SIZE DISTRIBUTION OF NAK DROPLETS FOR MASTER-2009

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ABSTRACT

This paper presents intermediate results in the development of a new NaK release model. A new size distribution function is introduced. The cause of the release is assigned to the procedure of the reactor core ejection. The generation of the NaK droplets is modeled as several individual events and not as a continuous leakage. In this work, an improved estimate of the mass is performed. The size distribution function is adjusted to the corrected estimate. The release events are simulated. The distribution of the droplets on orbits is evaluated. The long-term decay behavior is studied. Furthermore, the contribution of the NaK droplets to the entire space debris population is determined. The development of the model is not yet complete. It is therefore possible that the model actually implemented in MASTER-2009 may differ from this work.

1. INTRODUCTION

The latest version of the European Meteoroid and Space Debris Terrestrial Environment Reference model called the MASTER-2009 is currently in development. The study is carried out at the Institute of Aerospace Systems of the Technische Universität Braunschweig under ESA/ESOC contract. Within the scope of this study, individual source models are reviewed. This work deals with the modeling of one special source of space debris, the sodium-potassium liquid metal droplets, which have been released from orbital nuclear reactors onboard of satellites of the type RORSAT [5]. These droplets are usually referred to as "NaK droplets". The NaK droplets are a unique contribution to the space debris environment. They have an identical density, a spherical shape and a good visibility even for optical telescopes due to their high reflectivity [4].

The radar ocean reconnaissance satellites of the type RORSAT operated in low earth orbits close to 250 km altitude. Their reactors with the Russian name "Buk" were used to produce electric power on board these satellites. After the end of their operation, the reactors were transferred to higher orbits, mostly between 900 km to 950 km. (Two satellites, Cosmos 954 and 1403, failed in the execution of this maneuver.) This graveyard orbit allows the decay of the radioactivity before the reactors will re-enter Earth's atmosphere in a few centuries. After reaching this orbit, the reactor vessel (casing) was opened, and the reactor core, consisting of a small package of 37 uranium fuel rods, was ejected into space (s. Fig. 1). For 13 reactors this ejection has been confirmed. It is assumed that a total of 16 reactor core ejections took place. The opening of the reactor vessel means that also the primary cooling loop has been opened. The reactor vessel and the cooling loop are depressurized during the opening process [6]. The coolant, consisting of the eutectic sodium-potassium liquid metal alloy (NaK-78), could be released into space during this process. They formed spherical droplets, and the larger of them are still in space today.

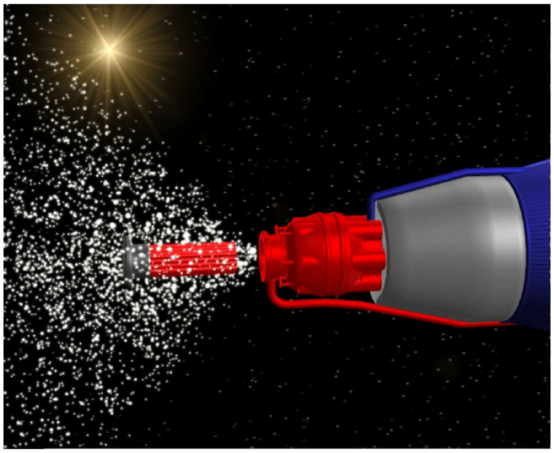

Figure 1. Buk reactor core ejection and assumed way of NaK coolant release, artist's impression (Ralf Wegemann ILR/TUBS)

In the literature, different ways of coolant release are discussed. These possible ways include

- the above mentioned release from the primary cooling loop during the operational reactor core ejection [3, 5, 6, 7, 11],
- the release from the primary cooling loop due to a breakup or an explosive destruction of the reactor [8, 9],
- the leakage from the secondary cooling loop due to an impact of a space debris object on the radiator [3, 5, 13].

