COMPUTATION OF THE SURVIVABILITY OF SPACECRAFT FUEL TANKS AFTER ORBITAL DECAY

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ABSTRACT

The present paper takes a look at a special problem occurring during the re-entry of a spacecraft with on-board tanks after an orbital period. The re-entry of a fuel tank is analysed in some detail, which resembles a "real" tank which was in orbit and going to re-enter. A parametric study is performed for the re-entry to analyse whether the tank survives the re-entry intact (with content) or not.

1. INTRODUCTION

Spacecraft re-entering the Earth's atmosphere at the end of their orbital lifetime pose a certain risk to the population on ground if they are large enough to withstand the aerothermal heating during their way down at least partially, leaving some surviving fragments impacting on ground. A special problem of interest is the re-entry of spacecraft with fuel tanks on board. A well-known example for this scenario is the ATV, which was docked to the International Space Station and re-entered the Earth's atmosphere loaded with waste and with some fuel left in its tanks. Even some small amount of residual fuel can force its container tank to burst, since due to the excessive heating during re-entry the pressure in the tank can easily exceed the tank's burst pressure, since in addition the strength of the tank wall is decreased by the heating at the same time. The bursting, or even some leaking, can result with some likelihood in an explosion. An explosion during re-entry enlarges the number of fragments relative to the non-explosion case, while the total surviving mass is diminished, with the footprint of the survivors being enlarged on the other hand.

A different view to the problem of re-entry with tanks is to raise the question, what is the risk to the ground population if the tanks do NOT burst/explode, keeping in mind the potentially toxic contents of the tanks released if they reach ground and break on impact. Usually tanks which survive the extreme conditions during re-entry without bursting (e.g. Titanium tanks) are somewhat likely to withstand also the impact event or contain a neglible amount of liquid contents. The situation becomes different for a satellite re-entering after an extended orbital period with well filled tanks, e.g. a contingency case where the satellite did not resume a proper working state after launch and where the tanks are not temperature-controlled. In such a case the fuel in the tanks may become frozen before re-entry. With a frozen content much more heat is needed to reach a bursting state.

The present paper deals with the latter problem. In a previous study two sample cases of a "warm" and a "cold" re-entering fuel tank filled with Hydrazine were examined [1] by numerical calculations with the SCARAB software [2]. From the results it was concluded, that the question of tank bursting or not depends on the assumptions made for the initial tank state and the heat conduction mechanism into the tank. In the present paper additional cases will be investigated, focussing on the sensivity of the bursting conditions on different parameters.

2. COMPUTATIONAL RESULTS

The sample scenario selected is a Titanium tank with 1 m diameter and a wall thickness of 3 mm, filled with 450 kg Hydrazine and 0.189 kg Helium. With this load the tank pressure is about 18 bar at 300 K.

The initial conditions are:

Altitude	122 km
Velocity	7.41 km/s
Flight path angle	-0.1°
Azimuth angle	60°
Roll, pitch, yaw	0°
Roll rate	5°/s
Pitch rate	10°/s
Yaw rate	15°/s

For a sensivity analysis following conditions were varied:

- Wall thickness
- Content mass
- Rotation mode

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

- Initial temperature
- Heating onset
- Wall integrity

2.1. Wall thickness

The reference case of 3 mm wall thickness was compared to the cases of 1 mm and 5 mm thickness.

Fig. 1 shows the flight altitude as function of time. There is no visible difference between the curves for different wall thickness. This is due to the large mass of the tank content, which is large compared to the wall mass. The curves end after 520 seconds at an altitude of 63 km, where the tank state analysis detects bursting conditions (see below).

