THE HISTORICAL CONTRIBUTION OF SOLID ROCKET MOTORS TO THE ONE CENTIMETER DEBRIS POPULATION

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ABSTRACT

The measured small particle population in Earth orbit contains centimeter-sized objects that are not accounted for by fragments from breakups. It has been proposed that slag ejection in solid rocket motor (SRM) burns is a contributor to this population. The direct evidence for such slag ejection follows from: (1) observations of the exhausts of vehicles in flight and (2) engineering data from static firings.

Particle production by slag accumulation may be characterized as follows. SRMs, which incorporate an aluminized propellant, produce aluminum oxides as a combustion product. A small amount of metallic aluminum melts and forms large droplets which do not burn but rather flow along the motor wall to the rear of the motor. A small fraction of the aluminum oxide forms large droplets which, while partially entrained in the exit gas flow, impact the motor nozzle rather than exiting the motor and contribute to a growing pool of melted metallic aluminum and aluminum oxide at the rear of the motor. Ground tests and models have shown pronounced internal slag motion and subsequent particle escape after trapping.

In this paper we present a source model to account for a debris contribution due to slag expulsion in solid rocket motor burns. We account for mass and velocity distribution of the slag effluents and present this as a source term in the debris environment model. This model is based on available data from observed slag ejection in SRM burns and on models for slag development and ejection that were part of the SRM study.

1. INTRODUCTION

1.1 Space Debris 100 μm to 1 cm in Size

Large particles from SRM operations in orbit have been the subject of recent papers by various associated researchers (Refs. 1-4). From an operational standpoint the principal candidate source of SRM-produced large particles is the action of the vehicles performing geosynchronous transfer orbit injections (LEO-GTO) and apogee circularization kick at geosynchronous altitude (GTO-GEO) (Ref. 3).

In this paper we present an extension of Ref. 3 by presenting observational evidence from visual observation and radar measurements for SRM-produced particles. We add some new discussion of the on-orbit space motor slag production and possible debris production not discussed in Ref. 3.

Large particles will mean ejecta in the size range of 0.1 mm to somewhat larger than 1 cm. The ejecta may consist of a combination of aluminum, aluminum oxide, and materials associated with liners and insulators. In particular we are seeking to improve our understanding of SRMs as a source of large particles of debris and our modeling thereof.

1.2 Motivation

The motivation for continued study of large solid rocket motor particle contributions to the orbital debris environment is expressed in three lines of evidence: (1) radar observations of the debris environment, (2) impacts on spacecraft surfaces and the space shuttle orbiter, and (3) evidence of large particle production from aluminized propellants in SRMs.

1.2.1 Population Radar Observations

Reynolds and Matney (Ref. 2) compared Haystack radar measurement data to the mathematical model EVOLVE and found that there was an inconsistency between the observed population and model population in the size range below 20 cm. Haystack was seeing more debris with decreasing size than predicted by EVOLVE. The data implied more objects with sizes in the 1 cm range and smaller than accounted for by breakups. In 1996 Reynolds and Matney (Ref. 4) presented a comparison of Haystack observations with an updated model of EVOLVE which incorporated a model by Ojkangas (Ref. 5) accounting for SRM particles. The Reynolds

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and Matney (Ref 4) study was successful in constructing a model environment that was in agreement with the radar measurements of the particle population but left open questions such as how the 1 mm to 1 cm population is partitioned between breakups and SRM particles and the further important questions of how to gain a more quantitative understanding of the SRM debris component and how to extend the Ojkangas model.

1.2.2 Impacts on Spacecraft Surfaces

Kessler (Ref. 6) and Zhang and Kessler (Ref. 7) presented evidence that the origin of μm-sized debris impacts on the trailing surfaces of LDEF are attributable to objects in highly elliptical orbits that seem to be associated with GTO mission activities. Hörz, et. al. (Ref. 8) have presented analysis of the chemistry of the impacts of μm-sized particles on the trailing edge of LDEF that shows about 80% of the man-made impacting objects contained aluminum, with the most likely source being SRMs.

Impacts on the Space Shuttle have been a subject of ongoing study, and it is known that the vehicle has taken several 1 mm debris impacts during recent missions (Ref. 9). Some recent aluminum and aluminum oxide impact examples are: (1) the largest window impact on STS-71 which was about 2 mm in diameter, and (2) on STS-73, 2.4 and 3.4 mm craters on the port payload bay door and a L/H Elevon Tile, respectively (Refs. 9,10).