The analysis of the literature reveals that the coolant outflow during the operational reactor core ejection is the most likely cause for the NaK release. The reactor

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core is directly exposed to space without a container that surrounds the fuel rods. Taking into account that the fuel rods previously have been directly in contact with the coolant, NaK must be released during the reactor core ejection. The ejection of the reactor core causes a loss of sealing of the primary cooling loop.

The reactor core ejection mechanism is an additional radiation safety system, which was implemented after the crash of Cosmos 954 in Canada in 1978. The task of this system is to ensure a dilution of the nuclear fuel in the upper layers of the atmosphere to avoid nuclear fallout on the Earth's surface in the case of an accidental re-entry of the reactor. This additional radiation safety system is also called "aerodynamic dispersion system" (ADS). The first and only "successful" use of the ADS was shortly before the re-entry of the satellite Cosmos 1402. Since the existence of the ADS, it was always activated operationally in the graveyard orbit. The reason for this activation is unknown. It can be speculated that either the reliability of the ADS was tested, the orbital lifetime of the disposed cores were to be extended, or the shut-down of the reactor was to be guaranteed by separating of the nuclear fuel from the reflector. The activation of the ADS in the graveyard orbit is responsible for the release of NaK coolant. Sixteen Buk reactors were successfully transferred into a graveyard orbit after the crash of Cosmos 954. (Cosmos 1402 failed.) The cores of the three satellites Cosmos 1670, 1677, and 1900 have not been detected. But because NaK droplets have been discovered for Cosmos 1900, it can be assumed that they have also been released from Cosmos 1670 and 1677. It is unknown which mechanisms exactly caused the coolant outflow. The estimation of the ways of droplet generation and the development of a size distribution model are associated with several uncertainties. It has been confirmed that the reactor core ejection is responsible for coolant release. But the thermodynamic conditions, the mass of the released NaK, and the exact number of events are unknown. These parameters have been estimated [14]. The estimation of the released mass will be improved here. The mass is an important parameter which is used to determine the total number of droplets in space.

2. RELEASED COOLANT MASS

It is necessary to revise the size distribution function of the NaK model for two reasons. There has been new information made available concerning the released coolant mass. Furthermore there exist revised radar measurement data which can be used for the validation of the model. The size distribution function which is currently implemented in MASTER-2005 is based on an estimated released mass of 8 kg NaK per reactor core ejection event. This mass is distributed on droplets within a defined size regime. Consequently the mass is one important parameter which determines the overall number of released droplets. But it is likely, that much less than 8 kg has been released. According to a statement of a Russian expert, given in a discussion on the Fourth European Conference on Space Debris, the total mass of NaK in the primary coolant loop is 13 kg. In the opinion of Russian experts, only 3.5 kg of NaK should have been released during each ejection event.

2.1 Estimated Mass in the Reactor Vessel

To describe the number of released droplets, a mass or volume size distribution function is used. The number of droplets is therefore a function of the released coolant mass. In this work, the mass of NaK which is released per core ejection event is reduced from 8 kg to 5.3 kg. It should first be checked whether this reduction is justified. This will be done by two separate mass estimates. In a first step it is estimated how much coolant mass is located between the fuel rods and at the top (head) and the bottom of the fuel rod assembly. This mass is the minimum amount of coolant which must leave the reactor vessel during core ejection. The volume in the reactor vessel between the fuel rods is estimated on the basis of geometric considerations using published drawings of the reactor design [10]. This coolant volume should be about 1.77 liters. The coolant mass is a function of the density which can vary between 1.23 kg and 1.55 kg depending on the temperature (see Tab. 1).