Figs. 2 and 3 show the flight velocity as function of time. In Fig. 2 the curves end at bursting conditions, while in Fig. 3 the curves are continued until the end of the hypersonic regime (Mach 6), where the 6D calculation of the SCARAB software stops. Before bursting there is a slight variation in velocity with wall thickness. After bursting the difference in velocity becomes much more pronounced, since for a dumped tank the deceleration becomes inversely proportional to the wall mass, which for thin walls is directly proportional to the thickness. The aerodynamic deceleration is shown in Fig. 4 as function of altitude. It can be seen that the deceleration values immediately after bursting are 270 m/s^2, 90 m/s^2, and 54 m/s^2, corresponding to a 5:3:1 ratio, for 1 mm, 3 mm, and 5 mm respectively.

Fig. 5 shows the aerodynamic heating in the stagnation point. Since trajectory and velocity are insensitive to the wall thickness before bursting, the same is true for the heating. After bursting the heating is higher for higher wall thickness, since the deceleration is lower then. Since the heating is approximately proportional to the third power of the velocity, the effect of the wall thickness on heating after bursting is more pronounced than on the velocity.

Figs. 6-8 show the effect of the heating on the tank temperature. Surprisingly the wall temperature (max. and mean) increases before bursting with wall thickness, although the heating is the same for all cases and the wall heat capacity increases with its mass. Obviously this is due to the heat conduction to the tank content, since the tank content temperature is indeed highest for the lowest wall thickness. After bursting the temperature jumps fastest for the lowest thickness, as expected.

Fig. 9 shows the result of the tank burst analysis. The calculated tank pressure is compared with the tank burst pressure. The tank pressure depends on the (increases with higher) content temperature, while the burst pressure depends on the (decreases with higher) maximum wall temperature. For higher wall thickness the content temperature and therefore the tank pressure is lower, while the wall temperature is higher and thus the burst pressure is lower as well. Both effects work in the same direction, resulting in burst conditions at almost the same trajectory point for all thicknesses.

2.2. Tank content

The reference case of 450 kg Hydrazine was compared to a case with just half of this content. The Helium content was adapted to give the same initial pressure of 18 bar.

Figs. 10 and 11 show the flight altitude and velocity as function of time. The trajectories are quite similar, but the bursting occurs somewhat later for the lower content mass. The difference in deceleration is more pronounced than for the wall thickness variation since the content mass is much higher than the container mass. The velocity difference results in a different heating, shown in Fig. 12. In this figure the stagnation point heating and the heatflux averaged over the tank wall are compared. For a spherical tank the ratio between this two flux values is about 4.

Fig. 13 compares the mean wall temperature and the content temperature for both content loads. Both temperatures are higher for smaller content mass, but bursting occurs later in this case. Why this is the case can be seen in Fig. 14, where the pressures are shown. For higher content mass the wall temperature is somewhat lower and therefore the burst pressure is higher, but the tank pressure increases much faster in this case, despite the fact that the content temperature is lower than in the lower content case as well. This shows that the bursting behaviour may depend on a parameter variation in an unexpected way.

The reason for the observed behaviour is the Helium gas content. Both cases considered here differ in a Hydrazine content mass by a factor of two. But it was assumed that the total pressure in the beginning was the same. This means, that the Helium content has to be more than four times larger in the case of the lower liquid content mass. For the temperature range observed in the calculations the pressure increase with temperature is mainly due to the ”expansion” of the Helium. This can be seen very clearly in Fig. 15, where the reference case is compared to a case where the Helium was removed in the beginning. Then the tank pressure is built up solely by the vapour pressure of the Hydrazine. It can be seen that the vapour pressure is not sufficient to result in a bursting at all.

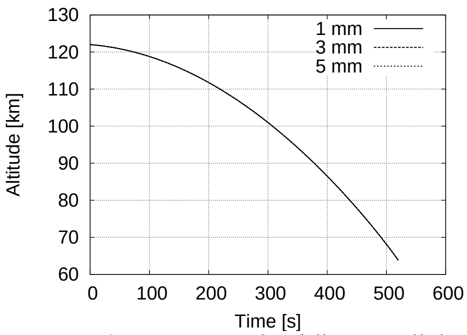

Figure 1. Trajectories for different wall thickness.

