MICRO-SATELLITE IMPACT TESTS TO INVESTIGATE MULTI-LAYER INSULATION FRAGMENTS

Junko Murakami (1), Toshiya Hanada (1)(2), J.-C. Liou (3) and Eugene Stansbery (3)

(1) Department of Aeronautics and Astronautics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka-shi 819-0395, JAPAN, Email: junko_m@aero.kyushu-u.ac.jp

(2) ISAS/JAXA, 3-1-1 Yoshinodai, Sagamihara-shi, Kanagawa 229-8510, JAPAN, Email:toshi@areo.kyushu-u.ac.jp

(3) NASA/JSC, Mail code KX, 2101 NASA Parkway, Houston, TX 77058, USA

Email: jer-chyi.liou-1@nasa.gov, eugene.stansbery@nasa.gov

ABSTRACT

This paper summarizes two satellite impact experiments completed in 2008. The objective of the experiments is to investigate the physical properties of satellite fragments, including those originated from Multi-Layer Insulation and a solar panel. One test generated approximately 1,800 fragments while the other produced only 1,000 fragments. This difference came from the number of needle-like fragments from carbon fiber reinforced plastics. All collected fragments were analyzed using the same method as described in the NASA standard breakup model and compared with the breakup model. This paper will present: (1) the area-to-mass ratio, size, and mass distributions of the fragments, and (2) the differences in fragment properties between the two tests.

1. BACKGROUND

Space debris is a topic that has drawn considerable interest during the last 30 years [1].

To predict the future orbital debris environment, the NASA standard breakup model was developed and is being referred to for estimating the outcome of satellite impact fragmentation. The NASA standard breakup model is derived from some on-orbit experiments and ground hypervelocity impact tests. These experiments provide empirical data to be incorporated in the model. The satellite impact tests contribute to increase the test data and to expand the versatility of the breakup model.

During the Chinese anti-satellite missile test in January 2007, the Fengyun-1C weather satellite was hit by a warhead and broke up into thousands of fragments scattered in space [2]. About 2,700 Fengyun-1C fragments were being tracked by the U.S. Space Surveillance Network by March 2008. The area-to-mass ratio distribution of the Fengyun-1C fragments shows that there are more fragments, and more lightweight materials than the NASA prediction of the fragments for an average breakup of a similar-sized space vehicle. Fragments contributing to this difference are from plastics, solar panel, and Multi-Layer Insulation (MLI) pieces. The targets used during the development of the NASA standard breakup model did not have these modern light-weight materials.

As new satellite materials continue to be developed, for example Carbon Fiber Reinforced Plastics (CFRP), there is a need for impact tests based on modern materials to better characterize the outcome of future on-orbit fragmentations. The results will be utilized to improve our understanding of high area-to-mass ratio objects, and to improve breakup models for better modeling of the orbital debris environment.

Kyushu University and NASA Orbital Debris Program Office collaborated to conduct micro-satellite impact tests since 2005 [3], [4]. In 2005, we conducted the tests to investigate the outcome of hypervelocity impacts and low-velocity impacts. After these tests, in 2007, we performed three more tests to investigate the effects of impact direction. Finally, in 2008, we conducted the two impact tests described here. The target satellites were almost the same as in the 2007 experiments and the difference is the two materials added in the 2008 tests, which is MLI and solar panel.

The objectives of these experiments are (1) to investigate the fragments from MLI and solar cells, and (2) to compare the results from these two impact tests with the predictions of NASA's standard breakup model.

2. NASA STANDARD BREAKUP MODEL

The NASA standard breakup model describes the outcome of satellite fragmentation based on hypervelocity impact tests. The model includes the size distribution, area-to-mass ratio (A/m) distribution, and size-to-area conversion.

This on-orbit breakup model is used as a source for debris environment models. The update provides a model that is consistent with the latest data. The data sources used for the update were laboratory data, primarily from the Satellite Orbit Debris Characterization Impact Test (SOCIT) and the Space

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Surveillance Network (SSN) catalogs for on-orbit fragments.