2.2 Estimated Mass in the Expansion Tank

In a second step the additional coolant mass resp. volume from the pipes of the primary coolant loop is estimated which can escape due to the decompression of the expansion tank. The expansion volume is estimated which can be stored in the expansion tank. This is a rough measure of the amount of NaK which can be released from the pipes. The expansion volume is derived from the temperature-dependent variation of the coolant density. The coolant can have a maximum temperature of up to 700 centigrade (973 K). As the minimum temperature, the melting point of NaK-78 at 262 K is defined. Taking into account the temperature difference from the melting point up to this maximum temperature, the density is reduced from 876.23 kg/m³ to 692.53 kg/m³ (using an equation from [12]). This corresponds to a volume increase of 26.5 %. Referring to a total mass of 13 kg, the volume of the coolant in the primary cooling loop at the melting point is 14.84 liters. After heating up to the maximum temperature, the volume would increased to 18.77 liters. Thus the volume stored in the expansion tank can reach a maximum of 3.93 liters. If the primary loop would be opened at the maximum temperature, then an additional coolant mass of 2.73 kg would be released from the pipes into space. The sum of this value and the coolant mass in the vessel, yields a total of 3.96 kg. The idea of reducing the released coolant mass from 8 kg to a lower value is therefore reasonable.

Table 1. Estimated released coolant mass per reactor core ejection event for different temperatures

Coolant included in:	Temp. [K]	Density [kg/m³]	Volume [m³]	Mass [kg]
Reactor vessel	262 973	876.23 692.53	0.00177 0.00177	1.55 1.23
Expansion tank	262 973	876.23 692.53	0.0 0.00393	0.0 2.73

According to the rough estimation carried out here, the released coolant mass could vary between 1.55 kg and 3.96 kg, depending on the temperature. The accuracy of this estimate is low. A higher value of the released mass is possible, because the preload of the elastic mechanics within the expansion tank is unknown. It is also unknown to what extent the described centrifugal force of the rotating reactor can increase the outflow [3]. The value of 5.3 kg, chosen here, lies above the estimated mass. This value however agrees well with revised radar measurement data [1, 2, 15].

3 NAK RELEASE MODEL

There is no information available about the details of the reactor core ejection procedure. It is assumed that outflow of coolant is a tolerated but uncontrolled accompanying effect of the core ejection. This means that there are probably no special outflow devices, such as valves. It is assumed that the core ejection causes an opening of the primary cooling loop at two positions. This results probably in two different types of interfaces with different orifice diameters. It is believed that at the top of the reactor a cooling pipe will be opened, which may have a diameter of a few centimeters. At the reactor bottom, a manifold similar to a sprinkler head is presumed, which may have several orifices with diameters of some millimeters. The different orifice diameters may lead to different droplet sizes. Consequently there are two size distribution functions necessary to describe the entire droplet distribution. The overall distribution is thus believed to be bimodal. The resulting function, shown in Fig. 2 is a combination of two distribution functions. The maximum droplet diameter, released after the core ejection, is estimated to be 5.67 cm. The minimum droplet diameter is estimated to be 0.5 mm.

In Fig. 2, the new size distribution function is compared with that which is currently implemented in MASTER-2005. The reduction of the mass from 8 kg to 5.3 kg reduces the number of released drops. This reduction mainly affects the small size regime.

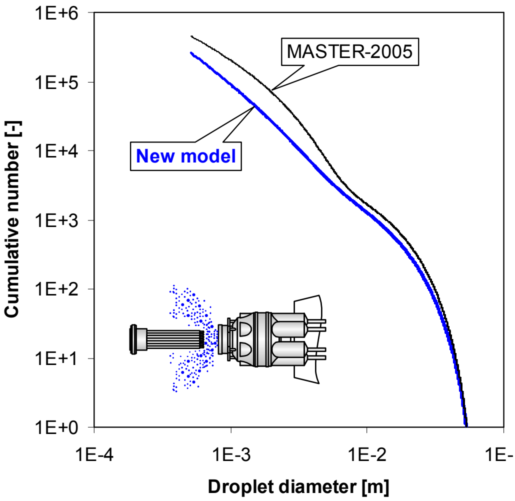

Figure 2. NaK-droplet size distribution model for one reactor core ejection event

The mass distribution of an event is shown in Fig. 3. According to the model most of the mass (4.5 kg) is released in form droplets larger than one centimeter.