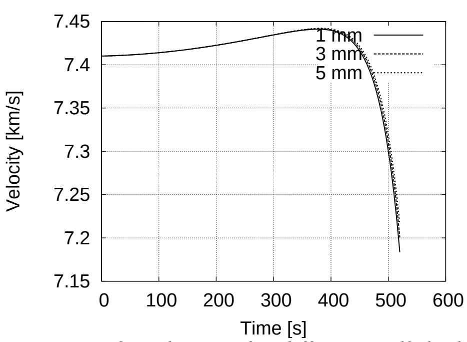

Figure 2. Velocities for different wall thickness.

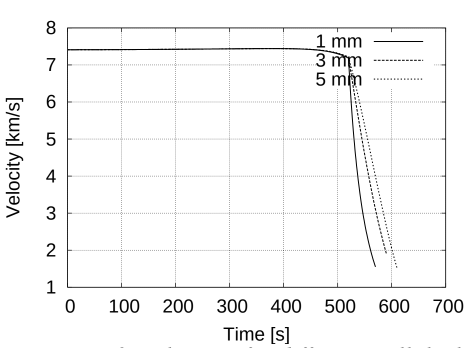

Figure 3. Velocities for different wall thickness.

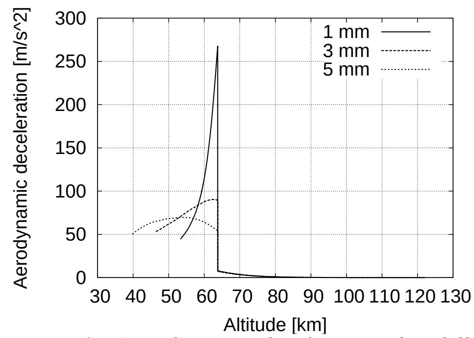

Figure 4. Aerodynamic deceleration for different wall thickness.

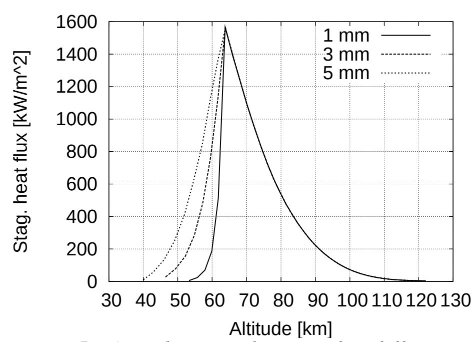

Figure 5. Aerodynamic heating for different wall thickness.

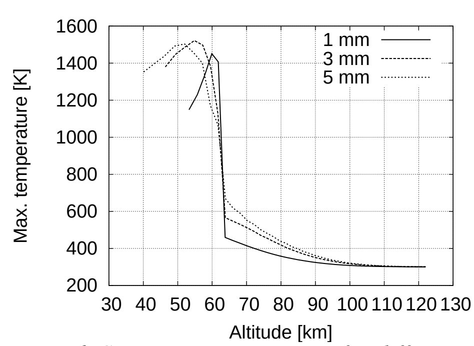

Figure 6. Stagnation temperature for different wall thickness.

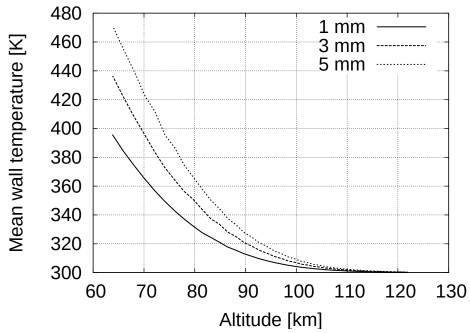

Figure 7. Mean temperature for different wall thickness.

