THE CONTRIBUTION OF NAK DROPLETS TO THE SPACE DEBRIS ENVIRONMENT

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ABSTRACT

One important space debris source is sodium-potassium (NaK) droplets. They are the second largest contribution to the space debris environment at altitude regimes around 900 km following the fragmentation debris. All NaK droplets were released from orbital nuclear reactors, operated in space before the end of the eighties. NaK droplets have already been considered in previous versions of the European space debris model MASTER. Currently, the latest version of this model is being developed. The NaK model is also revised and extended. It has now been divided into two sub-models, the already existing “NaK release model” and the new “NaK leakage model”. The release model has been slightly revised. The leakage model was newly implemented in the software. The droplets added by leakages are very small in number. The contribution of NaK droplets is compared to other space debris sources.

1 INTRODUCTION

Although two different mechanisms are known to have led to the distribution of liquid metal droplets, the release from the Buk reactors is the dominant one. The corresponding satellites are also referred to as RORSAT. The Buk reactors were usually transferred to an elevated decay orbit after the end of their operation. This is referred to as Sufficiently High Orbit (SHO). It is estimated that 16 of these reactors have ejected their cores since 1980. The initial hypothesis was that the droplets were released during the reactor core ejection. As a result, the releases are simulated as individual events. Kessler et al. [1] quote a statement from a Russian designer of the satellites that confirms that droplets can be released during reactor core ejection. The model was developed based on this hypothesis. The liquid metal droplets which have been released during the ejection of the reactor cores account for a substantial portion of the contribution to this space debris source. The essential part of this work will therefore comprise the modeling of this contribution. In the following, the development steps of this model will be summarized.

Sodium-potassium droplets are a very special kind of space debris. They all consist of the same material, the eutectic sodium-potassium alloy NaK-78. All NaK droplets are spherical and have the same density. Only the size is different. The maximum diameter is about five and a half centimeters [2]. Today's population of NaK droplets is dominated by centimeter objects. All smaller objects have already decayed and re-entered the atmosphere. This source is mainly a historical contribution to the space debris environment. Apart from two smaller leakages, which occurred in the recent past, the droplets were released between 1980 and 1989. The predominant amount was released during the operational opening of the primary cooling circuit of Buk type reactors. A smaller amount came from two leakages of TOPAZ type reactors.

The ejection of the reactors cores has also been described in Russian publications. One document clearly shows the ejection of the reactor core [3]. However, the emerging droplets are not shown. The first graphic showing the reactor core ejection is accompanied by a droplet cloud can be found in [4]. Thus, the initial hypothesis can be regarded as confirmed. The results of new simulation calculations are presented. The individual contributions are presented in terms of spatial density.

2 RELEASED MASS

An important model parameter is the released mass or the volume of liquid metal. This parameter determines the released number of droplets. In early publications, it was assumed that 13 kg of eutectic NaK could escape into space from each reactor [5, 6, 7, 8, 9]. The initial assumption regarding the released mass was continuously reduced in the course of the following publications. Subsequently, the mass was reduced from 13 kg to 8 kg [10, 11] and then to 5.3 kg. This mass has remained to this day. A comment from a Russian specialist following a presentation [8] at the Fourth European Conference on Space Debris clarified that 13 kg represents the total mass of the liquid present in the primary cooling circuit. In his opinion, only 3.5 kg could have been released during the reactor core ejection. A review of the Russian statement revealed that this figure is a reasonable measure. Considering only the liquid volume within the reactor vessel and the

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volume of liquid that can be pushed out by a relaxation of the expansion tank, a comparable amount is obtained. Depending on the possible release temperatures, a mass between 1.55 kg and 3.93 kg was calculated under simplifying assumptions [12, 13]. This fits very well with the Russian statement. This simplifying calculation is, however, a very conservative estimate. It did not take into account the existence of other possible mechanisms which may lead to an additional release. It might be speculated that a pre-load of the flexible parts inside the expansion tank or centrifugal forces might have played a role. Therefore, this conservative estimate was increased to a total of 5.3 kg released liquid mass in order to be able to reproduce radar measurement data.

3 THE SIZE DISTRIBUTION FUNCTION

The size distribution function itself was first formulated in a very simple form. In a first unpublished version, a simple Weibull distribution was used to describe the diameter distribution of the droplets. In subsequent studies, attempts were made to replicate published measured values by adjusting the distribution in such a way that it could reproduce the measurement results. A first variant of this can be found in [5]. This function was further modified over time and finally led to a version which was published in [14], p. 85. These variants are still characterized by a very high amount of sub-millimeter droplets, which have only been inserted to reproduce a small number of impacts on spaceflight hardware, which were believed to be droplets. This would, however, lead to high droplet numbers in the smallest size regime. From today's point of view, there is no justification for the generation of such high droplet numbers in the small size regime as a result of reactor core ejections. The next important step was to move from a mere adaptation to measured values to a more systematic approach. Therefore, a review was made for a size distribution function which sufficiently describes droplet distribution processes. The Rosin-Rammler distribution was finally selected, for it’s ability to reproduce measured values very well [6, 7, 11]. This function is used in a modified version until today in modeling [13].