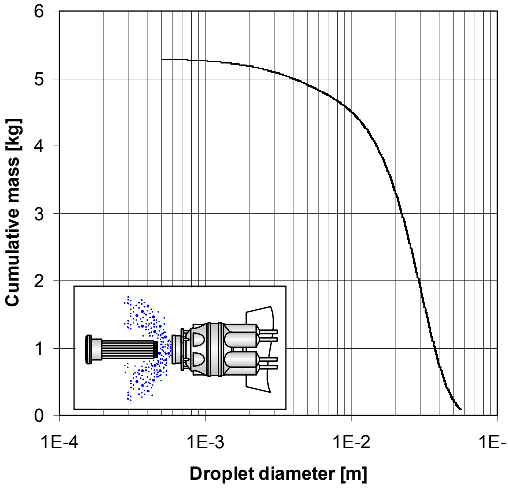

Figure 3. Mass distribution of the NaK droplet size distribution model

The bimodal character of the function can be made particularly clear, if the volume frequency is determined. The result is shown in Fig. 4. The droplet sizes are distributed around two medium diameters.

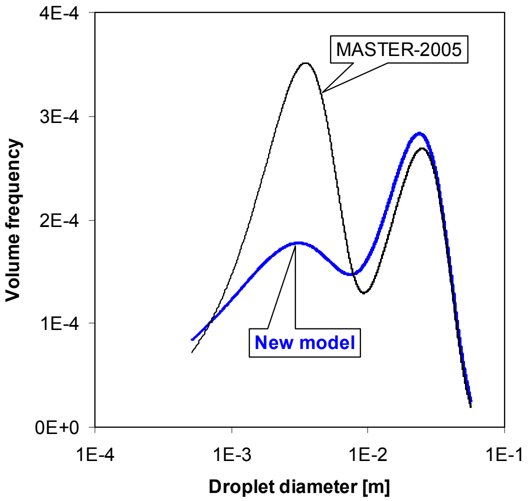

Figure 4. Volume (or mass) frequency of the NaK droplets size distribution model

4 SIMULATION OF NAK RELEASE EVENTS

The goal of the simulation is to determine the contribution of each NaK release event to the space debris environment. The results are presented for the reference epoch May 1, 2009 and for a long-term simulation up to the year 2060.

4.1 Propagation to the Reference Epoch

Starting with the Cosmos 1176, each RORSAT released an additional coolant mass of 5.3 kg into space. Fig. 5 shows the evolution of the total droplets mass in space. An initial increase can be observed due the 16 core ejections in the 1980s. The main part of the mass is released in the form of droplets with a diameter greater than 1 cm. The decay of the droplets due to the residual drag of the atmosphere correlates with the eleven-year cycle of the solar activity. According to the model, a total of 85 kg NaK has been released into space. With the end of the RORSAT program in 1988, no additional NaK droplets have been released since then. The total mass is reduced and reaches a value of about 69 kg at the reference epoch.

The simulation reveals that the total number of droplets in space to the reference period is approximately 29,500. Tab. 2 gives the cumulative number of droplets, which is still in space, comparing it to all released droplets. The smallest droplet in orbit at the reference epoch has a diameter of 4.63 cm.

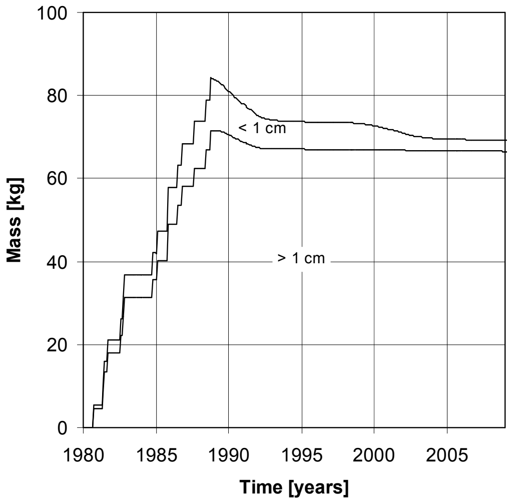

Figure 5. Simulated mass of NaK droplets in orbit

Table 2. Cumulative number of NaK droplets larger than a given diameter as a result of a simulation, comparison of released droplets with the droplets still in orbit at the reference epoch (May 1, 2009)