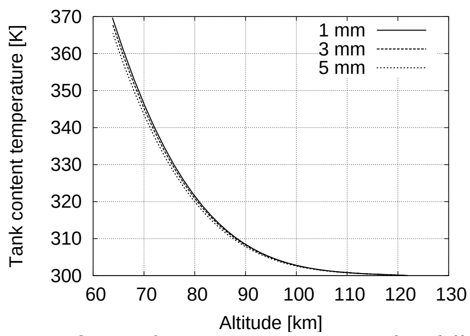

Figure 8. Tank content temperature for different wall thickness.

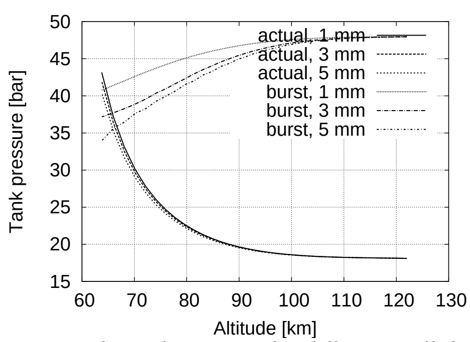

Figure 9. Tank pressure for different wall thickness.

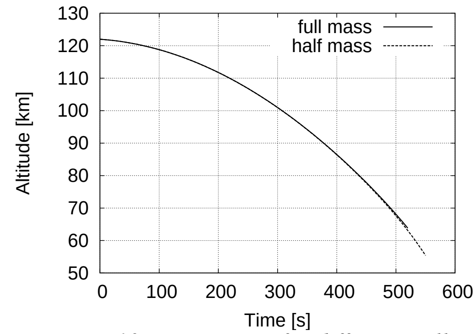

Figure 10. Trajectories for different wall content.

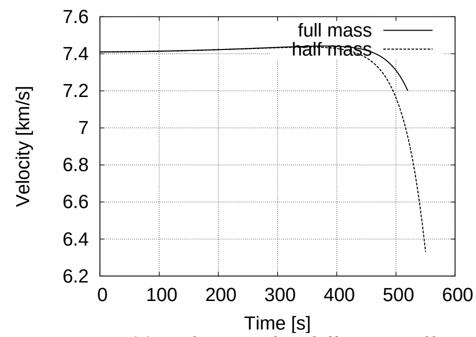

Figure 11. Velocities for different wall content.

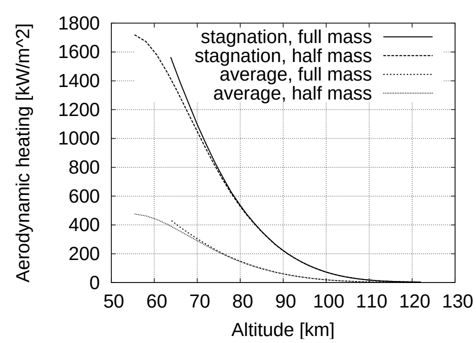

Figure 12. Aerodynamic heating for different wall content.

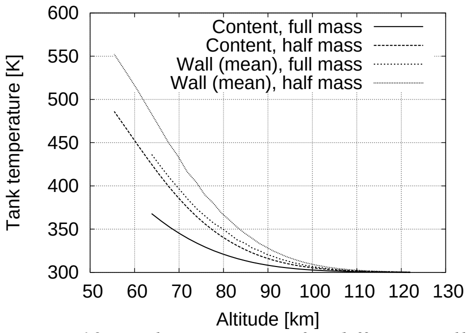

Figure 13. Tank temperature for different wall content.

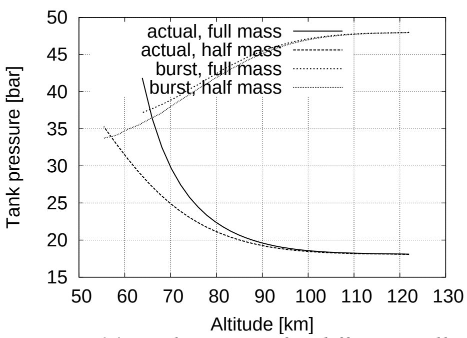

Figure 14. Tank pressure for different wall content.