Another attempt for a systematic approach was to estimate selected droplet sizes based on physical mechanisms. Above all, average droplet sizes played a role as well as the maximum and the minimum droplet size. The droplet size should typically be distributed over the orifice diameter. Therefore, the estimation of the diameter of the possible orifices is first of all important. Two possible orifices were identified. One is located on the bottom of the reactor and presumably consists of a distributor (similar to a showerhead) that distributes the droplets to the interstices between the fuel rods. A larger orifice may be found at the reactor head, where probably one of the larger pipes is opened while the reactor core is being ejected [6, 7, 11]. The diameters of the two openings were estimated from geometric data on the reactor. The Rosin-Rammler equation was then applied twice. In an early version, an attempt was made to determine a physical weighting factor for the ratio of the liquid volumes exiting at each of the two orifices. Later, this ratio was arbitrarily set to reproduce the number of large droplets compared to measured data. These modifications were accompanied by a reduction in the total mass. While initially the mass was distributed to about 16 % in small droplets (released from the small orifice), the amount of small droplets was arbitrarily reduced to 8 % after the reduction of the total mass to 5.3 kg, in order to be able to maintain the number of observable larger droplets. This arbitrary determination is quite acceptable since it has been shown that the orbital lifetime of the small droplets is so short that they have disappeared from space. In other words, minor inaccuracies in the estimation of the number of small droplets are of little importance in modeling in the long term.

Another important step towards the systematization of the distribution function was the estimation of the function’s parameters. The Rosin-Rammler distribution is actually an empirical function that is fitted to measured droplet distributions. The parameters are usually determined by means of regression analysis from measured data. This procedure is not possible here, because no measured droplet size distribution exists. Therefore, a different approach was used. A meaningful estimate was made for the largest and the smallest droplet. These "endpoints" then served as a basis for estimating the parameters of the distribution function.

For the estimation of the largest released droplet diameter, Rayleigh's capillary jet breakup is used [15, 16, 17]. This theory best considers the physical conditions under which the droplets have been released. When a low viscosity liquid is released into a vacuum, the diameter of the largest emerging droplet can be calculated as 1.89 times the orifice diameter. From published technical data on the dimensions of the large pipes of the reactor [18], a diameter of about 3 cm was derived. As a result, the largest droplet should have a diameter of 5.67 cm [6, 7]. This fits very well with radar observations, which for example measured a diameter of 5.68 cm [1, 19]. This also explains the findings made in [2] implying that there seems to be a process that does not allow the droplets to be larger than five and a half centimeters. Supposing the Rayleigh mechanism, a physical explanation for these observations has been found. For the estimation of the smallest droplet, a theory was used that is valid for effervescent atomization. Therefore, the smallest droplet has a diameter of about half a millimeter [6, 7]. The idea of the effervescent atomization was derived from a publication by Wetch [20], which suggests that gas pressure may be used as a driving force to eject the reactor core. This could mean a mixing between the coolant and the injected gas may occur. This assumption is purely hypothetical and cannot be proven. If it turned out to be inaccurate, however, the effect of the error on the final results would be low. The smallest droplets have a very short orbital lifetime and do not show a long-term impact on the overall space debris environment.

The Rosin-Rammler equation was applied first in MASTER-2005. After this, however, further improvement was necessary, because the Rosin-Rammler distribution has a disadvantage. Strictly speaking the function ranges from minus infinity to plus infinity. This function is cut off at the largest and the smallest droplet size. The mass above or below this droplet is ignored and is not considered in the mass balance. Normally, this does not play a significant role in liquid atomization processes, since most liquid sprays lead to relatively homogeneous size distribution, in which the droplet sizes hardly differ appreciably from one another. The largest droplet in such a case may account for one per mill of the total mass of fluid released [21] p. 92. Here, this is different. The largest droplet with a mass of a little bit less than 100 g makes up about 2 % percent of the total mass of the released liquid mass. Since the same mass fraction is also assumed to be cut-off below the smallest droplet, this leads to an error in the mass balance. Therefore, a variant of the Rosin-Rammler distribution, which compensates for this error, the so-called modified Rosin-Rammler function was used in subsequent models. This has the advantage that the mass balance is correct now. It means that the mass released during the simulation is completely converted into droplets. However, the disadvantage of using the modified version is that it leads to slight distortions in the physical significance of the parameters. This means, above all, that the parameters lose their physical meaning. This compromise is acceptable since, in the field of modeling the space debris, mass balances are essential, because it determines the number of objects being generated. The relation between mass and number is a dominant parameter in modeling. This variant of the modified Rosin-Rammler distribution was implemented in MASTER-2009 and is still used today in the model.