The updated NASA standard breakup model is quite different from other fragmentation models. Previously, mass and diameter were used interchangeably as the independent variable. However, with the incorporation of *A/m* distributions, this interchangeability is lost, and therefore the characteristic length was chosen as the independent variable. The following subsections will describe the collision model adopted in the NASA standard breakup model 1998 revision [5].

The creation of the NASA standard breakup model depended strongly on data collected since the early 1980's, including:

1) The Solwind (P78-1) and the USA 19(Delta-180) deliberate hypervelocity collisions in low-Earth orbit in 1985 and 1986, respectively.
2) The ground-based Satellite Orbit Debris Characterization Impact Test (SOCIT) series in 1991 and 1992. The test series consisted of one pre-test shot and four test shots summarized in Table 2.1.
3) The Ariane upper stage sub-scale explosion tests performed by the European Space Agency
4) An extensive compilation of historical orbital data (i.e., two-line element sets) for explosion and collision debris used to determine ejection velocity and area-to-mass ratio distributions.

For the reader to find the original equations, it should be noted that the details of the NASA standard breakup model can be found in [6].

3. IMPACT TESTS

The two satellite impact experiments were conducted using the two-stage light gas gun at the Kyushu Institute of Technology in Kitakyushu, Japan. The micro-satellite targets for the impact experiments are identical, and the details are as follows.

Structure

The target satellites are 20 cm by 20 cm by 20 cm in size and approximately 1,500 g in mass (including MLI). The main structure of each micro-satellite is composed of five layers (top and bottom layers and three inner layers parallel to the top and bottom layers.) and four side panels. They are assembled with angle bars made of aluminum alloy and metal spacers. The external layers and side panels are made of CFRP. The thickness of top and bottom CFRP panels is 2 mm and that of the side panels are 1 mm. The three internal layers are made of Glass Fiber Reinforced Plastics (GFRP) of 1 mm thickness.

Components

The interior of each micro-satellite was equipped with fully functional electric devices, such as a wireless radio, nickel hydride batteries, and a communication circuit, an electric power supply, and command and data handling circuits.

MLI and Solar Panel

The four side panels and the bottom layer are covered with MLI sheets and the remaining side is equipped with a solar panel. The MLI sheets have six layers (see Fig. 2) and consist of two sections, A and B, as shown in Fig. 3(right). The section A was attached to the bottom layer while the section B was wrapped around the four side panels. They were fixed to the satellite surfaces with Velcro. The top layer was equipped with a solar panel. The solar panel consists of six solar cells and an aluminum honeycomb sandwich panel with CFRP face sheet. Each solar cell is 56×42 mm in size.

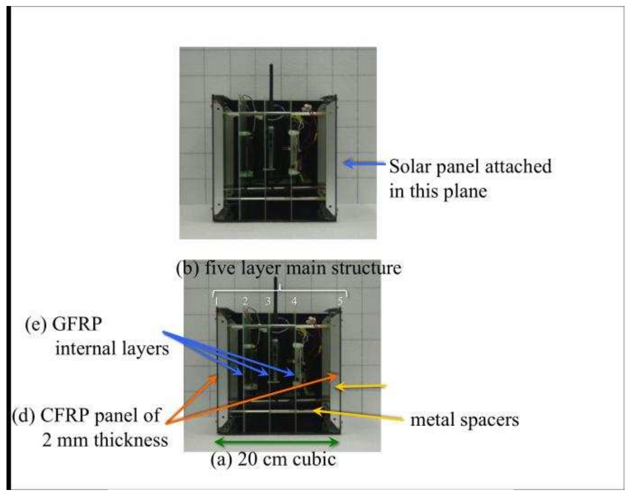

Figure 1. Satellite Structure

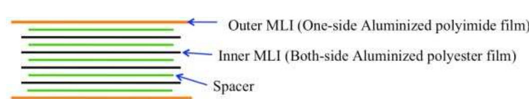

Figure 2. MLI Components

Figure 3. Target Micro Satellites and MIL; (left)Target Micro Satellite Not Covered with MLI, (center) MLI, (right) Target Micro-Satellite Covered with MLI.