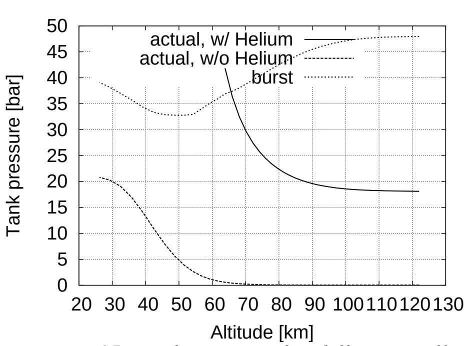

Figure 15. Tank pressure for different wall content.

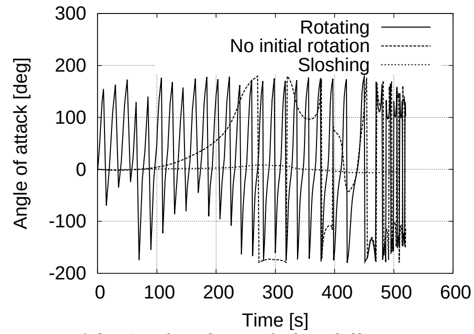

Figure 16. Angle of attack for different rotation conditions.

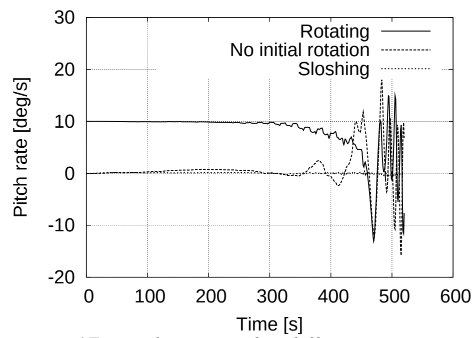

Figure 17. Pitching rate for different rotation conditions.

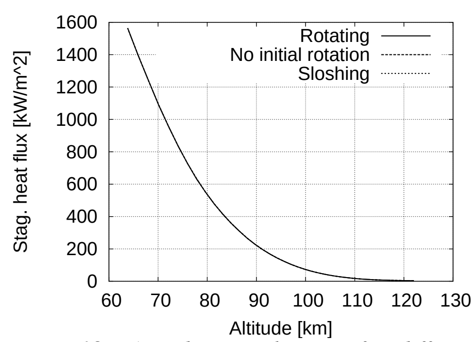

Figure 18. Aerodynamic heating for different rotation conditions.

2.3. Rotation state

Figs. 16 and 17 compare the attitude motion of the tank for different rotation conditions. "Rotating" means an initial rotation as specified in the reference case, "non-rotating" means no initial rotation and "sloshing" means consideration of sloshing motion of the liquid tank content. In the other cases the content is considered as mass point in the dynamic motion calculations.

In the rotating case the initial rotation, while undisturbed in the beginning, becomes disturbed at lower altitudes. In the non-rotating case the tank starts to rotate slowly with time, tending to stabilize and oszillate at an angle of attack of about 180°, while the sloshing case is very stable, since the high content mass tends to move to the stagnation point, which moves the center of mass in front of the center of pressure.

Figs. 18-20 show the heating, the max. wall temperature and the content temperature. The heating is the same in all cases. The max. wall temperature is slightly higher for less rotation, but there is almost no difference in the content temperature.

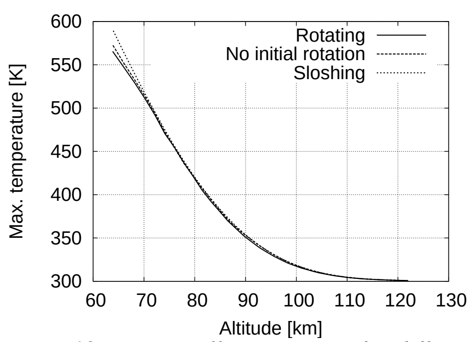

Figure 19. Mean wall temperature for different rotation conditions.