The fact that two Rosin-Rammler functions have been applied leads to a bi-modal distribution (s. Fig. 4 in [12]). For the representation of the number of droplets (which are currently in space) the part of the bi-modal distribution is important which describes the distribution of the larger droplets. Today's population is dominated by centimeter droplets. All smaller droplets have already descended long ago. The estimation of the largest and smallest droplet diameters is closely related to the physical mechanisms of generation which can reasonably be assumed to describe atomization of the liquid volume. In one of the first publications fundamental mechanisms were reviewed [5]. Without proving this, it was assumed that a so-called flash evaporation may be considered as a mechanism. If a liquid with a low vapor pressure is exposed to the high vacuum, a spontaneous boiling can occur, thereby sputtering the liquid volume into a large number of small droplets. However, a subsequent examination of the conditions for a flash evaporation revealed that the temperatures, which can occur in the reactor, are not suitable for spontaneous boiling [9]. The vapor pressure of the eutectic sodium-potassium alloy is too low to allow such a mechanism. For this reason, a flash evaporation was excluded as atomization mechanism.

4 RELEASE VELOCITY

The release velocity determines the distribution of the droplet population over different orbital altitudes. Compared to other debris generation events, the additional velocity of the NaK droplets is very low. Smaller inaccuracies do not impact the modeling. Initially a maximum release velocity of 30 m/s was assumed [5]. Later this order of magnitude was confirmed from the presumed internal pressure inside the reactor [9]. The average release velocity is in an order of magnitude of 15 m/s. This assumption agrees with early analyses from [1, 22]. It has not been changed since then.

Another parameter is the release direction. This is associated with the direction in which the reactor core is ejected. Originally it was assumed that the reactor cores were ejected in the direction of flight. Only in the case of one reactor it was explicitly assumed that this is contrary to the direction of flight, since a reference has been explicitly pointed out [23]. This approach is now changed for the first time. Now all the reactor cores are assumed to have been ejected against the direction of flight. This change is due to a discussion of the problem by Sven Grahn, who has elaborated carefully on the transfer maneuver, the spin stabilization of the satellite during the maneuver, and the assumed position of the reactor after reaching the SHO. He has presented his views on the topic convincingly on his website [24]. Technically, this would require the transfer engines to point in different directions. Meanwhile published graphics of the transfer engines confirm this assumption (s. for example Fig. 1 in [3]). Therefore the direction for all reactors is changed here. In the new MASTER model, all reactor cores will be ejected against the direction of flight. The effect on the model results is very low. This is due to the fact that these velocities are so low that their direction is of no practical importance.

5 SIMULATION OF RELEASE EVENTS

Figure 1 shows the total mass of NaK-78 released during 16 reactor core ejections. It can be assumed that today the population in space is dominated by centimeter droplets. The mass is plotted over time.

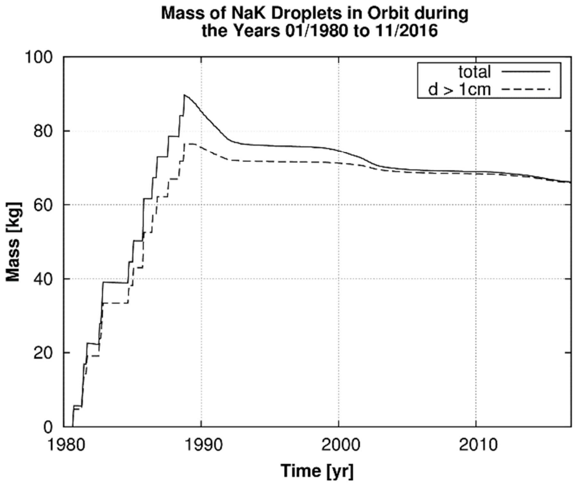

Figure 1. Simulated mass of NaK droplets in orbit

Reactor core ejections have simulated a release of 5.3 kg NaK per event. A total of 16 reactor core ejections are taken into account. For 13 reactors the ejections have been confirmed by observations. This corresponds to a total mass of about 85 kg having been released altogether. No more mass is added with the end of the release events. The two leakages from the TOPAZ reactors have not been considered here. Today, about 65 kg of sodium-potassium droplets are assumed to still be in space. The total mass is relatively small. The graphic distinguishes between objects larger than 1 cm and smaller droplets. It is shown that the majority of the NaK mass still present in space exists in the form of droplets larger than 1 cm.