Projectile

Aluminum alloy solid spheres, each with a diameter of 30 mm and a mass of approximately 40 grams, are prepared as projectiles.

Test Conditions

We prepared two satellite impact tests as shown in Fig. 4 to investigate the differences in fragments depending on the impact plane. Table 1 summarizes the impact parameters.

1) Shot F;
   The solar panel faces the incoming projectile.
2) Shot R;
   The solar panel was attached to the opposite side.

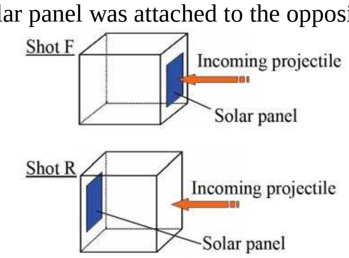

Figure 4. Test Conditions

Table 1. Impact Parameters

Shot	M_t [g]	M_p [g]	V_{imp} [km/s]	E_{imp}/M_t [J/g]	N_{frag}
F	1,515	39.2	1.74	40.7	1,800
R	1,525	39.3	1.78	39.3	1,000
2007	1,300	39.2	1.66	41.5	1,300

M_t = Target Mass, M_p = Projectile Mass
V_{imp} = Impact Velocity
E_{imp} = Impact Energy (= $M_p \times V_{imp}^2 / 2$)
N_{frag}= Number of collected fragments

4. TEST RESULTS

4.1 Fragmentation

The impact fragmentation was viewed from two directions: edge-on and diagonally backward. Figure 5 shows the impact fragmentation viewed edge-on.
Some differences in the impact fragmentation could be caused by the impact direction with respect to the solar panel.

1) Shot F generated a flame but Shot R did not.
2) The debris cloud in Shot F is larger than the one in Shot R.
3) The fragmentation of MLI wrapped around the side panels was different between Shot F and Shot R:
   - Shot F; side MLI fragmented as coming unstuck.
   - Shot R; side MLI was torn into three large fragments.

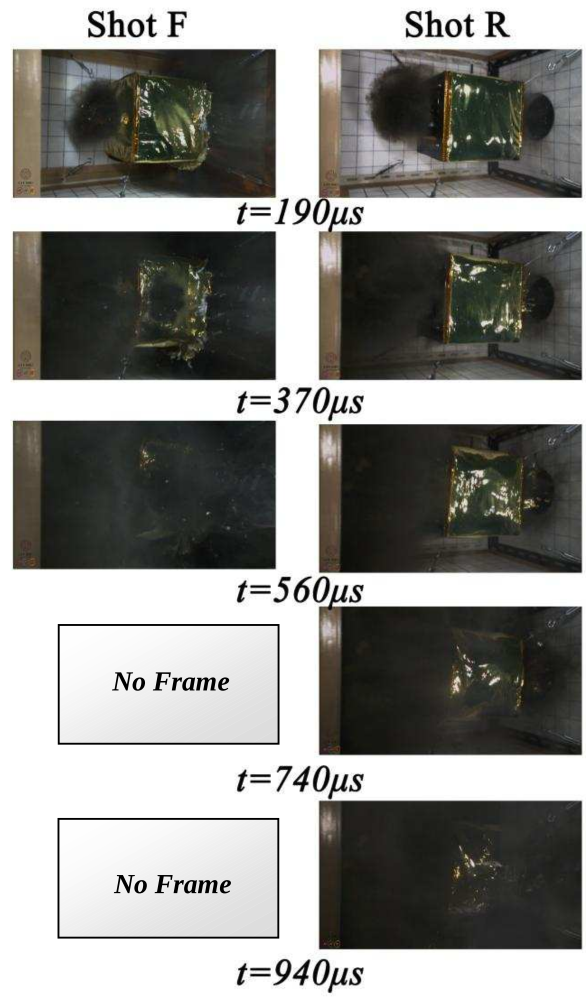

Figure 5. Impact Fragmentation

4.2 Overview of fragments

Figs. 6 and 7 show fragments and MLI pieces collected from the tests. There are noticeable differences between the two sets.