1.3 Radar Observation of an Ascending SRM

Visual observations of the Shuttle boosters have provided evidence for copious amounts of particle ejecta at burnout (Ref. 3). The Haystack radar has been used recently to track an ascending upper stage rocket flight from the NASA Wallops Island facility. The data are displayed in Fig. 1. The data in the plot start at 72 seconds after burnout, and the radar reflections off the particles are displayed in time versus range from the vehicle. Fig. 2 displays a plot of the cumulative number of debris and ejection rate as a function of time reduced from the radar tracking data (Ref. 11).

1.4 Slag and Non-Slag Large Particle Production

The process of SRM slag-produced particles was reviewed in Ref. 3. However it should be mentioned that there maybe some non-slag large particle production during tail off and shutdown of an SRM (Ref. 12). The burning of the last of the propellant and the out-gassing of hot post-burn motors may produce particles in the range of 100 μm to 1 mm that could escape the motor. Boraas (Refs. 12,13) and Price (Ref. 14)

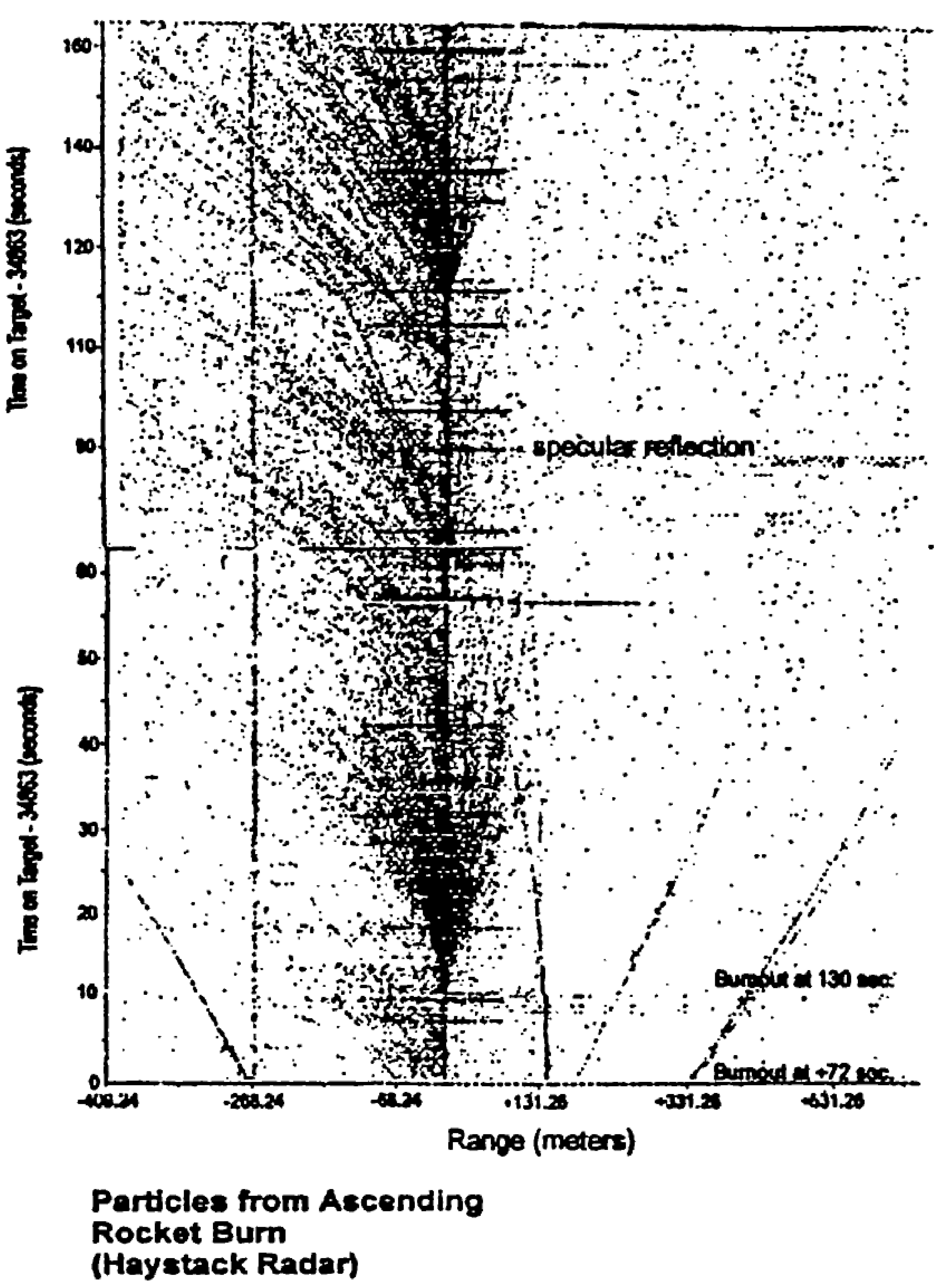

Figure 1. Portion of Radar Track of Ascending SRM Vehicle (MIT Lincoln Laboratory, NASA JSC).