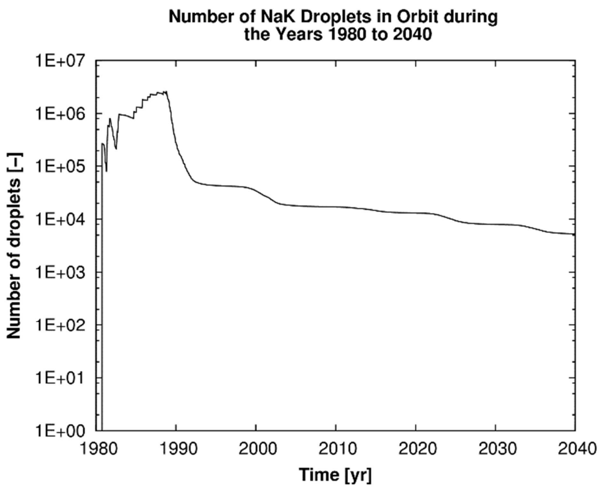

Figure 2. Simulated evolution of the number of NaK droplets in orbit

Figure 2 shows the simulated number of droplets on Earth orbits between the years 1980 and 2040. The representation includes all modelled droplets released from Buk reactors. The model assumptions result in a minimum droplet of about half a millimeter in size. In particular, the very small droplets re-enter Earth's atmosphere relatively quickly, whereby the total number of droplets decreases. The illustration shows only the droplets that have escaped the Buk reactors. The droplets from the leakages of the two TOPAZ reactors are not significant due to their very small number. The quality of representation is primarily determined by the orbit propagation. The material properties of the droplets, their area-to-mass ratio, are relatively well known. Uncertainties are low in this field. The quality of the orbit propagation depends mainly on the prediction of solar activity.

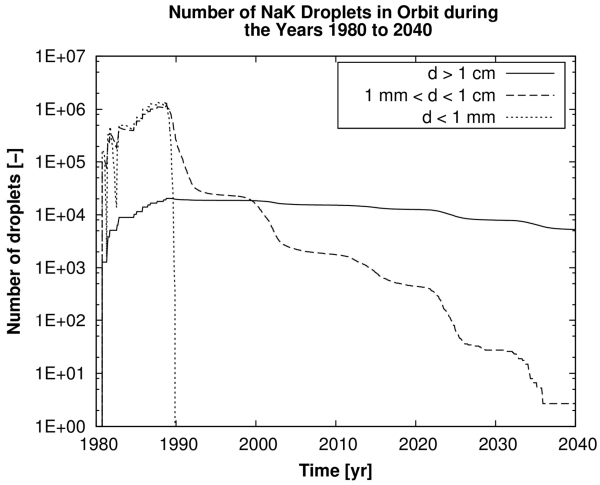

Figure 3. Simulated evolution of the number of NaK droplets in orbit

Figure 3 visualizes the number of descending droplets broken down to different size classes. Droplets are shown that are smaller than 1 mm, larger than 1 cm, and the size class in between. Figure 3 shows very clearly that all droplets smaller than 1 mm have re-entered Earth's atmosphere immediately after the end of the RORSAT program. If in the modeling of these small droplets inaccuracies have occurred, these do not have a long-term impact on the space debris environment. Furthermore, it can be seen that by the year 2000, centimeter droplets became the dominant population. They are likely to be very long-lasting.

Figure 4 shows the simulated descending behavior of the droplets over time. The number of droplets, which have re-entered Earth's atmosphere each month, is shown. It can be noted that the decay rate is very high after the end of the RORSAT program. There are decay rates of up to 100,000 droplets per month. This applies in particular to the very small droplets which have a very large area-to-mass ratio and can therefore be very easily decelerated by the residual drag of the atmosphere. The decay rates are today approximately on the order of 10-100 droplets per month. The rate depends essentially on the influence of the solar activity. The simulated eleven-year cycle of the solar activity is clearly visible. During periods of increased solar activity, the decay rates rise significantly, as the atmosphere expands to higher orbital altitudes. These results are also very similar to previous publications [12].

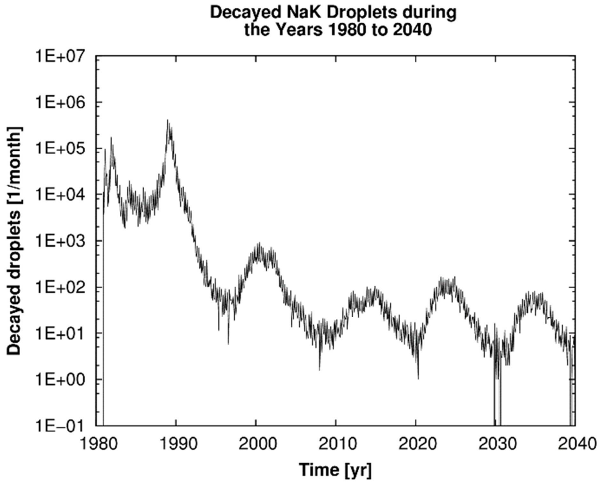

Figure 4. Simulated decay behaviour of NaK droplets shown as monthly decayed number of objects

Figure 5 shows the decay rate as a monthly re-entered mass. The simulation results suggest that in the future they will decay in the order of 100 g per month.