Minimum droplet-diameter	Released NaK-droplets (one event)	Released NaK-droplets (16 events)	Droplets in orbit at the ref. epoch
0.5 mm	263,900	4,222,400	
1.0 mm	89,562	1,432,992	
4.63 mm	4,743	75,888	29,500
5.0 mm	4,074	65,184	29,400
1.0 cm	1,256	20,096	18,000
2.0 cm	318	5,088	4,700
3.0 cm	81	1,296	1,170
4.0 cm	17	272	226

4.2 Long-Term Simulation

Fig. 6 shows the temporal behavoir of the total number of drops in orbits, divided into three size classes. Immediately after the release a high number of droplets smaller than 1 cm exit. Due to the high area-to-mass ratio, the small droplets decay relatively fast. The orbital lifetime of the small droplets of between 0.5 mm and 1 mm is very short. Droplets with a diameter smaller than 1 mm from space disappeared since 1990. Since 2002, the NaK population is dominated by droplets larger than 1 cm.

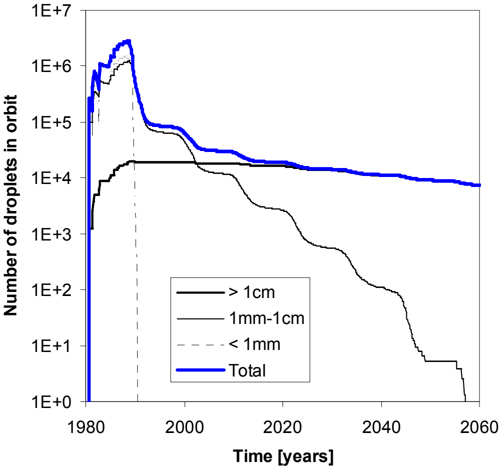

Figure 6. Simulated evolution of the number of droplets in orbit

Fig. 7 and 8 show the influence of solar activity on the decay rate of the droplets. The expansion of the atmosphere during phases with high solar activity, every eleven years, increases the decay rates significantly. The maximum decay rate occurred around of 1990.

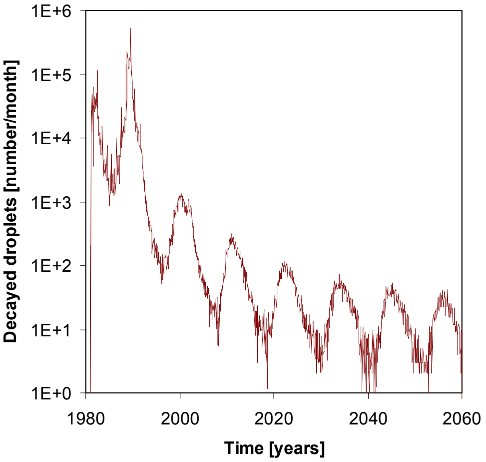

Figure 7. Simulated decay behavior of NaK droplets, shown as a monthly decayed number of objects

The NaK population is propagated to the year 2060 to investigate the long-term orbital behavior of the droplets. A question of interest is whether the decaying droplets may lead to an increased spatial density at lower orbits in the future. This issue is related to satellite constellations or sun-synchronous satellites on orbits between 700 km and 800 km altitude. The evolution of the spatial density of NaK droplets from 1980 to 2060 is shown in Fig. 9.

