RISK ASSESSMENT FOR DESTRUCTIVE RE-ENTRY

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ABSTRACT

From 2007 to 2008, Hypersonic Technology Göttingen (HTG) worked on a study called *Risk Assessment for Destructive Re-entry* (RADR). The main purposes of this study were to identify and to quantify the inherent uncertainties of re-entry analysis tools, and to provide possible risk mitigation measures. For these purposes, three basic risk scenarios were specified: a 1-ton-class satellite without propulsion for uncontrolled re-entry, a 6-ton-class satellite with propulsion and the capability to perform a controlled re-entry, and a 1-ton-class launcher upper stage re-entering uncontrolled. Based on the identified uncertainty parameters, variation analyses were conducted for these scenarios with the two ESA tools for re-entry analysis SCARAB (Spacecraft Atmospheric Re-entry and Aerothermal Breakup) and SESAM (Spacecraft Entry Survival Analysis Module). This paper describes the major results of the RADR study.

1. INTRODUCTION

Most of all space programs and projects use atmospheric destructive re-entry as a means to remove hardware (e.g. satellites, launcher orbital stages) from orbit at the end of mission. Atmospheric destructive re-entry is a disposal process by which a spacecraft is brought into the Earth's atmosphere to disintegrate as a result of aerothermal heating and aerodynamic loads. A considerable quantity of fragments can survive in the impact ground swath, typically 10% to 40% of the mass of larger objects. Thus, atmospheric destructive re-entry presents a potential threat to the Earth's population, and to public and private property, because of surviving fragments impacting on the ground.

Atmospheric re-entry is typically achieved by one of the following two procedures. The first entails using the spacecraft's propulsion system (if it is capable of doing so) to propel the spacecraft out of orbit into the Earth's atmosphere. This procedure is mostly used for controlled re-entries in which the ground impact area of surviving fragments is directed into uninhabited areas (e.g. South Pacific Ocean). The second procedure is achieved by leaving a spacecraft in an orbit with a sufficiently low perigee from which the natural atmospheric drag will eventually cause the spacecraft to re-enter the Earth's atmosphere. In general, this re-entry happens uncontrolled, i.e. without control of the footprint location.

The current re-entry rate of space objects which are not intended to be re-used or recovered is estimated to be about 400 tons per year or about 1.1 tons per day. Many surviving re-entry objects impacted near residences, and one person was actually hit by a light piece of debris but was not injured. The annual individual risk of a single person to be hit by a piece of space debris is estimated to be between $1:100\cdot10^9$ and $1:200\cdot10^9$. The annual individual risk to be hit by a lightning ($1:2\cdot10^6$) is about 50 to 100 thousand times higher. Nevertheless, several national space agencies demand the probability of *anybody* being hit by a fragment resulting from one re-entry event to be less than 1:10,000. The annual individual risk based on 100 re-entries per year and 6 billion people is $1:600\cdot10^9$ for this demand. That would be about four to six times less than the currently estimated risk.

Atmospheric re-entry is a hazard of growing concern as historically accepted practices and procedures have allowed man-made objects in orbit to be designed and manufactured without taking into account the risks associated with uncontrolled destructive re-entry at the end of their mission life. For the future, measures should be taken to reduce these risks by establishing design practices or operational procedures either to reduce the amount of debris surviving re-entry and reaching the Earth's surface, or to control the location of the ground footprint by post-mission disposal maneuvers.

2. RE-ENTRY ANALYSIS TOOLS

Re-entry analysis tools are necessary to verify the compliance of space projects with applicable standards and guidelines concerning re-entry safety aspects. Space agencies have already developed tools that assess the re-entry risk of spacecraft during their design phase and/or prior to their re-entry. These programs determine if and when an object/fragment disintegrates during re-entry. The final ground impact locations and the characteristic data of the surviving objects/fragments are calculated.

Two different approaches can be distinguished. The first more simple but also much faster method is named *object oriented* because only the major spacecraft components are modeled as a more or less artificial list of

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simplified geometric objects. Most existing programs are part of this group. The main representatives of this category are NASA's ORSAT (Object Re-entry Survival Analysis Tool) and DAS (Debris Assessment Software), and SESAM (Spacecraft Entry Survival Analysis Module) which is part of ESA's DRAMA (Debris Risk Assessment and Mitigation Analysis) software. The second group uses a so-called *spacecraft oriented* approach because the re-entering spacecraft is modeled completely and as close as possible to the reality in a 3D CAD-like system. To the authors, only one representative of this category is known: ESA's SCARAB (Spacecraft Atmospheric Re-entry and Aerothermal Breakup). In the RADR (Risk Assessment for Destructive Re-entry) study, one representative of both categories was used. Due to availability limitations concerning the NASA tools, these were the ESA tools SESAM and SCARAB.