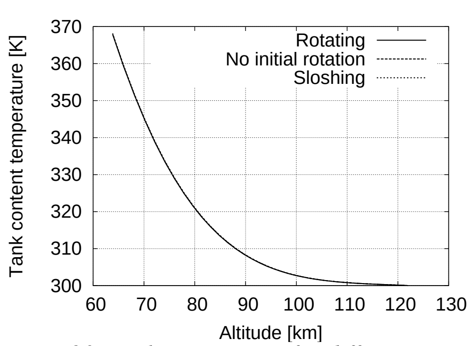

Figure 20. Tank temperature for different rotation conditions.

2.4. Initial temperature

A "cold" case was introduced, differing from the reference case only by the initial temperature. The content was assumed to be initially on freezing temperature, but also to be completely frozen.

Fig. 21 shows the aerodynamic heating of the tank. Again stagnation point heat flux and average heat flux are shown. There is no drop in the curves since no bursting was detected in this case. Fig. 22 shows the wall temperature (max. and mean) and the content temperature. The content temperature remains on freezing temperature of Hydrazine until enough heat is stored to melt the content. Then the temperature increases.

Fig. 23 shows the tank pressure. The burst pressure goes down and up, following its temperature dependence. The content temperature increase is not sufficient to increase the pressure above the bursting level.

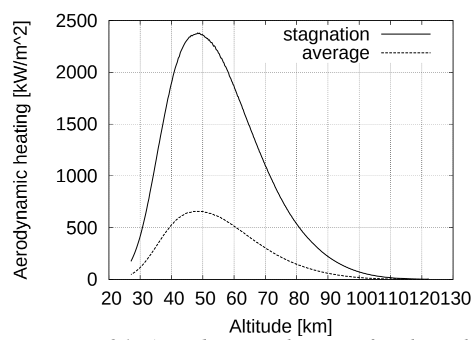

Figure 21. Aerodynamic heating for the cold case.

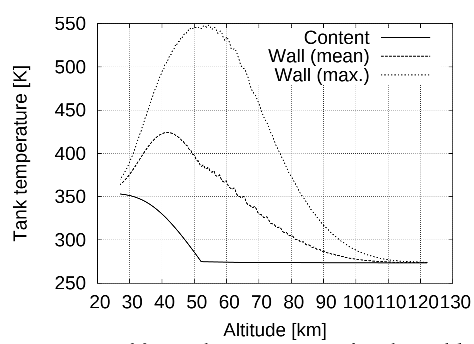

Figure 22. Tank temperature for the cold case.

2.5. Shielding

One more case was studied, assuming the reference tank to be shielded, e.g. by surrounding parts of a spacecraft

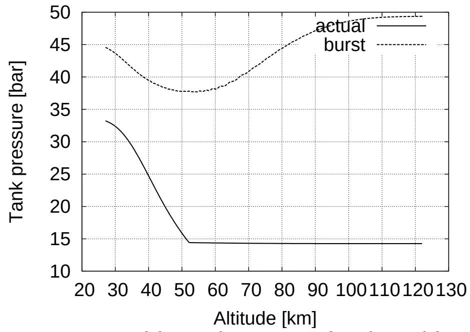

Figure 23. Tank pressure for the cold case.

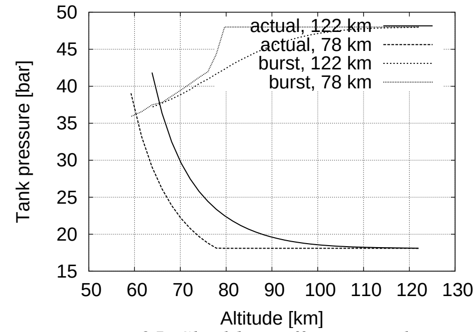

Figure 25. Shielding effect on tank pressure.

releasing the tank at an altitude below the reference altitude. Accordingly the aerodynamic heating was switched off above some altitude. Here 78 km was used as this value is often assumed as a typical break-up altitude.

