NOTE ON THE APPLICATION OF SCARAB TO THE MIR RE-ENTRY

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ABSTRACT

Many objects entering the Earth's atmosphere in an uncontrolled manner are being destroyed by mechanical or thermal loads exerted by the atmosphere. The destruction process can be examined theoretically in detail with the software system SCARAB ('Spacecraft Atmospheric Re-entry and Aerothermal Break-up'). This software has been applied to different test cases, ranging from simple spheres to very complex spacecraft. The present paper describes the results of an approach to compute the destructive re-entry of the MIR space station.

1. INTRODUCTION

Each object entering the Earth's atmosphere is subject to strong aerodynamic forces and heat loads.

The forces can lead to deformation of the object's structure, and finally to a disintegration by tearing parts away.

The heat loads reduce the strength of the object's structure and cause a destruction by melting and burning.

The disintegration of an object results in the generation of fragments, which continue the re-entry flight, until they disintegrate themself, or until they reach ground.

Fragments hitting ground impose a risk on humans.

2. THE SCARAB SOFTWARE SYSTEM

The SCARAB S/W system [1–5] consists of several modules:

- a system manager with a menu-driven user interface,
- a geometry module for the construction of a spacecraft from elements and for the generation of surface panels,
- a model definition module for the specification of model-dependent parameters (e.g. mass properties, reference quantities),
- a material data module containing material data tables,
- four re-entry analysis modules,
- a visualisation tool for an animated view of the re-entry history.

Test cases treated with SCARAB:

- Spheres
- Simple satellites
- Tank fragments
- Complex satellites (ATV)

3. APPLICATION OF SCARAB TO THE MIR RE-ENTRY

SCARAB performs a combined dynamic / aerodynamic / aerothermal / thermal / structural analysis. This comprehensive approach requires a lot of geometrical and physical data to be specified, especially for complex geometries. Detailed data were available, for example, in the ATV case. Very little information was available in the MIR case. Therefore only a simple model could be constructed, with guesses for most of the data.

3.1. MIR spacecraft model

The geometry of the MIR space station was modeled with the following main components:

MIR core	(module + 3 solar arrays)
Kvant	(module + 2 solar arrays + 1 boom)
Kvant 2	(module + 2 solar arrays)
Spektr	(module + 4 solar arrays)
Kristall	(module + 2 solar arrays)
Priroda	(module + 1 antenna)
Progress	(S/C + 2 solar arrays)

The total number of geometric primitives was 194. The number of surface panels was 15784.

Figure 1 shows a sketch of the geometrical model of the MIR.

For the volume model it was assumed, that all mass is concentrated in the walls. No interior elements were modelled. The wall material was assumed to be Aluminium throughout, and the wall thickness was adapted to yield a reasonable total mass. A value of 45 mm was adapted for the main modules, and 5 mm for the solar arrays + antennas. This gives a total mass of 135 tons.

For the structural analysis several cuts were defined where break-off may occur.

No.	Connected elements		D [mm]	T [mm]
01	Core	– Kvant 2	1400	45 / 5
02	Core	– Spektr	1400	45 / 5
03	Core	– Kristall	1400	45 / 5
04	Core	– Priroda	1400	45 / 5
05	Core	– Kvant+Prog.	1300	45 / 5
06	Kvant	– Progress	1300	45 / 5
07	Core	– solar array 1	35	5
08	Core	– solar array 2	35	5
09	Core	– solar array 3	35	5
10	Kvant	– solar array 1	35	5
11	Kvant	– solar array 2	35	5
12	Kvant-2	– solar array 1	35	5
13	Kvant-2	– solar array 2	35	5
14	Spektr	– solar array 1	35	5
15	Spektr	– solar array 2	35	5
16	Spektr	– solar array 3	35	5
17	Spektr	– solar array 4	35	5
18	Kristall	– solar array	35	5
19	Kvant	– Sofora boom	80	20

Table 1. List of cuts defined for the structural analysis. D = diameter, T = thickness.