The main difference between SCARAB and SESAM is that all SCARAB results are the outcome of a completely deterministic propagation of the specified realistic starting conditions [1]. The break-up process is subject to complex numerical simulations and not hard-coded like SESAM's parent/child object approach. SESAM results are also completely deterministic, but the starting conditions and the break-up process include implicit assumptions of the user/developer on how many fragments are generated at which point along the re-entry trajectory. Especially, not more than the modeled objects can survive the re-entry, and thus the maximum risk on ground is predefined and limited by the user.

For example, if 10 objects are modeled in SESAM, the maximum number of surviving objects is also limited to 10. In this case, the maximum surviving mass is given by the sum of the masses of each of the 10 objects (which is usually less than the total mass of the re-entry object). The maximum casualty area and the corresponding maximum casualty risk result if all 10 objects survive completely with their initial cross-sectional area.

In SCARAB, the maximum number of surviving fragments is not limited by the model of the re-entry object. The maximum surviving mass is limited by the initial mass of the SCARAB model (which is usually identical to the real mass of the re-entry object). The maximum casualty area/risk cannot be predicted prior to a SCARAB analysis and is in principle not limited. The casualty area and the casualty risk depend only on the results of the fragmentation and survivability analysis.

3. RADR STUDY

ESA's RADR study, conducted by Hypersonic Technology Göttingen (HTG), was mainly focused on the identification and quantification of the inherent uncertainties of re-entry analysis tools. For this purpose, the study considered the uncertainties resulting from the applied atmosphere model (such as density related parameters like date and daytime, the selected atmosphere model itself and solar activity, and the consideration of wind effects), solar radiation, aerodynamic force and aerothermodynamic heating, initial attitude motion, fragmentation model settings, orbital inclination, and residual fuel content. Systematic variation analyses have been conducted for three representative re-entry scenarios which are described in the following.

4. RE-ENTRY SCENARIOS

For the definition of three representative re-entry scenarios, all satellites and launcher stages with initial perigee altitudes less than 600 km were reviewed, launched between January 2000 and January 2007. The reviewed data was taken from the ESA DISCOS (Database and Information System Characterizing Objects in Space) database. All scenarios were modeled first in SCARAB. Afterwards, the SCARAB models were transfered into equivalent SESAM models.

4.1. Uncontrolled Re-entry Scenario

The satellites from the DISCOS database can be divided into three groups. The first group contains satellites which either have no propulsion system or a propulsion system which is not capable to perform a controlled re-entry maneuver, or which are known to re-enter uncontrolled. The satellites of the second group have a propulsion system which could probably perform a controlled re-entry. The third group had to be excluded from the following steps because of insufficient information.

For the group of uncontrolled re-entering satellites, some information on typical cases was extracted. The group consisted of 37 objects. Their mass range was between 500 and 4000 kg, with a mean satellite mass of 1192.5 kg. The DISCOS database also contains the deployed size of these satellites. The average length, height and width were 1.88 m, 3.28 m and 8.19 m, respectively. Solar array deployment is assumed for the width direction.

A view of the developed SCARAB model for the uncontrolled re-entry scenario (UNC) can be seen in Fig. 1. The satellite is box-shaped with two solar arrays. Its deployed size is 1.8 m x 3.2 m x 8 m. It has a mass of 1189.55 kg.

The UNC satellite contains the following subsystems: electrical power system (EPS), thermal control system (TCS), telecommand, tracking and control (TT&C), on-board data handling (OBDH), attitude and orbit control system (AOCS), solar arrays (SAS), structure (STS), payload (PL), and harness (HRNS).

For a representative distribution of the mass between the subsystems, three real satellite mission were analyzed: GOCE, BeppoSAX and TerraSAR-X. Detailed data for these three satellites are available at HTG because re-entry analyses were conducted in the past. All three are scientific satellites in the 1-ton class. These satellites gave the upper and lower limits of the mass fraction for each subsystem which are shown in Tab. 1. Also the real number of objects for each subsystem was analyzed to get an average number of components for each subsystem. The actual number of subsystem components was determined by the mass and the free space inside the structure.