2. SPACE MOTORS PARTICLE PRODUCTION AND ORBIT EVOLUTION

2.1 Small Particles (0.1 μm to 10 μm)

Small particles in size range 0.1 μm to 10 μm are produced during full thrusting. Studies have been made of the orbital evolution of small particles produced during the full thrust phase of space SRMs. We refer the reader to the papers of Mueller and Kessler (Ref. 15), Akiba et. al. (Ref. 16), Schmidt (Ref. 17), and Schobert (Ref. 18). The effects of various forces on the orbit evolution and lifetimes of particles in the 0.1 μm to 10 μm range are covered in these papers. It is noted that most small particles have quite short life times due to the effects of radiation pressure.

2.2 Large Particles (100's μm to 1 cm)

The question of large particle production from SRMs divides into two parts: (1) what evidence is there of

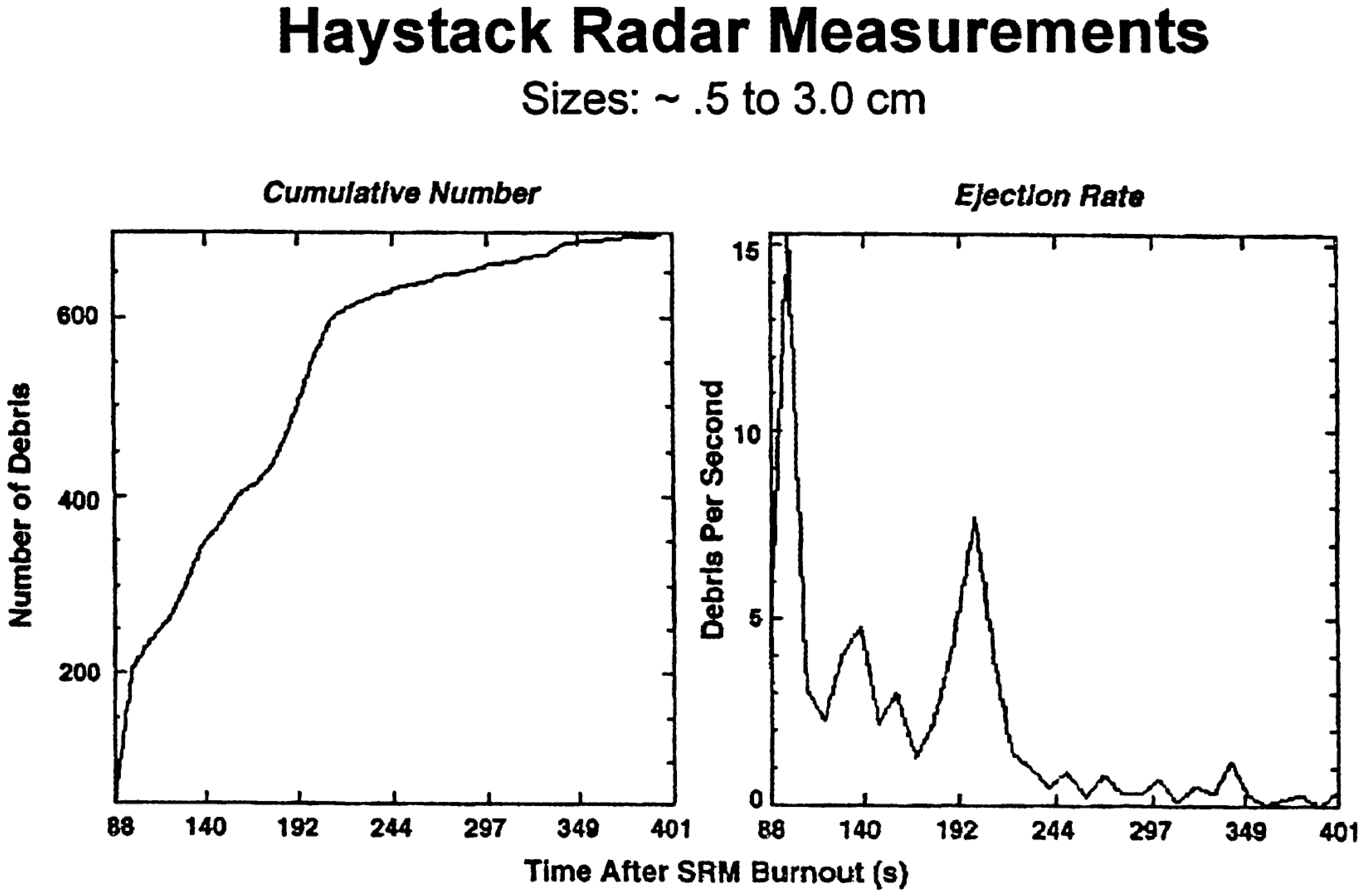

Figure 2. Number Counts and Rate from Data in Fig. 1. (MIT Lincoln Laboratory, NASA JSC).