3.2. Initial conditions for re-entry

Source: NASA, published March 16.

Conditions after final (3rd) de-orbit burn.

Initial orbital elements:

- Epoch: 2001/03/22, 05:48:31
- Semi-major axis: 6524.3 km
- Eccentricity: 0.009664
- Inclination: 51.6 deg
- Right ascension of ascending node: 256 deg
- Argument of perigee: 239.7 deg
- True anomaly: 240 deg

Actual re-entry day: March 23.

4. RESULTS

4.1. Separation of the solar arrays

Figure 2 shows the flight altitude of the MIR station as function of time. After 970 s flight time, at an altitude of 109 km, the first solar array is detected to break away. After this and each following break-up event the altitude in Figure 2 corresponds to the most massive fragment.

The initial conditions as given above correspond to an elliptical orbit with 210 km apogee and 83 km perigee. Figure 2 shows that the orbit is 'captured' by the atmosphere at about 90 km altitude.

In Figures 3 and 4 the stresses in the joints listed in Table 1 are shown up to the first breaking event at t=970 s. The stress values in the solar array joints are approximately four orders of magnitude larger than in the connections between the modules.

The first joint breaking is at cut #11. This joint holds one of the solar arrays of the Kvant module. This occurs at 109.2 km altitude. Only several seconds later and some 100 m lower one of the core solar arrays breaks away (cut #7). During the following 200 seconds one solar panel after another breaks away. The last break-off occurs at 99.3 km altitude, after 1180 s total flight time (cut #15). After loss of all solar panels the Sofora boom still remains attached, since the connection to the Kvant module was modelled to be more rigid than the solar array joints. It takes another 370 seconds until the boom breaks. This happens at an altitude very close to 90 km.

4.2. Disintegration of the modules

The subsequent history of the trunk of the orbital complex depends on the assumptions on the joints between the different modules. For an assumed wall thickness of 45 mm for the joint cross section, the next fragmentation occurs at 41 km altitude, after 2144 seconds total flight time, when the Priroda module and the Progress spacecraft break away at the same time. Within the next few seconds and some 100 m also the Kvant 2 and the Spektr module break off. This means, below 40 km altitude there remains a compound of the modules Kvant, Core module, and Kristall.

The computed disintegration altitude of 40 km does not fit the observed altitude, which is generally estimated to be about 80 km. Therefore a second computation was carried out with reduced wall thickness of the joints between the modules (45 mm $\rightarrow$ 5 mm). This thickness reduction has two effects: 1. Due to the reduced cross section in the cuts the stiffness of the connection is reduced and the stress increases; 2. Due to the reduced volume of the joints the heat capacity is reduced, resulting in a stronger temperature increase during re-entry, which reduces the breaking stress. The combination of these two effects is illustrated in Figure 5. In this figure the actual and the maximum stresses are shown for cut #2 (Core-Spektr) for wall thickness 45 mm (case 1) and 5 mm (case 2). Both the increasing actual stress as well as the decreasing breaking stress lead to a higher breaking altitude for the lower wall thickness. Actually the joint between Core and Spektr is the first to break in the second calculation. This happens at 69 km altitude. It is followed by the break-off of Kvant 2, Priroda, and Kristall during the following 6 km descent. Somewhat later, at 52 km altitude, the Progress spacecraft breaks off, and just 1 km lower the remaining Core-Kvant compound disintegrates. In summary this means, that in the altitude range between 69 km and 51 km the orbital complex disintegrates completely.

4.3. Summary of main results

- The initially elliptical orbit is 'captured' by the atmosphere at h=90 km
- The maximum aerodynamic heating occurs at h=50 km
- The maximum aerodynamic deceleration occurs at h=40 km
- The solar panels are torn away in the altitude range h=100–110 km
- The Sofora boom breaks at h=90 km
- The modules disintegrate below 41 km / between 51 km and 69 km in the two calculations with two different cut models
- The connections MIR-Kvant and Kvant-Progress are shadowed, which prevents heat transfer and thus strength degradation
- The thick walls heat up very slowly (underestimates thermal destruction)

5. CONCLUSIONS

The disintegration of objects during atmospheric re-entry can be computed with the software system SCARAB.