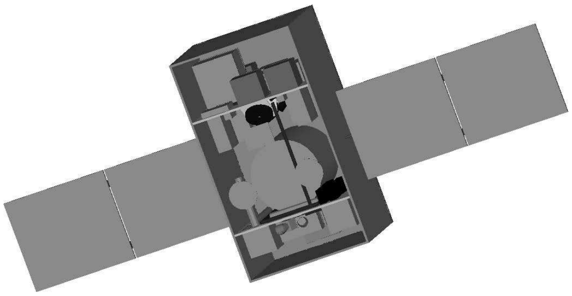

Figure 1. SCARAB Model of the UNC Scenario

Table 1. Subsystem Mass Budget of the UNC Scenario

Subsystem	**Limits**	**Mass UNC**	
	[%]	[kg]	[%]
AOCS	2−10	77.05	6.48
EPS	5−14	120.80	10.16
HRNS	5−8	69.25	5.82
OBDH	1−6	41.31	3.47
PL	33−43	429.82	36.13
SAS	0−8	85.67	7.20
STS	17−33	319.90	26.89
TCS	0−5	29.72	2.50
TT&C	1−3	16.03	1.35
Dry Mass		**1189.55**	

4.2. Controlled Re-entry Scenario

In the investigated time frame, 68 objects were launched which are considered to be spacecraft re-entering controlled. The average mass was 6212.8 kg. Several of these objects were Soyuz or Progress spacecraft, each with a mass of about 7200 kg. The average deployed size was is 2.6 m x 6.7 m x 7.8 m. For most reviewed satellites the solar panels increased the width as well as the height. The main satellite body should therefore be smaller than the average values in height and width direction.

In addition to the subsystems of the UNC satellite, a reaction control system (RCS) is needed for the final de-orbit boost maneuver.

The final model for the controlled re-entry scenario (CON) is shown in Fig. 2. It can be estimated by the figure that it has not the previously derived average dimensions. Due to the big impact of the Soyuz and Progress spacecraft the mean solar array size was too small for a years-lasting satellite mission. It had to be increased reasonably.

The CON satellite's main body is also box-shaped like the UNC. It has the dimensions of 2.2 m x 2.6 m x 6 m. Antennas, some payload components, and RCS thrusters are mounted on the outside as well as the solar arrays which have an area of 88 m^2. The final deployed dimensions of the satellite are 2.6 m x 6.3 m x 20.8 m.

Again, TerraSAR-X, GOCE and BeppoSAX data were analyzed for the determination of the mass budget. In addition, these data were compared with also available ROSAT (2.4 t satellite) data. ROSAT data were used to see how the mass fractions of each subsystem change if the satellite gets larger. The derived final mass budget for the CON scenario can be seen in Tab. 2. The table includes also the initial fuel loading at the beginning of the mission, and the final fuel loading before the de-orbit boost maneuver.

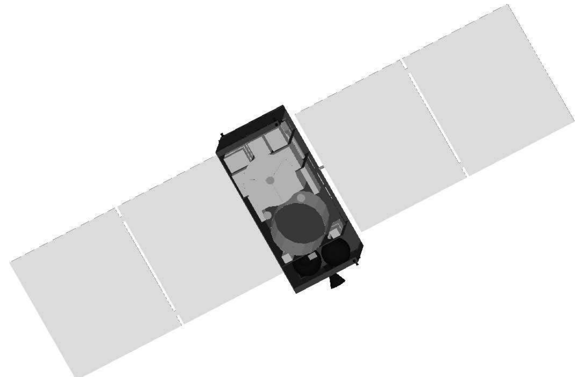

Figure 2. SCARAB Model of the CON Scenario

Table 2. Subsystem Mass Budget of the CON Scenario

Subsystem	**Mass CON**	
	[kg]	[%]
AOCS	259.06	4.26
EPS	256.30	4.21
HRNS	109.92	1.81
OBDH	84.11	1.38
PL	3040.31	49.96
RCS	291.64	4.79
SAS	960.70	15.79
STS	963.55	15.83
TCS	62.81	1.03
TT&C	57.56	0.95
Dry Mass	**6085.96**	
Initial Fuel/Oxidizer	720.00*	
Final Fuel/Oxidizer	102.86†	
Pressure Gas	0.4‡	

*270 kg MMH + 450 kg NTO
†38.78 kg MMH + 64.08 kg NTO
‡Helium

4.3. Launcher Stage Re-entry Scenario

The DISCOS database provided in principle three launcher mass classes with a significantly higher launch frequency. These were the 1-ton class, including mainly Delta-II second stages and CZ 4B third stages (51 cases), the 2.3-ton class, including mainly Molniya third stages (67 cases), and the 4.1-ton class, including mainly CZ 2F second stages and Proton-K third stages (47 cases).

The most frequently occurring stage was the third stage of the Russian Molniya rocket. There were also some Dnepr stages or the Briz stage included in the 2.3-tons class. The second most common class was the 1-ton class, closely followed by the 4.1-tons class.