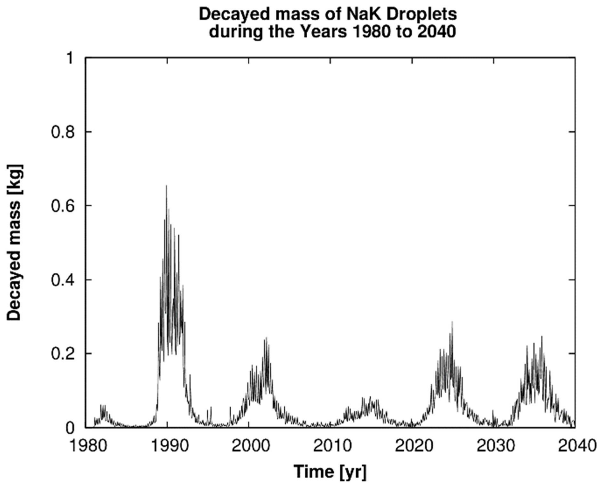

Figure 5. Simulated decay behaviour of NaK droplets shown as monthly decayed mass

Figure 6 shows a comparison of the model results with measured data. There are only few possibilities to validate the sodium-potassium model. Krisko et al. published such data in a paper (s. Fig. IV in [25]). These are compared with the model based on the assumption that the data reflect the situation in 2013.

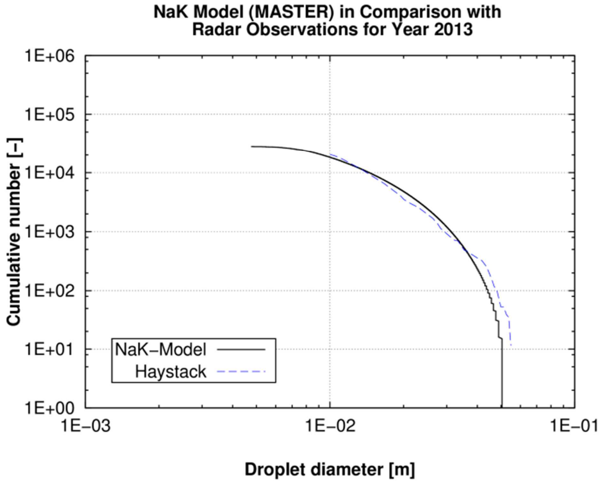

Figure 6. Comparison of the NaK size distribution model with radar measurement data taken from Krisko et al. (s. Fig. IV in [25])

Figure 6 shows the cumulative number of droplets in orbit versus the droplet diameter. Krisko et al. took into account all droplets that are larger than 1 cm. The comparison reveals that the simulated results agree nearly perfectly with the measured data, both in terms of the number of released droplets and concerning the shape of the size distribution function. This confirms that the selection of the modified Rosin-Rammler equation, the estimation of the droplet size parameters, and the calculation of the largest droplet diameter obviously represent a suitable model approach which reflects reality very well.

6 ORBITAL DISTRIBUTION

The next question, to be investigated here, is the distribution of the NaK droplets from the Buk reactors over different size classes. Figures 7 and 8 show the portions of droplets larger than 1 cm compared to smaller droplets. Figure 7 shows the situation in the year 2009 which corresponds approximately to the reference epoch of the MASTER-2009 model. Figure 8 shows the spatial density of the year 2016. In the time period between both figures, a considerable amount of droplets has decayed. The centimeter objects have their maximum slightly below 900 km altitude. The maximum of the millimeter objects is found at about 800 km. Furthermore, the sum of the individual subpopulations is shown. Looking at the individual components, it can be seen that the reduction took place most of all in the millimeter population. Due to their larger area-to-mass ratio, they decay much faster than the centimeter objects. The simulation shows that the NaK population is currently dominated by centimeter droplets. It is expected that this population will remain in space for a long time.