1) Shot F generated much more fragments (1,800) pieces than Shot R did (1,000). Shot R has some larger fragments than Shot F such as CFRP panels, GFRP panels and MLI.
2) Regarding the MLI pieces, a significant difference in size and number can be observed from Fig. 7. The largest MLI piece in Shot F is almost the same in size as the CFRP layers or side panels, whereas that in Shot R is about half of MLI wrapped around the four side panels.
3) The number of needle-like fragments (One example is shown in Fig. 8), broken up from CFRP, is also different between the two tests. This depends on

whether the CFRP panels split or not. Fragments from the impact plane and the back plane of impact are shown in Fig. 9.

4) The fractions of CFRP fragments are completely different between the two tests as shown in Figs. 10 (a) and (b). Figs. 11 (a) and (b) show the distribution of fragments when the CFRP fragments are excluded. The difference between the two tests in Figs. 11 is not so dramatic as in Figs. 10. The most notable differences are the solar cells and MLI. The difference depends on the direction that the projectile hit.

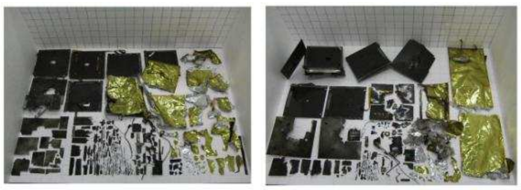

Figure 6. Overview of All Fragments; (left) Shot F, (right) Shot R

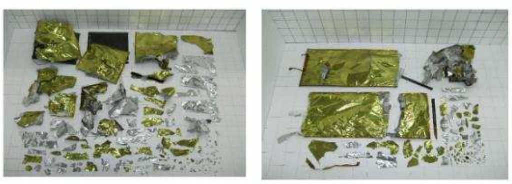

Figure 7. All MLI Fragment; (left) Shot F, (right) Shot R

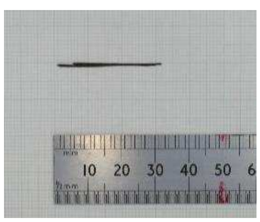

Figure 8. An Example of the Needle-Like Fragments

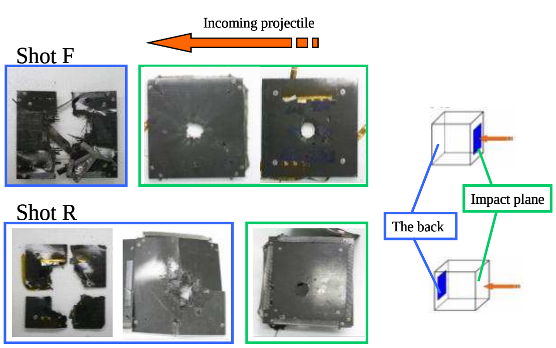

Figure 9. Impact Plane and The Rear Plane

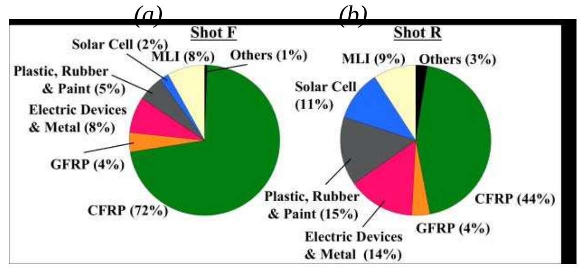

Figure 10. Material Distribution; (a)Shot F,(b)Shot R

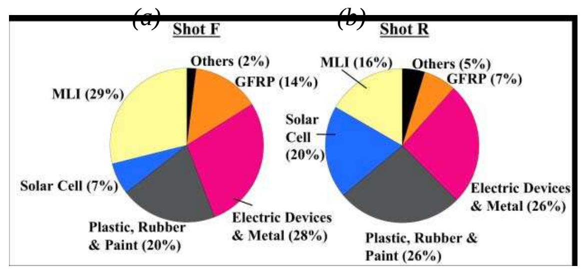

Figure 11. Material Distribution without CFRP Distribution; (a)Shot F,(b)Shot R

5. DISCUSSIONS

5.1 Size Distribution

Fig. 11 shows the cumulative distribution of the characteristic lengths. The vertical axis shows the cumulative number of fragments of the same size or larger than the number on the horizontal axis, i.e. the characteristic length. There is a measurement limit to the range above 10^{-3} m in characteristic length.

The test results and NASA predictions seem to have a similar trend. The NASA predictions underestimate the fragments in Shot F. On the other hand, in Shot R, it overestimates at the range above 2×10^{-2}m but underestimates at the range below 2×10^{-2}m. The main reason for the difference between Shot F and Shot R comes from the number of CFRP fragments. The size range that the NASA prediction underestimates in Shot R is containing many needle-like CFRP fragments (see Fig.8).