The choice for the representative launcher stage for this study was the second stage of the Delta-II launcher which has a mass of about 920 kg. The main reason for this choice was that only for this stage sufficient data is available to generate a SCARAB/SESAM model. The Delta-II data were mainly taken from [2] and [3] and some public web sources. The SCARAB model can be seen in Fig. 3. The dry mass of the model is 924 kg. It has a total length of 6.3 m. The main propellant tank has an outer diameter of 1.7 m. The miniskirt's outer diameter is 2.4 m. The mass budget can be seen in Tab. 3.

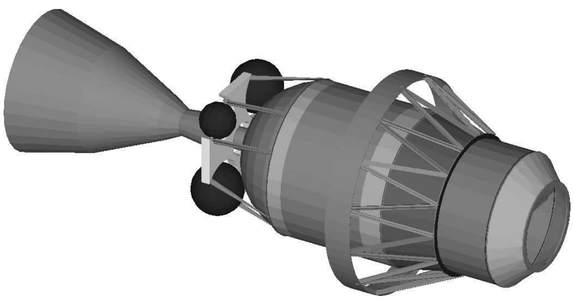

Figure 3. SCARAB Model of the Delta-II Second Stage Scenario

Table 3. Subsystem Mass Budget of the Delta-II Second Stage Scenario

Component	**Mass** [kg]
Propellant Tank	267.675
Thrust Chamber	45.801
Engine Support	52.175
Nozzle	99.594
Guidance Section	164.385
P/L Adapter	20.318
Gas Tanks	81.208
Gas Tank Support	47.802
Mini Skirt Structure	145.385
Dry Mass	**924.343**

4.4. Initial Conditions

The initial conditions in terms of the necessary input data for SCARAB and SESAM for all three nominal scenarios are summarized in Tab. 4.

The Delta-II second stage has the inclination of a sun-synchronous orbit. The UNC satellite mission is assumed to be an Earth observation mission also on a sun-synchronous orbit. Therefore, the starting conditions for the Delta-II second stage are also suitable for the UNC re-entry scenario. The semi major axis was selected such that the initial altitude is about 120 km. All other orbital elements were set arbitrarily for these scenarios.

The CON satellite is initially placed on an elliptical orbit with a perigee altitude of 143 km and an apogee altitude of 775 km. These initial conditions result from the assumption that the CON satellite was operating on a circular orbit with an altitude of about 780 km. At the end of mission, the perigee was lowered to an altitude of 143 km. This was achieved by a sequence of boost maneuvers which are not specified in here. The final de-orbit boost maneuver will be simulated by SCARAB, exhausting all of the final fuel/oxidizer.

The inclination of the CON satellite of 5.2 deg corresponds to a launch scenario in an eastward direction from the Kourou spaceport in French Guiana. This inclination might be unrealistic for an Earth observation mission in LEO, but the CON scenario should also be representative for the controlled re-entry of a GEO satellite stranded in LEO due to GTO injection failure.

The orbit has an initial eccentricity of 0.0462. The de-orbit boost maneuver starts at a true anomaly of 177 deg (near the apogee). Arbitrarily, the right ascension of the ascending node was set to 90 deg and the argument of perigee was set to 0 deg.

As SESAM cannot simulate the final boost maneuver and as the maximum altitude for the implemented US Standard 1976 atmosphere model is 150 km, SESAM needs special initial conditions which were provided by the SCARAB simulations at an altitude of 149.783 km (2071 sec after the beginning of the final boost maneuver), or at an altitude of 129.9998 km (2128 sec simulation time), respectively. The latter initial conditions are relevant for the inclination variation in SESAM as higher inclinations cause an increase of the initial altitude. Therefore, the initial altitude for low inclinations should be low enough to allow an inclination increase and still remaining below the 150 km limit of the atmosphere model. All SESAM initial conditions for the CON satellite (provided by SCARAB) are also shown in Tab. 4.

In SESAM all objects re-enter randomly tumbling. For SCARAB the attitude motion is not predefined. The nominal UNC and Delta-II scenarios started their re-entry in a tumbling motion. This is the most probable motion for them. In SCARAB this is modeled by giving the spacecraft initial angular velocities. The initial roll, pitch and yaw rates were arbitrarily set to 5 deg/s, 10 deg/s, and 15 deg/s, respectively. In a controlled re-entry it is most probable that the attitude of the object is controlled (at least until the beginning of the final boost maneuver). Therefore, the CON satellites starts its re-entry with a stable attitude and without angular rates. However, small angular rates can evolve during the boost maneuver (0.0004 deg/s roll rate, -0.02 deg/s pitch rate, and 0.03 deg/s yaw rate after 720 sec of thruster firing).