SCARAB performs a detailed analysis of the motion and disintegration during re-entry.

This detailed analysis requires detailed data about the re-entering object.

No detailed information was available for the MIR space station.

A re-entry analysis was initiated for the MIR case, using guesses for the required data.

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5. Fritsche B., Koppenwallner G., *Computation of Destructive Satellite Re-Entries;* Paper 11.06, presented at the 3rd European Conference on Space Debris, Darmstadt, Germany, 2001.

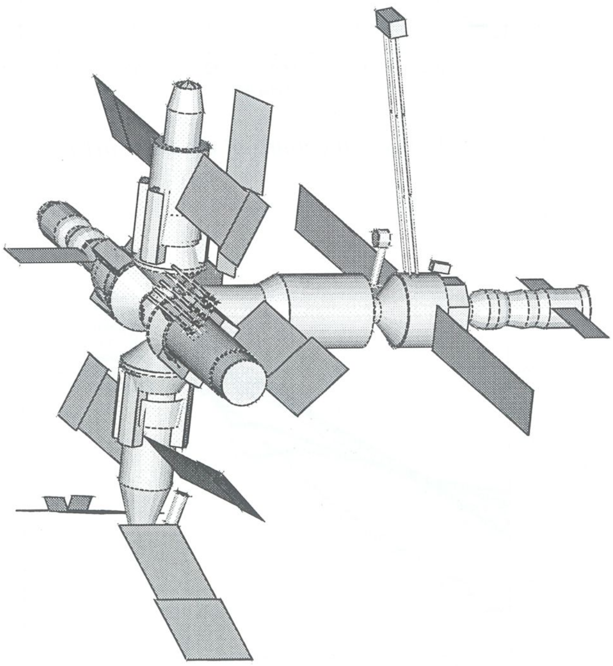

Figure 1. SCARAB model of the Mir space station

