investigations and the basic design of the TwinGun concept are ongoing.

C. Analysis to the German position to the economy and sustainability of space debris mitigation measures

The objective of the analysis is the support for the definition of the national position to the economy and sustainability of space debris mitigation measures in context of the scientific and technical discussions, and to support the position of the German delegation in ESA and international committees such as the IADC and the STSC of UN-COPUOS.

Based on earlier cost to benefit analyses within the frame of the 'Space Debris End-to-End Service' (SDETES) project the analyses here shall be performed more detailed. Other aspects as the historical consideration of space debris mitigation measures, already implemented in space craft design and operation, as well as the judgement of proposals to remove debris from space, expand these analyses.

A literature recherché gave a detailed overview on the basics of cost models as well as the applicability of space debris environment models for the determination of the risk of loss of space craft. Available cost models have been investigated with the result that a modified model has been taken as a tool for estimation of the damage cost of HVI on all historical satellite missions.

Based on the particle flux data of MASTER-2005 the influence of the space debris environment and the temporal development of the risk can be quantified by the combination of satellite cost estimations with risk analyses. The purpose of a systematic analysis of the influence of hypervelocity impacts on historical satellite missions is to estimate the temporal evolution of the threat posed by space debris for space missions and the resulting risk costs for satellite operators. Altogether 3893 satellites were examined and their analysis results evaluated. The determined service life is set to 7 years for all satellites. The respective orbits and the different dimensions of the satellites were considered. Other parameters, such as the design of the satellite wall and its dimensions or the number and types of payloads, were assumed to be identical for all satellites. For every satellite, the costs are estimated depending on its

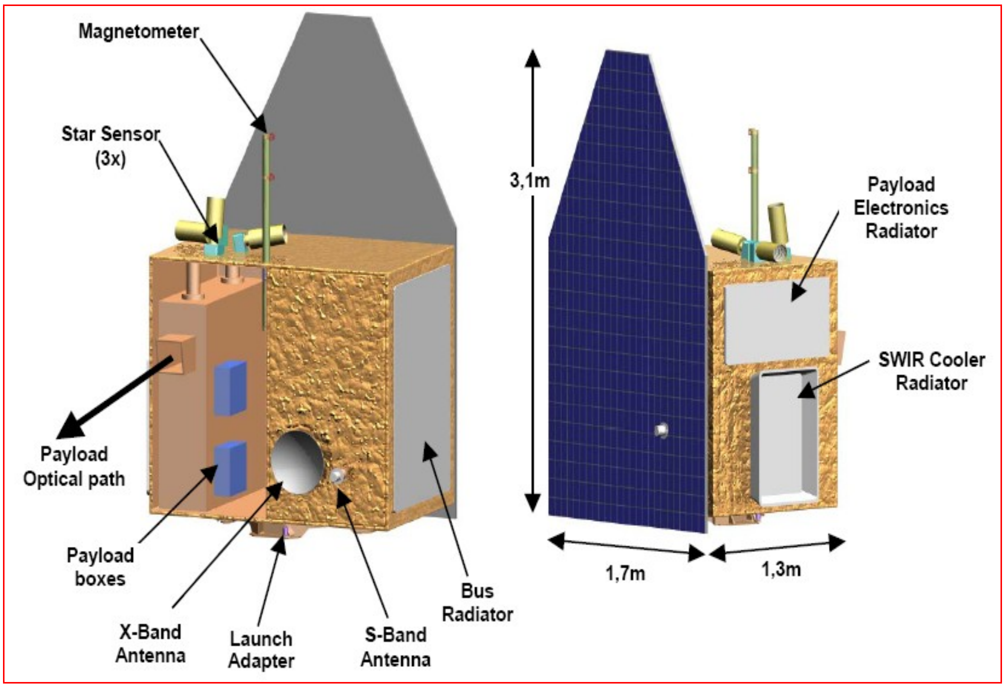
BoL (Begin of Life) mass. Using the space debris model MASTER-2005, an extensive database of the particle flux environment for each satellite is generated. Based on damage equations for wall structures it has been analyzed, which of the impacting particles would be able to penetrate the satellite wall. For every satellite the failure probability is determined. Finally the risk costs are determined from of the satellite costs and the failure probability. These costs indicate the probable loss to the investor by the premature failure of the satellite, because of damage due to particle impacts. The amortization loss indicates the risk costs due to particle impacts on a satellite. By summing up these costs, it is possible to determine the total economic loss due to damages for a particular point in time. The simulation is very complex, because it is necessary to conduct a risk analysis for about 4000 satellite, including the determination of subsystem distribution, failure probability, and cost estimates. The overall damage costs vary between 200 M$ and 700 M$ depending on the selected vulnerability model. This corresponds to the value of 2 or 5 lost satellites. Due to the strong simplifications in the definition of the vulnerability of satellites, these numbers should be understood only as an estimation of orders of magnitude. The work shows that a risk and cost analysis concerning the interaction of space debris with a high number of satellites is possible.

In this project also a literature recherché on various proposals of methods to remove debris from space has been performed. Essentially, the proposed methods for removal of space debris are based on the re- or de-orbiting of objects with laser or tether technologies or by robotics. The listing of the presently known proposals is available but a final evaluation of all these proposals is still open.

Investigation of Application of National Space Debris Mitigation Guidelines to German Space Missions

- EnMAP - “Environmental Mapping and Analysis Program”

  EnMAP is a German hyperspectral satellite mission with more than 200 channels within the broad spectral range from 420 nm to 2,450 nm and a ground resolution of 30 m. EnMAP will be carried by a dedicated small satellite based on existing state-of-the art bus technology and will be sent into an orbit approximately 650 km above the surface of the Earth.
  The main tasks of the EnMAP mission is related to the global determination of ecosystem parameters as well as biophysical, biochemical, and geochemical variables. EnMAP as well encorporates analysis capability for post natural disasters and environmental pollution of



land and water. The mission data will be used for the preparation of future commercialization and operative services.

The application of the National Space Debris Mitigation Guidelines, tailored from the European Code of Conduct of Space Debris Mitigation to the needs of the project, to EnMAP is under investigation.
The work packages comprise analysis of end-of-life measures (in particular the analysis of the passivation process and the implementation of disposal manoeuvre/s) and re-entry safety measures (in particular the assessment of debris stemming from the spacecraft potentially reaching Earth´s surface, the investigation of the related casualty risk to population and properties on ground, and assessment of the related risk of possible harmful contamination of the Earth environment).

- TET - “Technologie Erprobungs Träger” (Technology Test Carrier)

The goal of the programme is to qualify new technological solutions for their application in space projects. It focuses on the in-flight demonstration and verification of components and spacecraft subsystems such as power generation, guidance, navigation and control.

The German Space Agency DLR provides flight opportunities for novel technologies on various platforms and satellites. The core element of the programme is the micro-satellite TET. TET is a German-built satellite with an overall mass of about 120 kg (payload capacity of about 50 kg).

TET will be launched to the low earth orbit. The planned mission duration is one year. DLR provides the TET satellite in addition to the assembly, integration, and test of the system, the mission operations and the data transfer to the user.

The application of the National Space Debris Mitigation Guidelines, tailored from the European Code of Conduct of Space Debris Mitigation to the needs of the project, will be investigated within the frame of TET, focussing on the issues prevention measures (e.g. mission related objects, fragmentation), end-of-life measures (e.g. passivation, de-orbiting, disposal), and re-entry safety.