slag production in space motors? (2) does slag production in space motors invariably lead to particle production?

The process of slag production was described in Reynolds et. al. (Ref. 2); see also Salita (Ref. 19) as a primary source.

2.2.1 Is there Evidence of Slag Production in On-orbit Space Motors?

On-orbit space motors are, for example, the PAM motors used for GTO, the MAGE apogee-kick GEO insertion motors, and others. Slag accumulation in SRMs has been measured in ground testing of space-based motors of the type used for GTO insertion and GEO apogee kick. Haloulakos (Ref. 20), Chang (Ref. 21), Eber (Ref. 22) and Tingle et. al. (Ref. 23) have published research on the comparison of space SRM performance with ground-fired motors. Slag accumulation will affect the overall performance of a SRM burn and indeed slag induced performance degradation has been seen in flight data (Refs. 20-23). Further, there is another on-orbit flight performance factor associated with slag accumulation. Flight data from orbital SRM burns has shown there are moments induced during the end of burn of spinning motors that cause coning (Ref. 24). Research by Misterek et. al. and Meyer (Refs. 24,25) has eliminated gas-dynamic flow as the culprit. It is the conclusion of Meyer that trapped slag is the cause of these rotational instabilities. These lines of evidence lead to the conclusion that space motor SRMs do accumulate slag.

The STAR 48 motor is estimated to generate 10 lb. of slag during a standard mission burn as estimated from flight data. (Ref. 22). During ground tests a spinning STAR 48 generates only a few pounds of slag (Ref. 22).

2.2.2 Particles Associated with Slag Production in On-orbit Space Motors

From the preceding discussion we see there is evidence for slag production in space motors, but are large particles ejected? What we know with certainty about slag generated particles from large booster motors and ascending upper stage motors is not known with certainty about space motors. Circumstantial evidence leads us to infer that the slag produced in the space motors probably has accompanying particle ejection. It is known that during tail off and shut down there is post burn 'cook-off' with the attendant possibility of particle loss (Refs. 13,25). Further, more slag accumulates during a spinning translating burn than in a non-spinning motor or non-translating spinning motor (Ref. 22) and thus leads to a larger slag pool that might give rise to particle loss. In addition it may be that more pure aluminum is resident in the slag pool produced in spun rocket motors (Ref. 27), which may be the source of small aluminum impactors on the Space Shuttle mentioned in section 1.2.2.

For an existent slag pool in an SRM, tail off and shut down of the burn may be a critical period for the ejecta. Out-gassing activity due to a hot slag pool extending for several minutes [Akiba and Kohno, (Ref. 28)] may be important in transporting both aluminum oxide and aluminum particles out the nozzle. Ejection may occur during 'cook off' because of slosh, spill, streaming, boiling, and the eruption of trapped gas (Ref. 29). Any of these mechanisms could lead to loss of droplets or condensates in the form of particles in the size range of 0.1 mm to 1 cm. If the mass of ejecta were uniformly distributed with a lower bound of 0.01 mm and an upper bound of 1 cm then there could be of the order of one hundred thousand particles in the post burn plume, Fig. 3, even if only 100 grams of particles were ejected.