For readers' general interest, Fig. 13 shows the size distribution of FY-1C fragments. Please note that the scale of the axis is different from the one used in Fig. 12. This is because the size of the FY-1C satellite is completely different from the size of our target satellites. The comparison between the FY-1C fragments and those of our target satellite shows the same wavy trend in contrast to the NASA prediction.

5.2 Mass Distribution

Fig. 14 shows the mass distribution. In both tests, the NASA model overestimates the masses of the fragments. This is because of the fact that modern materials have changed to be lighter. The target used in the development of the NASA standard breakup model did not have such modern light-weighted materials. Shot F and Shot R show the same inclination

5.3 Area to Mass Distribution

The largest disagreement between the NASA model and our own test results is the *A/m* ratio distribution. The materials used for the target satellites have a direct influence on the *A/m* ratio distribution. For example, CFRP, one of the high *A/m* ratio materials, has been adopted for the satellite structure instead of metal since the 1990's. The significant two on-orbit experiments used for NASA's standard breakup model did not include CFRP structures. As shown in Fig. 15, the NASA prediction is a normal distribution whereas the test results seem to have two peaks in the 2007 test (see also Fig. 19) and three peaks in Shot F and Shot R(see also Figs.17 and 18).

In the 2008 tests, the *A/m* ratio distribution seems to be composed of three major groups. In the order of *A/m* from higher to lower, these groups are;

1) MLI
2) CFRP
3) The remaining fragments (GFRP, Electric device, Metal, Plastic, and Solar cell).

Furthermore, the MLI fragments seem to have been classified further into two more groups. The distribution of the outer MLI sheet can be classified into the CFRP fragments whereas the inner MLI sheet forms the new third group.

The FY-1C's *A/m* ratio distribution has the same tendency as our test results in terms of the three peaks and the abundance of the high *A/m* pieces. Please note in the locations of the peaks in Figs 15 and 16. This is caused by the different size of the FY-1C satellite relative to out target satellites. FY-1C launched in 1999 and it is expected to have a structure of CFRP. Therefore, the second peak of the *A/m* distribution is viewed as CFRP.

To predict the *A/m* ratio properly, it seems to be useful to consider the three groups. We are wondering if it would be possible to make a superposition model using the three groups as previously mentioned, which is MLI, CFRP, and others. This is likely to become an issue to be addressed in the future.