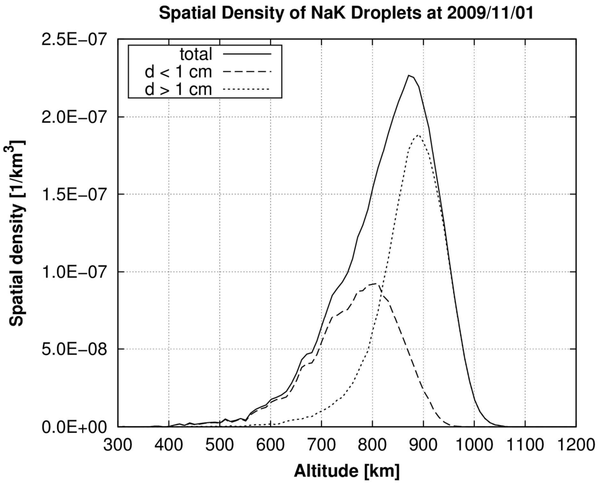

Figure 7. Spatial density of NaK droplets for two diameter classes in 2009

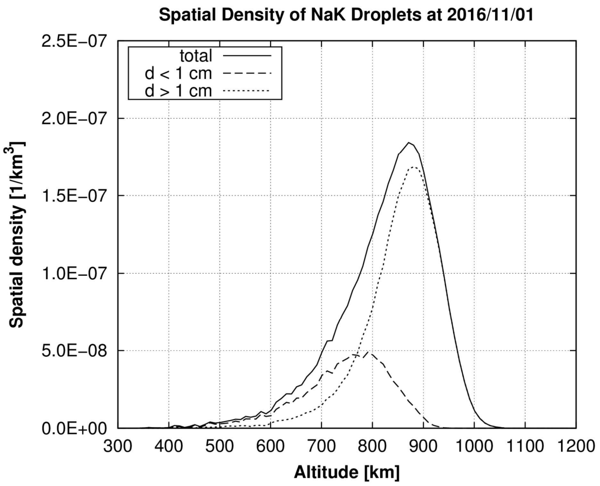

Figure 8. Spatial density of NaK droplets for two diameter classes in 2016

In the following, the contribution of sodium-potassium droplets to the other debris populations will be presented for objects larger than 5 mm (s. Fig. 9) and objects larger 1 cm (s. Fig. 10). With respect to the NaK droplets, it makes sense to look at objects that are larger than 5 mm only. Below this diameter, there are no droplets anymore. Three comparative populations are used, the slag particles, the fragmentation debris and the Launch and Mission Related Objects (LMRO). (The representation of the multilayer insulation is excluded here.) In the 5 millimeter range, the NaK droplets are below the contribution of slag particles. They only make a very small contribution even at an altitude of 800 km. It should be emphasized that the populations presented here refer to a currently ongoing investigation, which has not yet been completed. It is meant to lead to the development of a new version of the MASTER model. This is a presentation of preliminary results. The presented populations are based on new simulation results which have not yet been validated. The final results will differ from those presented here. But there is already a certain tendency to see how the new results will differ from previous ones.

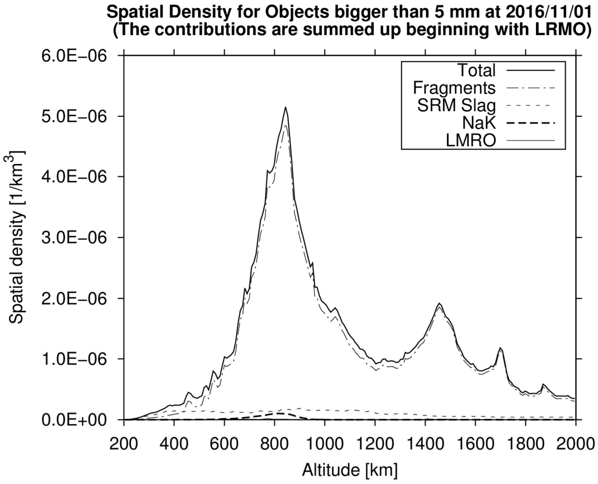

Figure 9. Spatial density of objects larger than 5 mm on low Earth orbits in 2016

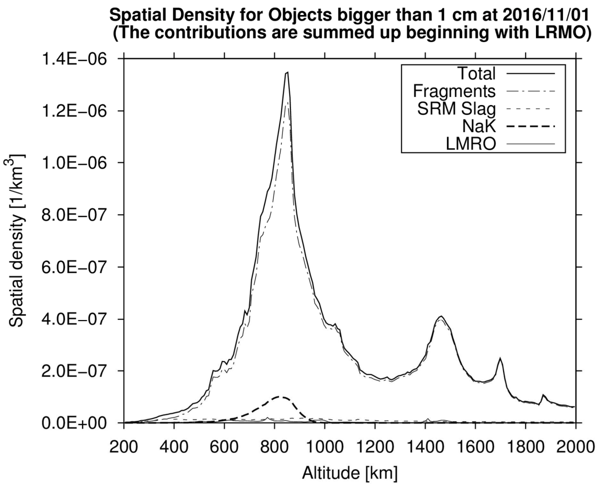

Figure 10. Spatial density of objects larger than 1 cm on low Earth orbits in 2016

According to the simulation calculations, the population of sodium-potassium droplets is now dominated by centimeter droplets. They are still the second largest contribution to the debris environment between 800 km and 900 km, following the fragments, followed by slag particles as seen in Fig. 10. However, their amount compared to fragments is much lower than in previous investigations [26]. This is due to the fact that, in particular, the Fengyun-1C event has released considerably more fragments than was estimated before. The amount of sodium-potassium droplets is comparable with what was already simulated before [13]. However, the importance of droplets for the risk of collision has now declined because of the greater consideration of fragments at this orbital altitude.