5. VARIATION AND RISK ANALYSES

Using the three previously presented scenarios, re-entries were analyzed with different variations concerning the applied atmosphere model, solar radiation, aerodynamic forces and aerothermodynamic heating, initial attitude

Table 4. Nominal Initial Conditions for the Re-entry Scenarios

Element	UNC/Delta	CON		
	SCARAB/SESAM	SCARAB	SESAM	
Date	15.04.2005			
Time, GMT [hh:mm:ss]	00:00:00		00:34:31	00:35:28
Semi Major Axis [km]	6495	6837	6779.509	6779.25
Eccentricity	0.002244	0.0462	0.05812141	0.05817408
Inclination [deg]	96.6	5.206	5.083394	5.083908
Right Ascension [deg]	344.7	90	89.13478	89.12762
Argument of Perigee [deg]	98.3	0	359.9497	0.05732701
True Anomaly [deg]	262.1	177	307.087	310.9761

motion, fragmentation model settings, orbital inclination, and residual fuel content. Each variation run was similar to one of the three nominal configurations except for one variation parameter.

Due to the differences in the two software systems SCARAB and SESAM it was not possible to do all variations equally with both programs. For example, in SESAM a variation of the break-up altitude can be done using a small step size. In SCARAB this special parameter does not exist and therefore it can not be influenced and nor be varied. Also SCARAB runs are very time intensive and may last several days. Therefore, the number of SCARAB runs needed to be reduced to a minimum and only extreme variation cases could be analyzed.

Tab. 5 shows a summary of all 30 SCARAB runs. A similar summary of all 95 SESAM runs is shown in Tab. 6. The ground risk for each analysis case was calculated in terms of casualty area [4]. The mean probability for human casualty P_c resulting from a re-entry event with a casualty area A_c can be calculated as follows:

$$P_c(i) = A_c \cdot \bar{\bar{\rho}}_p(i) \quad (1)$$

where $\bar{\bar{\rho}}_p$ is the average population density on the overflown ground as function of the orbital inclination i of the re-entry object.

6. RESULTS AND CONCLUSIONS

As a final summary, Tab. 7 shows the ground risk standard deviation matrix for all scenario variations analyzed with the two tools SCARAB and SESAM. Based on this matrix, the following conclusions can be drawn:

Negligible/minor variation effects ($< 5\%$): The effect of **atmospheric uncertainties** on the ground risk, i.e. general density uncertainties, including uncertainties resulting from re-entry date, daytime, solar activity, and particular atmosphere/wind model implementations, can be neglected ($< 2\%$).

The effect of **solar radiation heating** on the ground risk, taken into account only by SCARAB, could also be neglected ($\approx 2\%$). However, solar radiation heating is a real environmental effect. As an analysis option of SCARAB with only minor additional computing effort, this option should be activated by default to take into account the small effect on the ground risk.

Uncertainties concerning the **fuel loading** of the re-entry object, analyzed only with SCARAB, have only a minor effect on the ground risk ($< 5\%$). This margin of deviation could be avoided if the amount of residual fuel is known prior to the re-entry analysis. The possibility/risk of explosions has not been taken into account.

A variation of the **solar panel break-off altitude**, analyzed only with SESAM, has only a minor effect on the ground risk ($< 5\%$). This margin of deviation was higher for the UNC scenario ($\approx 8\%$) and lower for the CON scenario ($\approx 1\%$). Nevertheless, the uncertainties resulting from the unknown solar panel break-off altitude are still considered as negligible compared to other uncertainties.

Small variation effects ($\geq 5\% \cdots < 10\%$): A variation of SCARAB's nominal **aerodynamic pressure and shear stress computation** by $\pm 20\%$, which is considered to be a reasonable estimation for the accuracy of the aerodynamic algorithms, provided an average standard deviation of the ground risk of less than 10% for all scenarios. Since this margin of deviation results from a minimum/maximum variation of the aerodynamic forces/torques, the corresponding standard deviation of the ground risk is still considered as acceptable.

Medium variation effects ($\geq 10\% \cdots < 35\%$): Two cases of **initial attitude motion** were analyzed with SCARAB: stable and randomly tumbling. SESAM always assumes randomly tumbling. The two different initial attitude states provided an average standard deviation of the ground risk of 21% for the two uncontrolled scenarios (UNC, Delta-II). This margin of deviation was much lower for the UNC scenario ($\approx 3\%$) and much higher for the Delta-II scenario ($\approx 39\%$). The significantly higher sensitivity of the Delta-II scenario results from the aerodynamic stability of the launcher stage (stabilizing nozzle in the aft). Therefore, the initial attitude motion of a re-entry object and the possibility of aerodynamic stabilization should be considered since they could cause large margins of deviation for the ground risk. Nevertheless, this margin of deviation could be avoided if the attitude motion prior to the re-entry is well-known, e.g. through measurements or deliberate control.