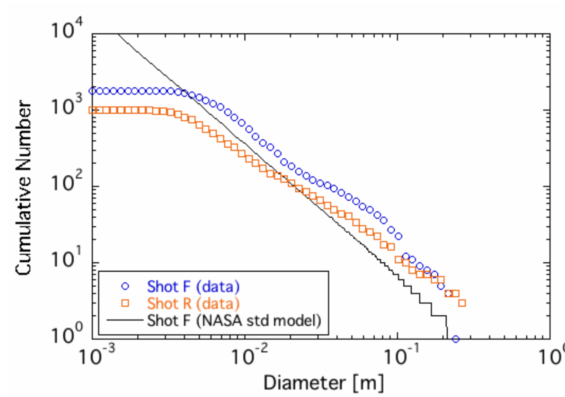

Figure 12. Size Distribution Comparison to NASA Model

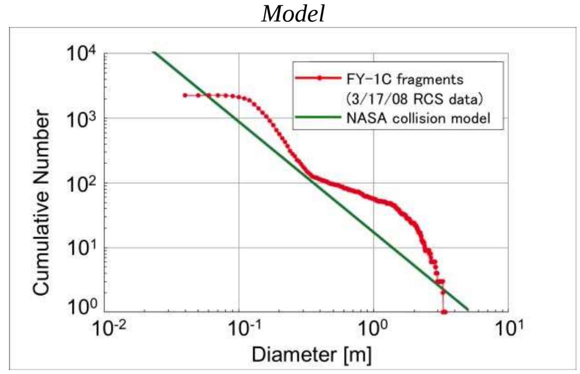

Figure 13. Size Distribution of FY-1C Fragments[2]

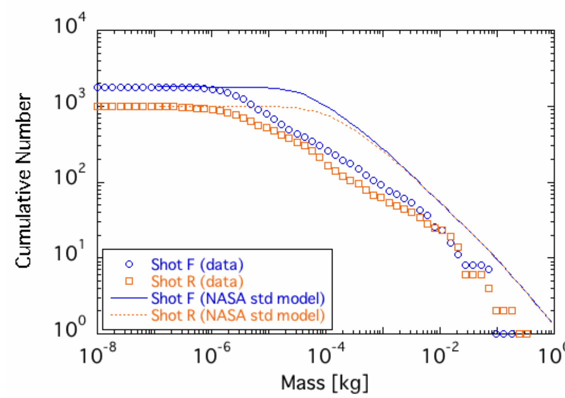

Figure 14. Mass Distribution

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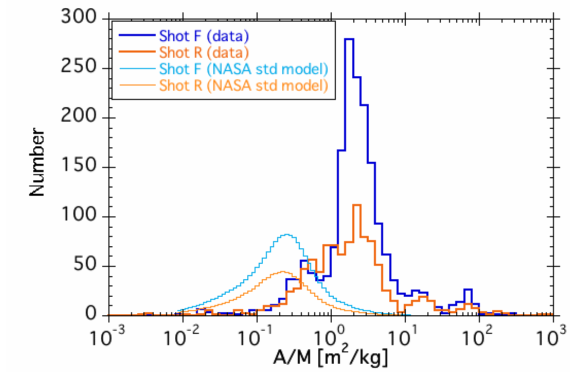

Figure 15. Area-to-Mass Distribution Comparison to NASA Model

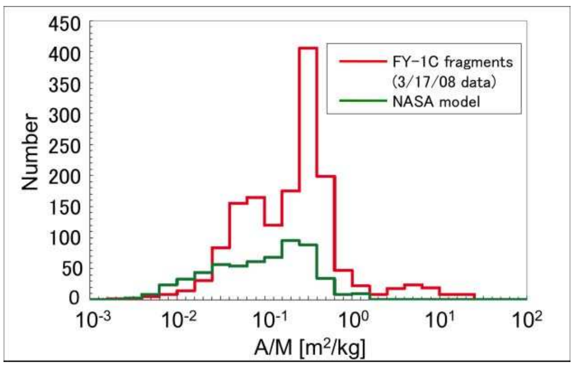

Figure 16. Area-to-Mass Ratio of FY-1C Fragments[2]