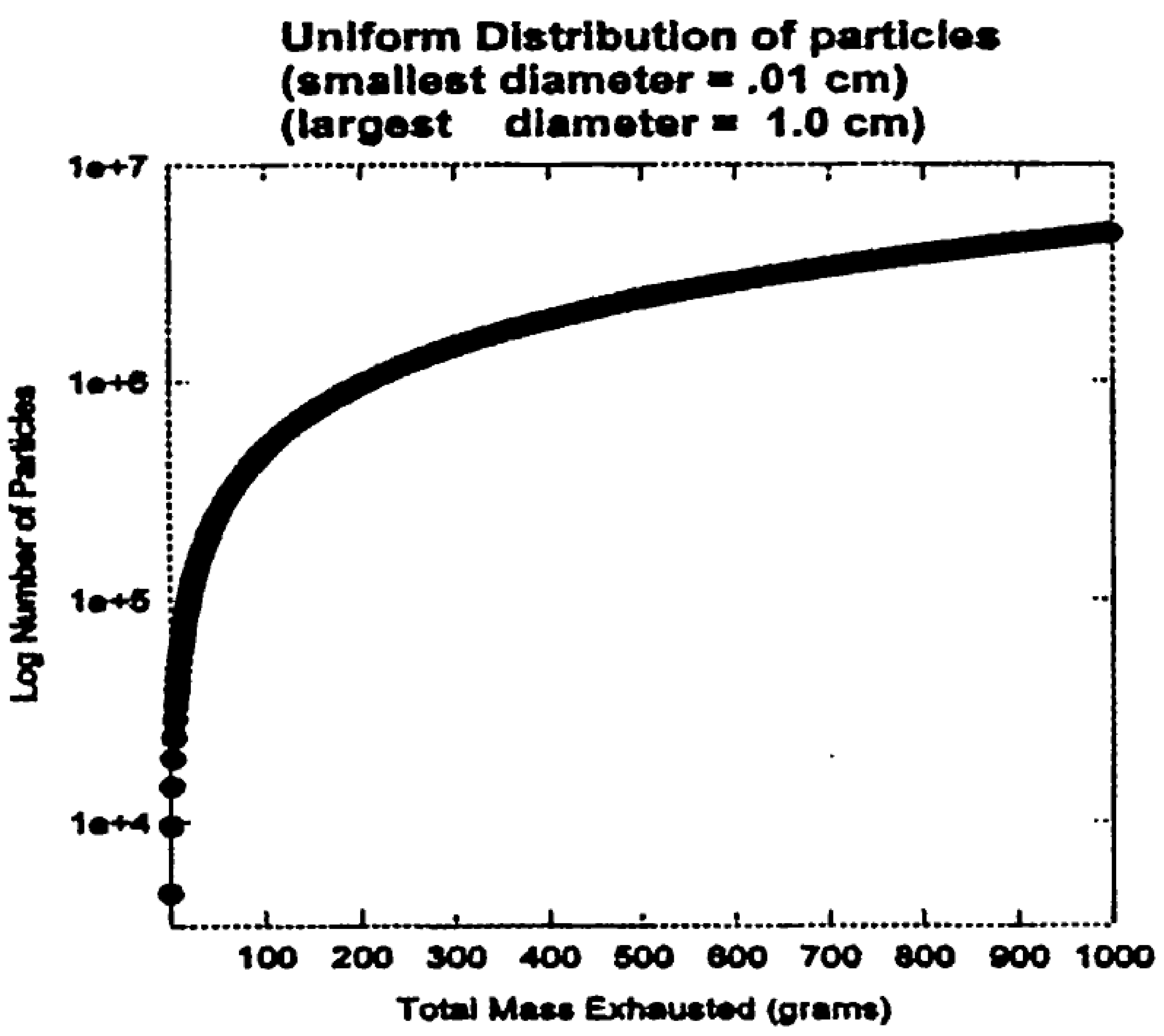

Figure 3. Number of Particles Exhausted if Uniformly Distributed.

2.2.3. A Caveat

Can the radial forces due to rotation of an on-orbit spinning motor restrain the ejection of most or all of the particles post burn? Ref. 5 records evidence of a 33 rpm ground test producing escaping particles. We have qualitative confirmation that 60 rpm spinners have done the same (Ref. 30), but quantitative proof from ground testing and on-orbit burns is not in hand. Further, a certain type of motor spinning at 60 rpm had a radar track that showed few or no escaping particles (Ref. 11).

3. EJECTION, ORBIT EVOLUTION AND SPATIAL DENSITIES

Let us consider the following extension of the Ojkangas model (Ref. 4). We will take the particles to be exhausted into a cone with angles given in Fig. 4. A GTO transfer orbit is taken with perigee 300 km and apogee 36000 km. with an inclination of 28.5°. Particles are ejected in a very short period of time. Take two different speeds of expulsion, 0.1 km/sec and 0.01 km/sec. The particles are assumed to have a representative area/mass ratio of 2.5 m^2/kg which is a 2 mm particle with density of 3 gm/cc. They are ejected with the angles which define a cone (see Fig. 4). The initial Sun angle was taken to be 180° and the particle orbits were followed in time. They were removed from the simulation if their perigee fell below 100 km. The force model for propagation contained perturbations due the Sun, Moon, Earth and air drag.