The sodium-potassium droplets are still one of the dominant contributions of space debris, even if this is essentially a historical source. The NaK population is dominated by the droplets which have been released from Buk reactors. The leaks from the two TOPAZ reactors have barely contributed to the debris environment. In the following, the relative proportion of these droplets in the present debris population is shown. First, the centimeter population is examined.

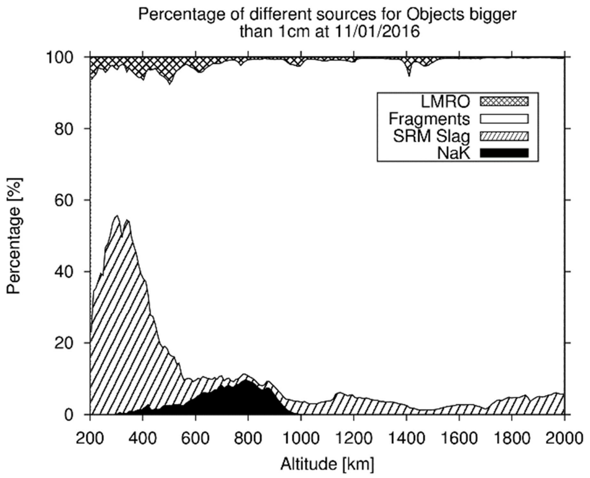

Figure 11. Relative contributions to the spatial density of objects larger than 1 cm on low Earth orbits in 2016

Figure 11 shows the four important contributions of the centimeter population relative to each other. The contribution of sodium-potassium droplets today at 800 km altitude is slightly less than 10 % of the total population. It can be seen that the dominant contribution results from fragments in 800 km. The contribution of slag particles and LMRO is very low.

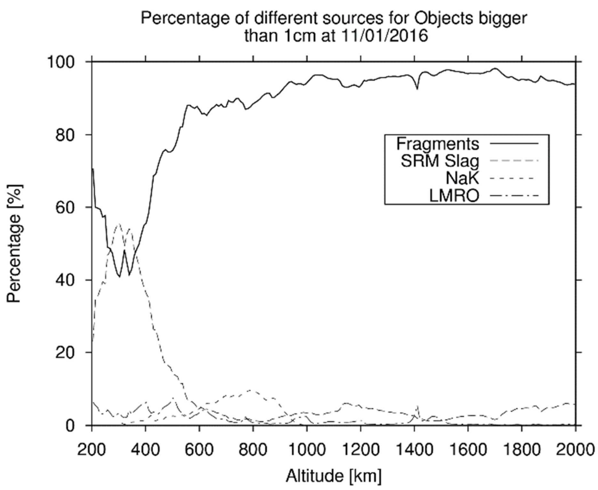

Figure 12. Relative contributions to the spatial density of objects larger than 1 cm on low Earth orbits in 2016

Figure 12 shows the same data in a different representation. It differs, because the contributions are represented individually, whereas in Fig. 11 they are summed up. In Fig. 12, it can once again be very clearly recognized that the smallest contribution in 800 km results from the slag particles and the LMRO, which make up only a few percent of the population at this altitude. The fragments dominate the population at this altitude with a little less than 90 %. This is a clear difference from previous representations [26]. It is due to the fact that the influence of the Fengyun-1C event (Chinese anti-satellite test) is now weighted much more strongly than in previous calculations.

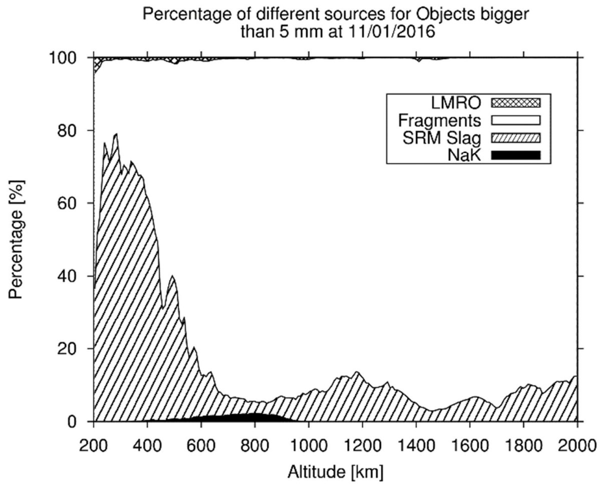

Figure 13. Relative contributions to the spatial density of objects larger than 5 mm on low Earth orbits in 2016