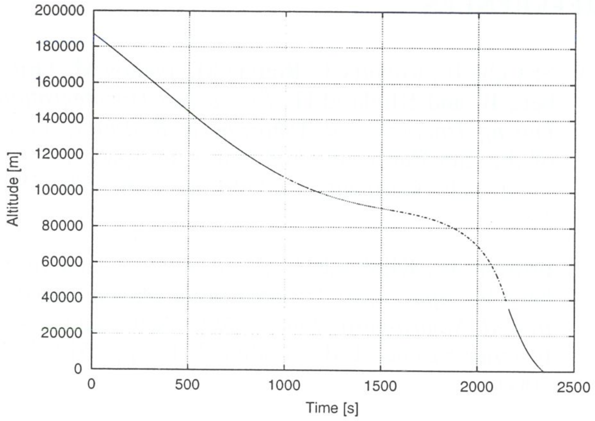

Figure 2. Altitude of the main fragment vs. time

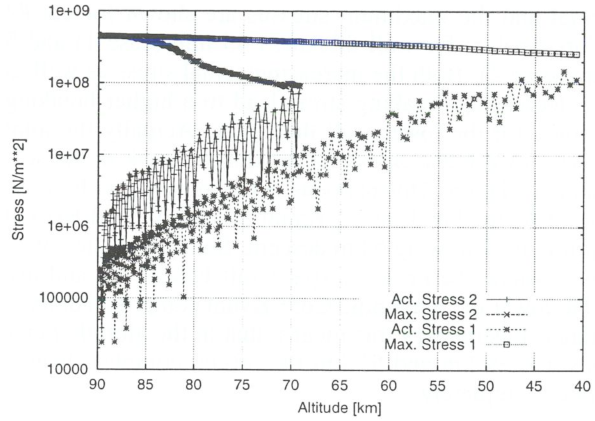

Figure 5. Stress in cut #2 during re-entry for two different cut cross sections

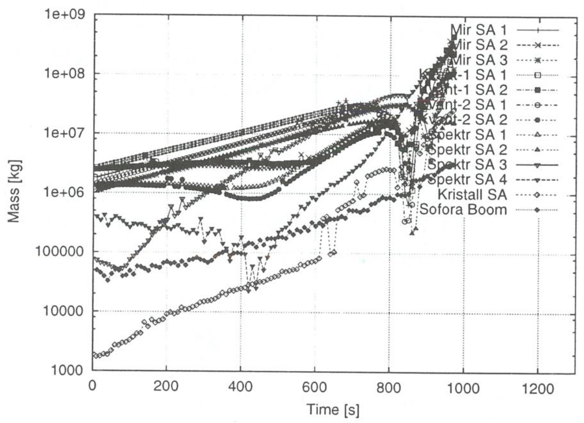

Figure 3. Stress in the joints of the solar arrays

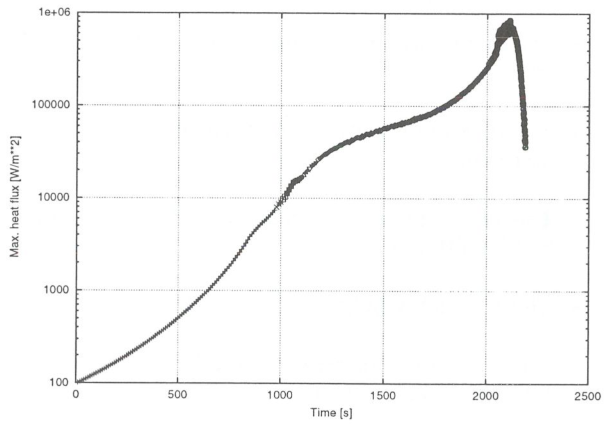

Figure 6. Max. heat transfer to the main fragment vs. time

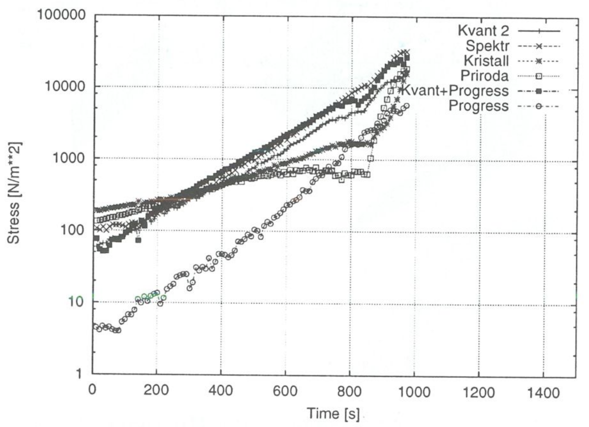

Figure 4. Stress in the joints between the modules

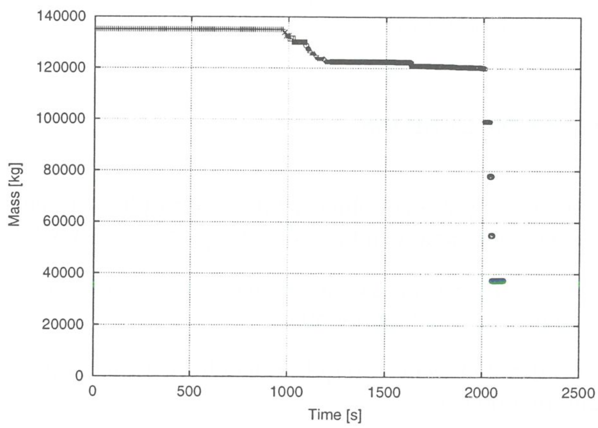

Figure 7. Mass of the main fragment vs. time

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