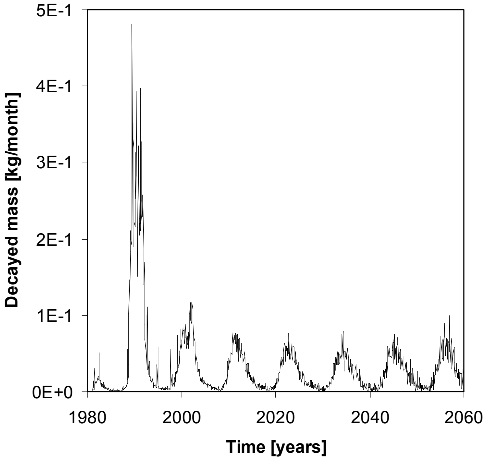

Figure 8. Simulated decay behavior of NaK droplets, shown as a monthly decayed mass

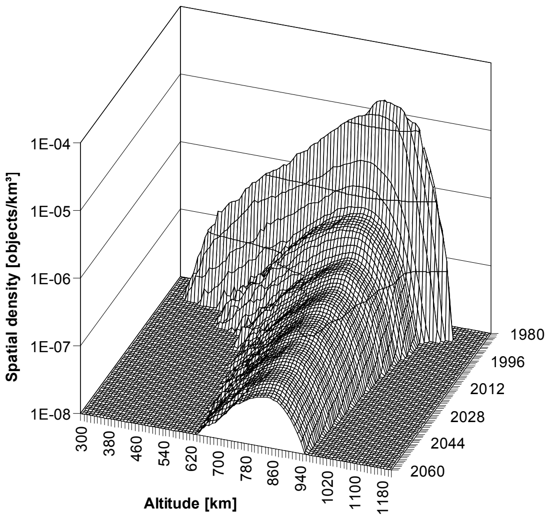

Figure 9. Simulated spatial density of NaK droplets in orbits between 300 km and 1200 km altitude in the years from 1980 to 2060

The maximum of the spatial density in 1980 is close to 850 km altitude. Smaller droplets decay faster, moving more quickly to lower altitudes. The peak of the spatial density is reduced by more then two orders of magnitude until the end of the simulation time. The significant reduction in the spatial density is due to the fact that the small droplets have a very short orbital lifetime. Due to the rapid decay of the small droplets, the spatial density on low orbits is initially very high.

Considering only the droplets larger than 1 cm, the maximum of the spatial density is shifting from 950 km (1990) down to 850 km (2060). This shift is illustrated in Fig. 10. It is important to notice that the spatial density at altitudes close to 800 km remains almost constant between the reference epoch and the end of the simulation. The risk for satellites does not change in this period. Fig. 10 also illustrates the behavior of droplets decay from Cosmos 1900. The satellite reached a lower graveyard orbit of 700 km altitude only, due to a malfunction. The release of NaK droplets took place a short time before the beginning of a period of increased solar activity. This means that all droplets of this event decayed very quickly and are no longer in space today.

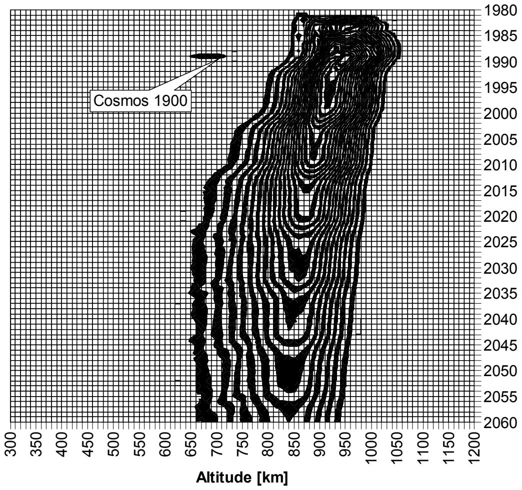

Figure 10. Simulated spatial density of NaK droplets larger than 1 cm in orbits between 300 km and 1200 km altitude in the years from 1980 to 2060

4.3 Spatial Density at the Reference Epoch

Fig. 11 shows the spatial density of space debris objects larger than 5 mm at the reference epoch (May 1, 2009). In this size regime, only the slag particles from solid rocket motor (SRM) firings and fragments are relevant sources, besides the NaK droplets. Furthermore the Launch and Mission Related Objects (LMRO) are shown. The debris population is dominated by the fragments.