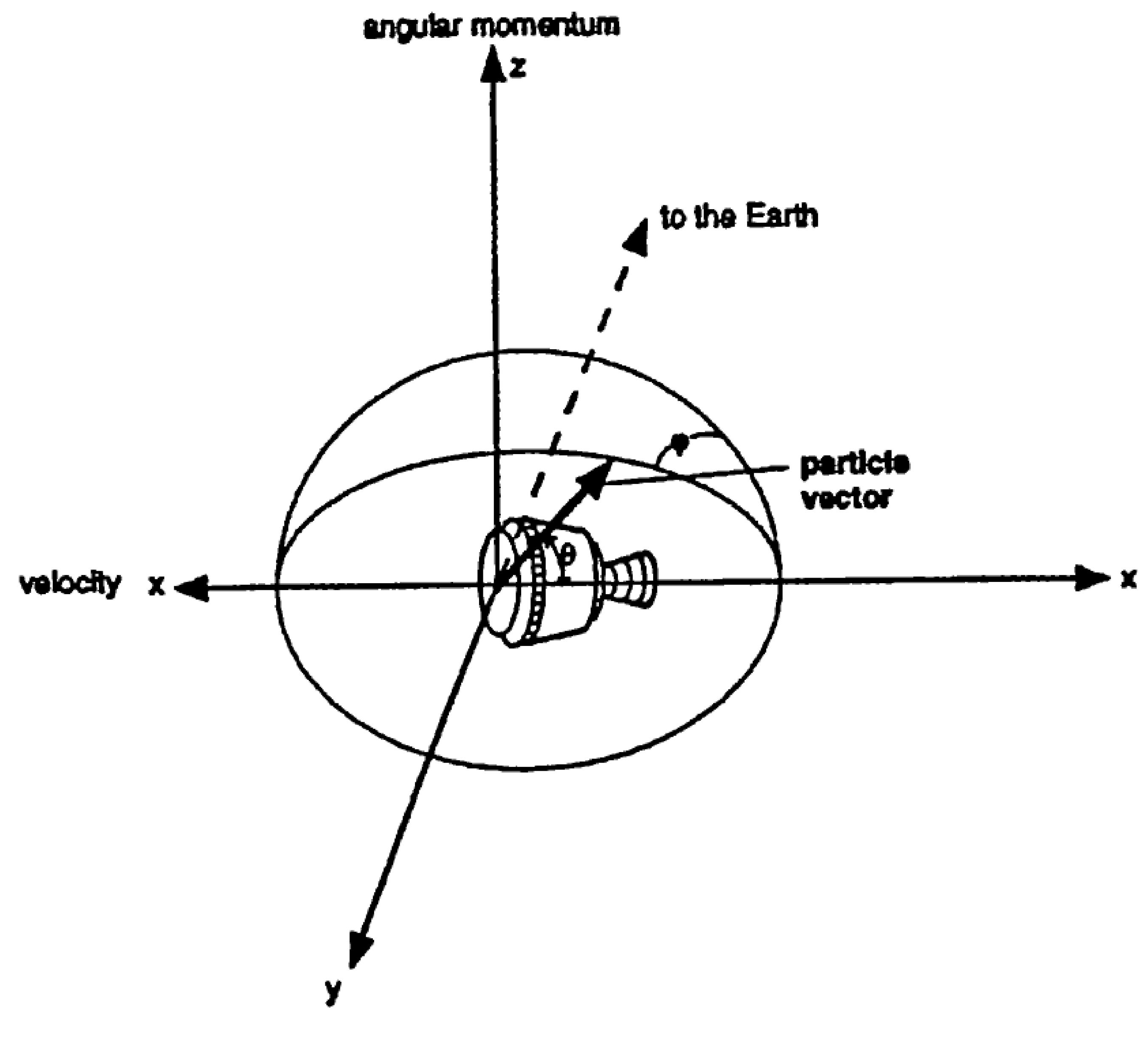

Figure 4. Ejection Cone Angle Definition.

The results of ejection at perigee are shown in a single mission spatial density profile in Fig. 5. On the figure the densities extend from 300 km to 35000 km. The 0.1 km/sec case causes the eccentricity of the resultant orbit to be less than the transfer orbit. One sees this in the apogee height of the 0.1 km/sec case compared to the 0.01 km/sec case. The evolution of the particle in the 0.1 km/sec case is much slower because of the reduced eccentricity. The 0.01 km/sec case almost matches the vehicle orbit. In this case it turns out the ejected particles have a short lifetime because of the placement of the node at 180°. The particles in the 0.01 km/sec case are driven to reentry by a combination of lunar/solar perturbations and the atmospheric drag on a time scale less than 5 years. The 0.1 km/case evolves somewhat more slowly and persists even after 25 years.