Table 5. SCARAB Variation Analysis Runs

Case	Variation Topic	Scenario	Variation Parameters					
			Epoch	Time	Atmos.	F10.7	Wind	Sol.-Rad.
RADR-1–3	nominal	All	2005/04/15	0:00	MSISE-00	100.0	no	no
RADR-4	atmosphere	CON	**2005/07/14**	0:00	MSISE-00	100.0	no	no
RADR-5	atmosphere	CON	**2005/10/12**	0:00	MSISE-00	100.0	no	no
RADR-6	atmosphere	CON	2005/04/15	**12:00**	MSISE-00	100.0	no	no
RADR-7	atmosphere	CON	2005/04/15	0:00	**US-Stand.-62**	100.0	no	no
RADR-8	atmosphere	CON	2005/04/15	0:00	MSISE-00	**250.0**	no	no
RADR-9	atmosphere	CON	2005/04/15	0:00	MSISE-00	100.0	**yes**	no
RADR-10	solar radiation	CON	2005/04/15	0:00	MSISE-00	100.0	no	**yes**
RADR-11–30	various	All	2005/04/15	0:00	MSISE-00	100.0	no	no

Case	Variation Topic	Scenario	Variation Parameters					
			Aerdyn. F.	Aeroth. H.	Motion	Fragm.	Incl.	Fuel
RADR-1	nominal	UNC	normal	normal	tumbling	normal	96.6	-
RADR-2	nominal	CON	normal	normal	stable	normal	5.206	residual
RADR-3	nominal	Delta-II	normal	normal	tumbling	normal	96.6	-
RADR-4–10	various	CON	normal	normal	stable	normal	5.206	residual
RADR-11	forces	UNC	**-20%**	normal	tumbling	normal	96.6	-
RADR-12	forces	UNC	**+20%**	normal	tumbling	normal	96.6	-
RADR-13	forces	CON	**-20%**	normal	stable	normal	5.206	residual
RADR-14	forces	CON	**+20%**	normal	stable	normal	5.206	residual
RADR-15	forces	Delta-II	**-20%**	normal	tumbling	normal	96.6	-
RADR-16	forces	Delta-II	**+20%**	normal	tumbling	normal	96.6	-
RADR-17	heating	UNC	normal	**-20%**	tumbling	normal	96.6	-
RADR-18	heating	UNC	normal	**+20%**	tumbling	normal	96.6	-
RADR-19	heating	CON	normal	**-20%**	stable	normal	5.206	residual
RADR-20	heating	CON	normal	**+20%**	stable	normal	5.206	residual
RADR-21	heating	Delta-II	normal	**-20%**	tumbling	normal	96.6	-
RADR-22	heating	Delta-II	normal	**+20%**	tumbling	normal	96.6	-
RADR-23	motion	UNC	normal	normal	**stable**	normal	96.6	-
RADR-24	motion	Delta-II	normal	normal	**stable**	normal	96.6	-
RADR-25	fragmentation	UNC	normal	normal	tumbling	**modified**	96.6	-
RADR-26	fragmentation	CON	normal	normal	stable	**modified**	5.206	residual
RADR-27	fragmentation	Delta-II	normal	normal	tumbling	**modified**	96.6	-
RADR-28	inclination	Delta-II	normal	normal	tumbling	normal	**51.6**	-
RADR-29	inclination	Delta-II	normal	normal	tumbling	normal	**5.206**	-
RADR-30	fuel content	CON	normal	normal	stable	normal	5.206	**full**

Table 6. SESAM Variation Analysis Runs

Case	Variation Topic	Scenario	Nominal Value	Variation		
				Lower Limit	Upper Limit	Step Size
RADR-31–39	density (factor) variation	UNC	0%	-20%	+20%	5%
RADR-40–48	density (factor) variation	CON	0%	-20%	+20%	5%
RADR-49–57	density (factor) variation	Delta-II	0%	-20%	+20%	5%
RADR-58–64	solar panel break-off altitude	UNC	95 km	80 km	110 km	5 km
RADR-65–71	solar panel break-off altitude	CON	95 km	80 km	110 km	5 km
RADR-72–78	break-up altitude	UNC	78 km	60 km	90 km	5 km
RADR-79–85	break-up altitude	CON	78 km	60 km	90 km	5 km
RADR-86–92	break-up altitude	Delta-II	78 km	60 km	90 km	5 km
RADR-93	fragmentation acc. to SCARAB	UNC	nominal model	modified model and fragmentation altitudes		
RADR-94	fragmentation acc. to SCARAB	CON	nominal model	modified model and fragmentation altitudes		
RADR-95	fragmentation acc. to SCARAB	Delta-II	nominal model	modified model and fragmentation altitudes		
RADR-96–105	inclination	UNC	96.6 deg	0 deg	180 deg	20 deg
RADR-106–115	inclination	CON	5.206 deg	0 deg	180 deg	20 deg
RADR-116–125	inclination	Delta-II	96.6 deg	0 deg	180 deg	20 deg