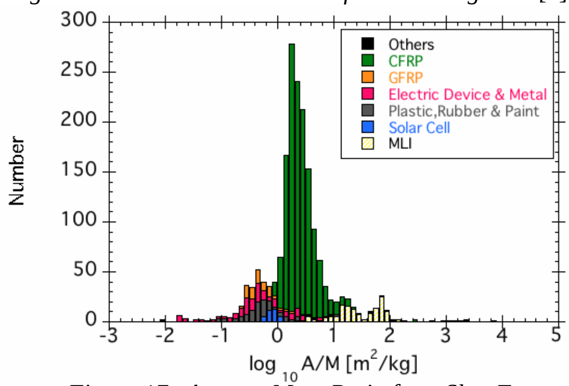

Figure 17. Area-to-Mass Ratio from Shot F

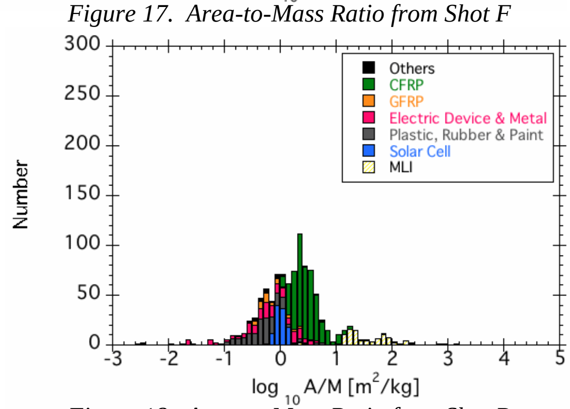

Figure 18. Area-to-Mass Ratio from Shot R

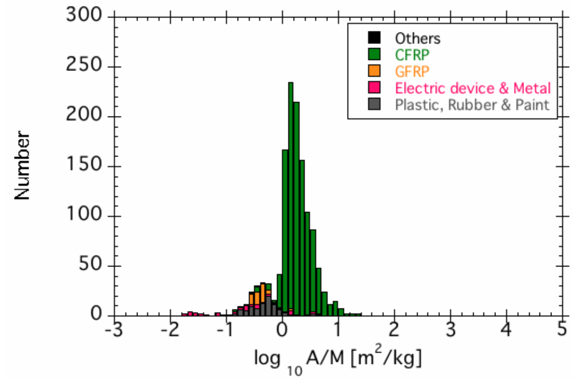

Figure 19. Area-to-Mass Ratio from one of the 2007 tests

6. CONCLUSION

This paper analyzed the fragments properties from the two tests and compares the results with the NASA standard breakup model. We can draw the following conclusions:

1) In terms of the size distribution, the NASA standard breakup model and test results seem to have a similar trend. Almost all the relatively large fragments were measured but there are still some small fragments close to the measurement limit. The size distribution has a direct influence on the number of collected fragments. Thus we must measure more fragments.
2) In the mass distribution, the NASA prediction overestimates the masses of the fragments. It depends on the materials used for satellites, which have become lighter over time, e.g. CFRP and GFRP.
3) The mass distribution and the *A/m* ratio distribution are greatly influenced by the materials adopted. In these tests, we can find three peaks in the *A/m* distribution, i.e. the MLI group, the CFRP group and the others. Therefore, consideration of materials is required for modeling those distributions adequately.

As the results from these experiments, consideration of satellite materials is required for the modeling. It is very hard to generalize satellite components. It may be useful to classify by the three groups, i.e. the MLI group, the CFRP group, and the remainder group.

Furthermore, the division between catastrophic and non-catastrophic collisions is the relative kinetic energy. However, the energy transfer during impact is unclear and the energy actually used in the fragmentation is unknown. Thus, if possible, the measurement of the projectile velocity after the penetration of the target satellite would be useful to evaluate the impact energy.

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