The spatial density of objects larger than 1 cm is given in Fig. 12. The distribution of the NaK droplets is limited to altitudes between 800 km to 1,000 km, where they were produced originally. The reason for the lack of NaK on other altitudes is mainly due to the small additional velocity which was simulated with an average value of 15 m/s [14].

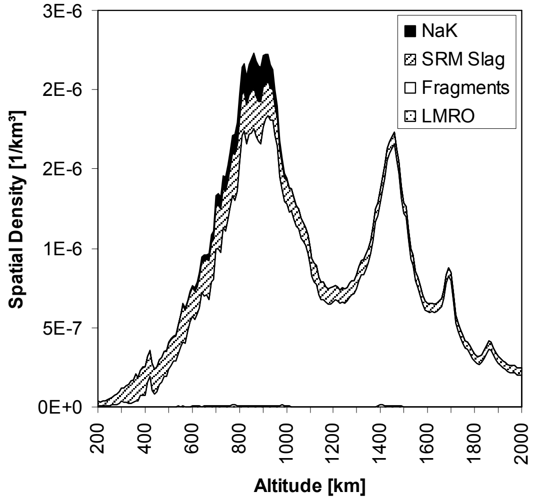

Figure 11. Simulated spatial density of objects larger than 5 mm, valid for May1, 2009 (the envelope curve is the total spatial density)

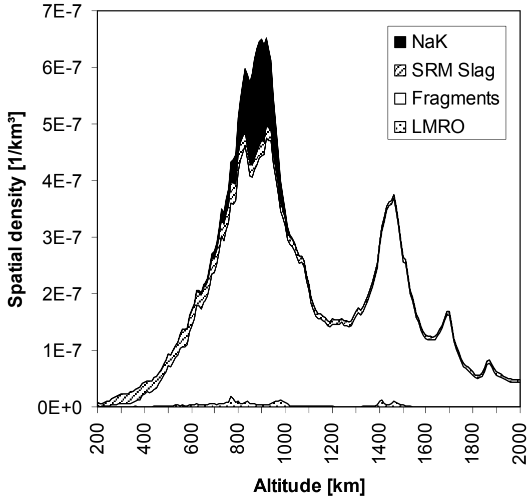

Figure 12. Simulated spatial density of objects larger than 1 cm, valid for May1, 2009 (the envelope curve is the total spatial density)

Comparing the sources of centimeter objects on all orbits, including the geostationary orbit (GEO), the number of NaK droplets is much lower than other contributions. But the droplets occur in one narrow altitude band in high numbers. The liquid metal droplets in the centimeter range can be found today only in orbits close to 900 km, where they contribute to about 30 % to the space debris environment. Fragments and slag, however can be found in all orbital altitudes up to GEO.

5 CONCLUSION

The subject of this investigation is to verify whether a reduction of the released coolant mass is advisable. This assumption is confirmed by an approximation. Consequently, the mass is reduced compared to the previous model. The released mass is reduced to 5.3 kg per reactor core ejection event, because the value is in good agreement with radar measurements. The NaK release model has the advantage that it is based on a small number of parameters and can be varied relatively easy (in the case that new details about the reactor design are revealed or new results of radar measurement campaigns are published). Although it is based on many assumptions, the model provides a realistic description of the contribution of the droplets to the space debris environment. The mass based size distribution, which is converted into a number distribution, agrees qualitatively with the measured size distribution. Concerning the estimated droplet numbers, the largest uncertainties are expected to occur in the small size regime. These inaccuracies do not affect the reference epoch, as it was shown that all small droplets decayed in the 1990s.

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