Table 7. Ground Risk Standard Deviation Matrix

Variation	Tool / Scenario	SCARAB UNC	SCARAB CON	SCARAB Delta-II	SCARAB All
Thermal Fragmentation Criterion	(at or after melting)	±90.0%	±48.9%	±39.3%	±59.4%
Combined Fragmentation	(all fragmentation related)	±41.7%	±25.3%	±45.4%	±37.5%
Orbit Inclination	(0–90/180 deg)	-	-	±31.5%	±31.5%
Aerothermal Heating	(nominal heat load ±20%)	±25.8%	±7.1%	±43.1%	±25.3%
Initial Attitude Motion	(stable/randomly tumbling)	±2.6%	-	±39.3%	±21.0%
Aerodynamic Forces	(nominal forces ±20%)	±10.1%	±10.8%	±7.3%	±9.4%
Fuel Loading	(empty/+10% of dry mass)	-	±4.3%	-	±4.3%
Solar Radiation Heating	(on/off)	-	±2.0%	-	±2.0%
Atmospheric Uncertainties	(density, wind models)	-	±1.6%	-	±1.6%
All		±37.7%	±15.6%	±44.6%	±32.6%
Tool Related Uncertainties		±41.7%	±16.2%	±45.4%	±34.4%
Mission Related Uncertainties		±2.6%	±4.3%	±44.8%	±17.2%

Variation	Tool / Scenario	SESAM UNC	SESAM CON	SESAM Delta-II	SESAM All
Combined Fragmentation	(all fragmentation related)	±108.7%	±18.0%	±15.7%	±47.5%
SC Break-up Altitude	(60–90 km)	±100.4%	±23.7%	±16.6%	±46.9%
SESAM Model	(standard/modified)	±39.9%	±7.5%	±12.4%	±19.9%
Orbit Inclination	(0–90/180 deg)	±29.4%	±16.1%	±0.1%	±15.2%
SP Break-off Altitude	(80–110 km)	±7.6%	±1.1%	-	±4.4%
Atmospheric Uncertainties	(density, wind models)	±0.2%	±1.3%	±0.0%	±0.5%
All		±98.9%	±18.7%	±10.5%	±42.7%
Tool Related Uncertainties		±110.3%	±14.9%	±12.7%	±46.0%
Mission Related Uncertainties		±29.4%	±16.1%	±0.1%	±15.2%

A variation of SCARAB's nominal **aerothermal heat load computation** by ±20%, which is considered to be a reasonable estimation for the accuracy of the aerothermodynamic algorithms, provided an average standard deviation of the ground risk of approx. 25% for all scenarios. The differences between the three scenarios were quite large: UNC $\approx$ 26%, CON $\approx$ 7%, Delta-II $\approx$ 43%. A trend seems to exist that the standard deviations of the ground risk become smaller for more compact and heavier reentry objects. However, a margin of deviation of ±25% should be considered for SCARAB's ground risk results to take into account the uncertainties resulting from the implemented aerothermodynamic computation methods.

High inclination orbits lead to higher relative velocities of the re-entry object w.r.t. the rotating atmosphere. Therefore, the deceleration during descent takes longer and the aerothermal heat loads are higher. The ground risk is higher for low inclination orbits, and vice versa. Only three specific **orbit inclinations** (5.206, 51.6, and 96.6 deg) were analyzed with SCARAB for only one scenario (Delta-II). These three analyses provided a standard deviation for the ground risk of $\approx$ 32%. SESAM variation analyses were carried out for an orbit inclination regime of 0–180 deg (step size 20 deg) for all three scenarios. These analyses provided an average standard deviation of the ground risk of approx. 15% for all scenarios. The differences between the three scenarios were quite large: UNC $\approx$ 29%, CON $\approx$ 16%, Delta-II $\approx$ 0%. Nevertheless, this margin of deviation could be avoided if the orbit inclination of the mission is known. If the orbit inclination can be deliberately chosen, this measure could be utilized to reduce ground risk by choosing high inclination orbits.

The nominal **SESAM models** of the three scenarios were modified according to the fragmentation results provided by the nominal SCARAB analysis runs (*SCARAB calibrated SESAM models*). These SESAM model modifications provided an average standard deviation of the ground risk of approx. 20% for all scenarios. The differences between the three scenarios were again quite large: UNC $\approx$ 40%, CON $\approx$ 8%, Delta-II $\approx$ 12%. SESAM models have a significant influence on the ground risk results. Therefore, a margin of deviation of at least ±20% should be considered for SESAM's ground risk results to take into account the uncertainties resulting from the modeling process.