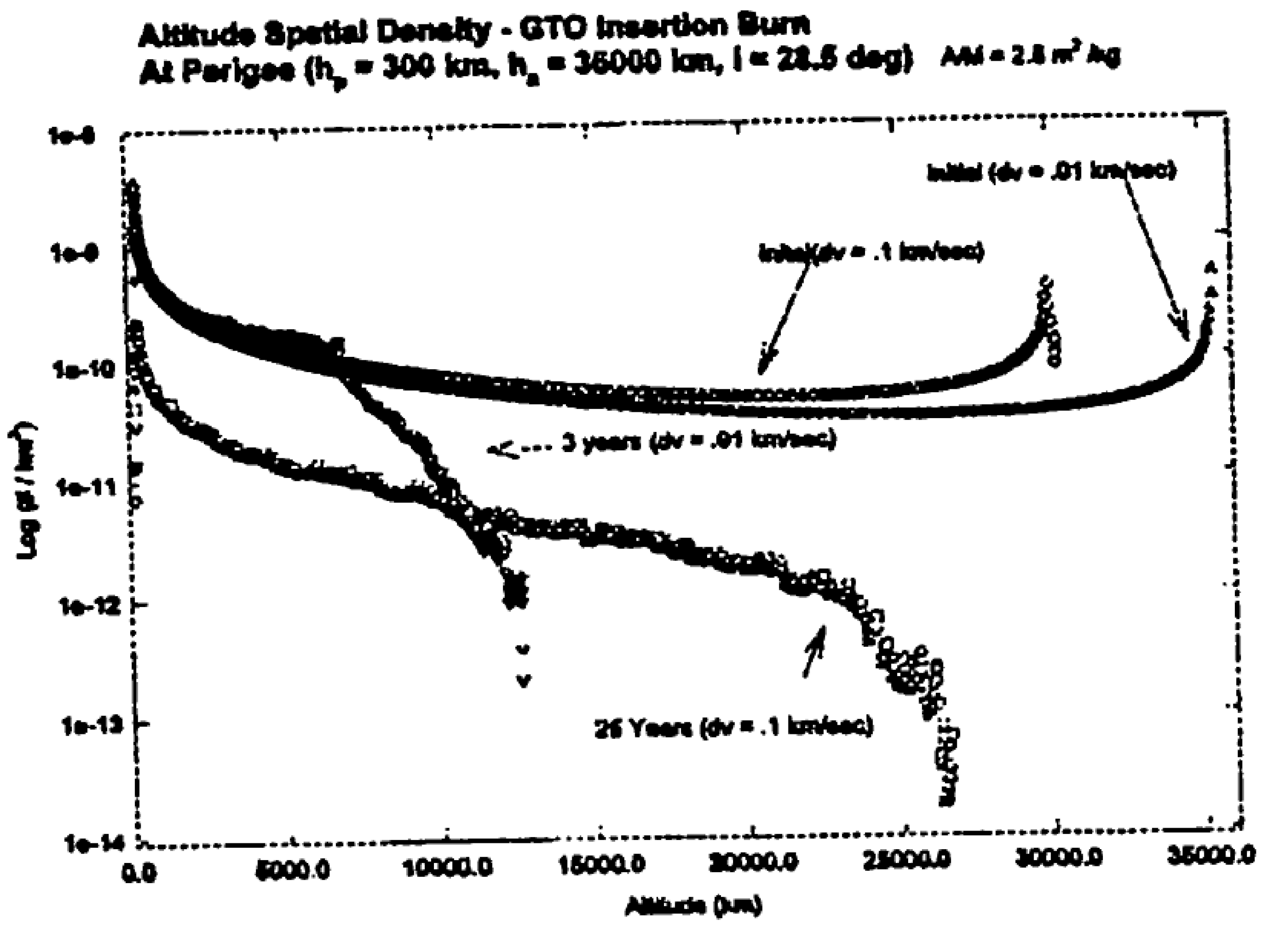

Figure 5. Example Case of Expulsion at Perigee of a GTO Transfer Case.

Fig. 6 shows an apogee kick case. The vehicle is almost in its final circular orbit at 33600 km when it expels particles into a cone. A propagation of the particles shows the altitude distribution does not spread much for an expulsion speed of 0.01 km/sec.