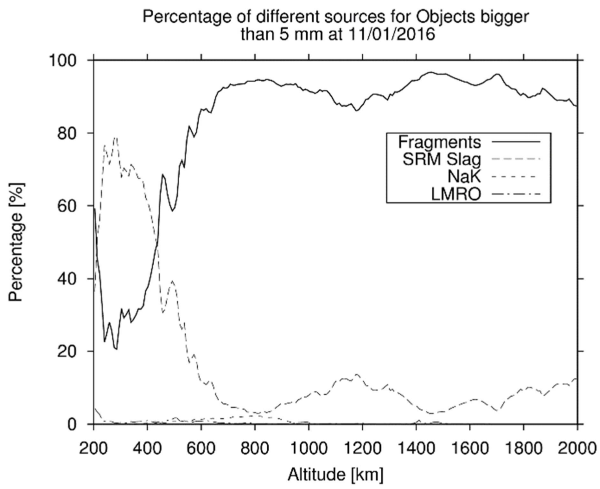

Figure 14. Relative contributions to the spatial density of objects larger than 5 mm on low Earth orbits in 2016

Analogous representations have also been generated for the objects larger than 5 mm. In Figs. 13 and 14 it can be seen that NaK droplets hardly represent a significant portion of the overall debris population. This is due to the fact that most droplets smaller than 5 mm have already decayed. The remaining population is dominated by the droplets larger than 1 cm. And these make up only a small part in the 5 mm population.

7 LEAKAGE EVENTS

Figure 15 shows an updated version of a graph previously published in [27], taking into account the additional contribution of sodium-potassium droplets from TOPAZ reactors. It was shown in detail that the number of droplets that leaked from the two TOPAZ reactors is low. These two leakage events are distinctly different from the previous reactor core ejections. They have taken place long after shut-down of the reactors. Furthermore, the total mass which has leaked is significantly lower as for the Buk reactors. In the case of the TOPAZ reactors, a depressurization of the expansion tank is assumed as the only cause of the leakage. Approximately 250 g have leaked per event. The number is estimated to be just 35 droplets per event. All of them are in the centimeter range. The logarithmic representation of the spatial density shown in Fig. 15 makes this contribution visible. It can be seen that it is more than one order of magnitude less than the contribution from the Buk reactors. For the total number of objects in space, these two leaks play only a minor role.

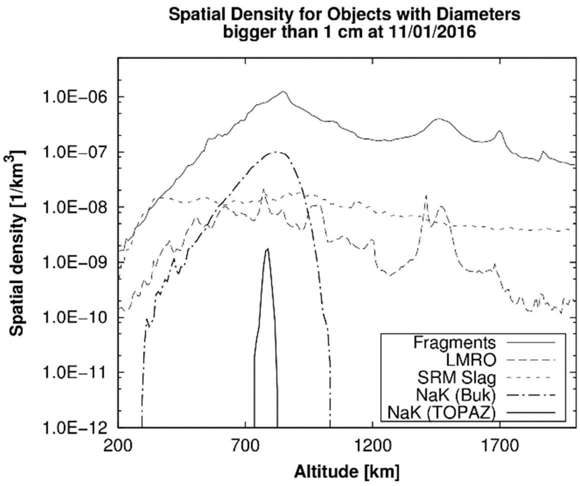

Figure 15. Spatial density of objects larger than 1 cm on low Earth orbits in 2016

8 SUMMARY

In this examination a preliminary presentation is investigated, in which the current population of the sodium-potassium droplets is compared to the current space debris population. Since there has been little change in the NaK release model and since the contribution of the newly added NaK leakages is only small, there are hardly any changes to the previous simulation results. The basic model assumptions proved to be correct and have been largely retained here. Only slight corrections, for example with respect to release direction, have been made. There are two important findings of this work. It can be seen that the model describes reality very well. The results are consistent with the few available measurements on both, the number of droplets as well as the shape of the size distribution. This confirms that the selection of the Rosin-Rammler distribution and the application of the Rayleigh mechanism in the calculation of the largest droplet have proven to be adequate approaches to describing the problem of NaK release. The second important result is that from today's perspective, the relative amount of sodium-potassium droplets appears smaller than originally assumed. However, this is entirely due to the fact that the Chinese anti-satellite test is today viewed as a more serious event than was the case in previous analyses. However, it must be emphasized that the population presented here is not yet validated and is only an interim result of a current investigation. The results can still change.

9 ACKNOWLEDGEMENT

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