Large variation effects (≥ 35%): SESAM's **spacecraft break-up altitude** is the main fragmentation assumption of this tool. A variation of the spacecraft break-up altitude (60–90 km, step size 5 km) has a large effect on the ground risk. These SESAM analyses provided an average standard deviation of the ground risk of approx. 47% for all scenarios. The differences between the three scenarios were again quite large: UNC $\approx$ 100%, CON $\approx$ 24%, Delta-II $\approx$ 17%.

The main fragmentation assumption of SCARAB is the so-called **thermal fragmentation criterion**, i.e. fragmentation on panel level at melting temperature or after complete melting (default). A variation of SCARAB's thermal fragmentation criterion has a large effect on the ground risk. These SCARAB analyses provided an average standard deviation of the ground risk of approx. 59% for all scenarios. The differences between the three scenarios were again quite large, especially for the UNC scenario: UNC $\approx$ 90%, CON $\approx$ 49%, Delta-II $\approx$ 39%.

In order to compare the margins of deviation for the ground risk resulting from the different fragmentation approaches of both tools, all directly **fragmentation related variations** were combined. For SCARAB, these are the aerodynamic and aerothermal load variations, and the variation of the thermal fragmentation criterion. For SESAM, these are the two fragmentation event variations, i.e. spacecraft break-up and solar panel break-off (except for the Delta-II scenario), and the variation of the SESAM model. The combined SCARAB analyses provided an average standard deviation of the ground risk of approx. 38% for all scenarios. The differences between the three scenarios were: UNC $\approx$ 42%, CON $\approx$ 25%, Delta-II $\approx$ 45%. The combined SESAM analyses provided an average standard deviation of the ground risk of approx. 48% for all scenarios. The differences between the three scenarios were quite again large, especially for the UNC scenario: UNC $\approx$ 109%, CON $\approx$ 18%, Delta-II $\approx$ 16%.

All large variation effects must be seriously considered with the given margins of deviation for ground risk results provided by either SCARAB or SESAM to take into account the uncertainties resulting from the corresponding fragmentation approaches.

Tool related uncertainties: Some of the analyzed influence factors can be attributed to uncertainties concerning the tools themselves.

For SCARAB these are atmospheric uncertainties, solar radiation heating, aerodynamic forces, aerothermal heating, and the thermal fragmentation criterion. The standard deviations of the ground risk for the corresponding variation cases are: UNC $\approx$ 42%, CON $\approx$ 16%, Delta-II $\approx$ 45%. The average standard deviation for all corresponding scenarios/variation cases is approx. 34%. This value can be considered as the general uncertainty of SCARAB results for the ground risk. Again, there seems to be a trend that the standard deviations of the ground risk become smaller for more compact and heavier re-entry objects.

For SESAM, the tool related uncertainties result from the atmospheric density, the solar panel break-off, the spacecraft break-up, and the SESAM model. The standard deviations of the ground risk for the corresponding variation cases are: UNC $\approx$ 110%, CON $\approx$ 15%, Delta-II $\approx$ 13%. The average standard deviation for all corresponding scenarios/variation cases is approx. 46%. This value can be considered as the general uncertainty of SESAM results for the ground risk.

Scenario dependencies: SCARAB ground risk results show a larger sensitivity for the variations of the smaller (925–1200 kg), uncontrolled scenarios UNC and Delta-II. The variations of the heavy (6 tons), controlled scenario CON provide smaller deviations for the ground risk. The current interpretation of this result is that the standard deviations of the ground risk become smaller for more compact and heavier re-entry objects. As a consequence, higher margins ($\approx$ 45%) of deviation should be considered as the uncertainty of SCARAB ground risk results for scenarios like UNC and Delta-II. Lower margins ($\approx$ 16%) of deviation could be acceptable for scenarios similar to the CON scenario.

SESAM ground risk results show a very large sensitivity for the variations of the UNC scenario, and a quite low sensitivity for the Delta-II scenario. The reason for this behavior is the different fraction of objects with high melting temperatures (like stainless steel, titanium) in the three SESAM models. These objects survive in almost any variation cases providing a constant basic level of ground risk. If their fraction is high, as for the Delta-II scenario, not much additional ground risk can be caused by the variation cases. If their fraction is low, as for the UNC scenario, additional ground risk can be caused, especially by variation cases facilitating the survival of aluminum objects, i.e. through lower spacecraft break-up altitude. As a consequence, special attention should be paid to SESAM analyses where the fraction of high melting temperature objects is less than 10%, especially if the assumed spacecraft break-up altitude (nominal value: 78 km) is questionable, e.g. for a very compact structure of the re-entry object.

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