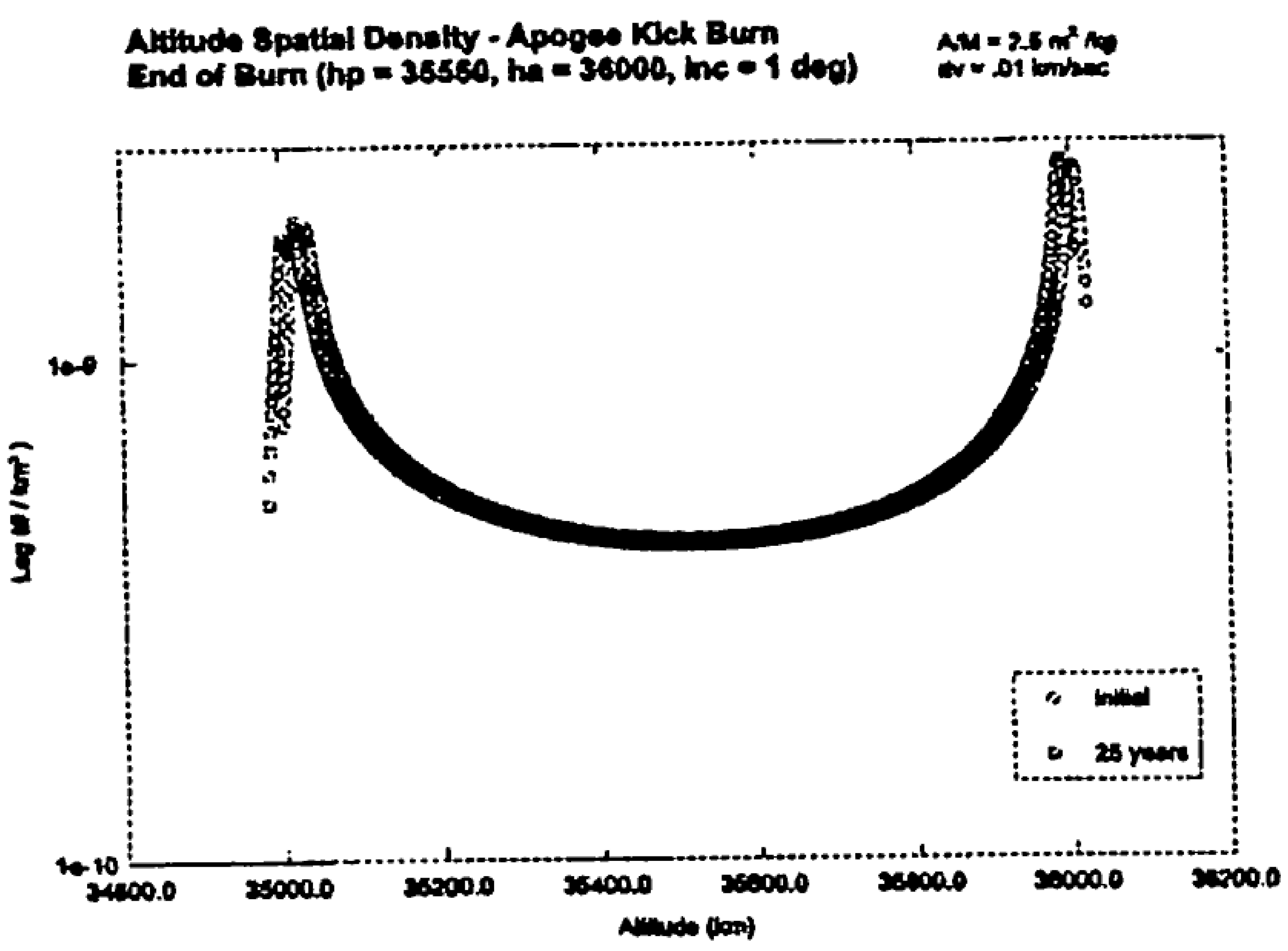

Figure 6. Altitude Spatial Density - Apogee Kick Burn.

6. CONCLUSIONS

Evidence has been presented suggesting space SRMs may be a source of 0.1 mm to 1 cm sized particles deposited in the Earth orbit debris population. A simple model of post-burnout expulsion of particles shows their spatial distribution can be persistent at the initial perigee altitude for some period of time. However, there is a great need for more observational data as follows:

(1) Orbital distribution of existent particles in the 1 mm to 1 cm size range.
(2) Data from SRM testing for particles in the range of 100 μ m to 1 cm for:
  - mass distribution
  - area to mass distribution
  - velocity distribution
(3) Remote observation of on-orbit SRM burns.
(4) The effect of spin on particle flux from space fired SRMs.

As soon as a higher fidelity model of particle flux from SRM burns can be established it will be folded in with the historical data base of solid rocket motor burns in our debris analysis tools.

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