Fig. 24 shows the content temperature in this case. For the shielded case the temperature remains on its initial value until beginning of heating. Then the temperature rises steeper then in the non-shielded case, but it remains below. Nevertheless bursting occurs, as can be seen in Fig. 25, but somewhat delayed.

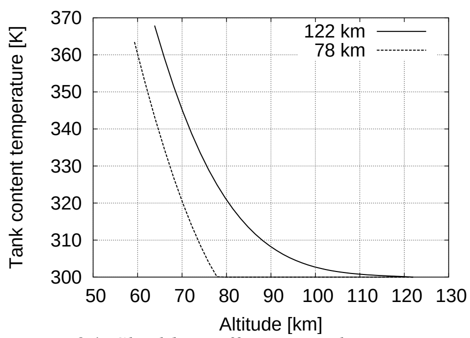

Figure 24. Shielding effect on tank content temperature.

2.6. Pressure loss by gas outflow

Another interesting point to look at is the question, whether tank bursting may occur despite the existence of a hole in the tank wall, where the content can flow out. This may for example happen if the tank is released during break-up of a spacecraft and a feed line is ruptured. Usually at break-up the ambient pressure of the atmosphere is quite low, while the content pressure can be several bars, like in the reference case discussed here. If the hole is not "too large" and the gas pressure is not "too low", the gaseous tank content will flow out as a supersonic free jet. It will depend on the hole dimensions and the gas volume how fast the gas flows out. If we assume a circular hole with diameter d and a gas volume V, then a gas with specific heat ratio κ will flow out with a time constant

$$\tau = \frac{4}{\pi\sqrt{\kappa}} \left(\frac{\kappa+1}{2}\right)^{\frac{\kappa+1}{2(\kappa-1)}} \sqrt{\frac{M}{RT}} \frac{V}{d^2} \qquad (1)$$

Fig. 26 shows the calculated time constants for the reference case for a hole diameter range from 1 to 10 mm. Note that the scale is logarithmic, the dependence is a power law, not linear. Due to its higher molecular weight Hydrazine would flow out significantly slower than Helium. But for both gases the time constant is of the order of some 100 s for a hole diameter of 1 mm, which means that in this case the hole outflow would probably to slow to prevent bursting. On the other hand, for a 10 mm hole the time constants are of the order seconds, thus it is very likely in this case, that bursting will be prevented.

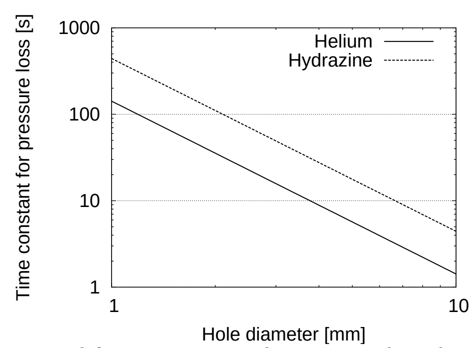

Figure 26. Time constant for pressure loss through a tank hole.

3. SUMMARY AND CONCLUSIONS

In the present paper a parametric study was performed for the re-entry of a fuel tank with the SCARAB software. The reference parameters were selected similar to a ”real” tank, which was in orbit and going to re-enter. The question was whether the tank would survive the re-entry intact (with content) or not. In the present study the sensivity of the survivability on different parameters was examined. There are several more parameters which could be varied, but this study already shows, that it depends very much on the real conditions, whether a tank may survive (do not burst) or not (will burst and release its contents into the atmosphere).

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[2] Lips T., Fritsche B., Homeister M., Koppenwallner G., Klinkrad H., Toussaint M. (2007). Re-entry Risk Assessment for Launchers – Development of the New SCARAB 3.1L. In Proc. of the Second IAASS Conference, Session 40, Chicago, USA, ESA-SP 645.