

## OVERVIEW OF THE MPAC EXPERIMENT - DEVELOPMENT OF DUST COLLECTORS, HYPERVELOCITY IMPACT EXPERIMENTS, AND POST FLIGHT ANALYSIS -

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The Micro-Particles Capturer (MPAC) is a passive experiment designed to evaluate the micrometeoroid and space debris environment, and to capture particle residues for later chemical analysis. Three MPAC units were aboard the Russian SM (Service Module) of the ISS (International Space Station), performs experiments regarding capturing dust particles in orbit. Silica aerogels and polyimide foams are used as the dust (or the dust's fragments) capturing materials, and metal plates are used as measuring materials of dust fluxes. The MPAC unit is complete passive equipment and does need no electrical power or communication. The exposure duration of each unit is about 1, 2 and 4 years respectively. After the exposure duration, MPAC units were brought back to the earth and retrieved. One more unit is installed on the front surface of "KIBO" (JEM : Japanese Experiment Module). In this paper we describe on the overview of MPAC experiment, which includes (1) Development of the MPAC unit, (2) Hypervelocity impact experiments, and (3) Post flight analysis (PFA).

**Keywords:** MPAC, ISS Service Module, JEM, Space Debris, Meteoroid, Dust, Aerogel, ESEM, SOCCOR, Comet, Asteroid, Ejecta, Micro Particle, Space Environment

### 1. Introduction

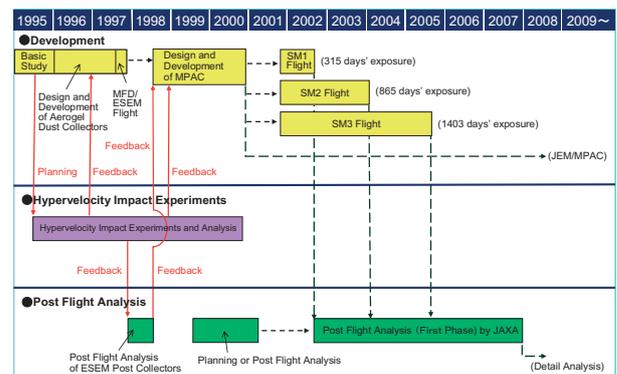
The Micro Particle Capturer (MPAC) is a passive experiment designed to evaluate the micrometeoroid and space debris environment and to capture particle residues for getting material information by chemical analysis. The MPAC experimental equipment is consisting of three identical units (numbered SM1 to SM3) deployed on the exterior of the Russian Service Module (SM) of the International Space Station (ISS). MPAC is mounted on a frame about 1 m long, which it shares with the Space Environment Exposure Device (SEED), a materials exposure experiment. MPAC experiment is not only useful for evaluation of the dust environment in the orbit of ISS, but also useful in estimating the effects of dust collisions on the ISS, and getting material information of dust particles to identify dust origin.

MPAC experiments on SM (hereafter, SM/MPAC) are the first systematic debris capturing experiments in the world. Since three units are complete same structures, it is able to purely evaluate space environment effects (ex. Impact flux, varieties of chemical data for impact residues) only by difference of exposure duration. And since aerogels are used as dust capturing material, material information of the captured dust particle, and impact parameters (incident direction, particle diameter, and impact velocity) are estimated. As the results, SM/MPAC(&SEED) mission is important not only as a precursor mission of ISS's exposed experiments, but also as a great opportunity of research of dust origin through the material information of captured dust particles.

Each MPAC equipment contains aerogels, polyimide foams with polyimide films and an aluminum witness plate. The most important material is Silica-aerogel [hereafter aerogel]. It is used for intact capturing of dust particles and also used for estimations of impact parameters (incident direction, particle diameter, and impact velocity) based on the impact track morphology.

### 2. Overview of the MPAC experiment

Fig.1 shows the project scenario (mission outline) of SM/MPAC. The project consists of major three tasks; 1) Development of dust collectors, 2) Hypervelocity impact experiments (calibrations of dust collectors), 3) Post flight analysis (PFA). In following sections, details of the tasks are described.



**Fig.1 Project Scenario (Mission Outline) of SM/MPAC**

## 2.1 Development of Dust Collectors for the SM/MPAC

The mission plan of “SOCCER” (Comet Coma Sample Return Mission) was propped in 1988. Hypervelocity impact experiments and simulations on many kinds of low density materials were performed for basic study for the SOCCER [1]. But the mission was not accepted, because no comets which have encounter velocity less than 6 km/sec were found in that time. In addition, the mission plan of the SOCCER was succeeded by “STARDUST”.

Based on the SOCCER heritage, the developments for aerogel dust collectors were started in 1995 for focus on measurement of micro debris. Characteristics of the aerogel are followings. 1) Since the aerogel is very low density ( $\sim 0.03 \text{ g/cm}^3$ ) material, it is effective for intact capturing of dust particles. 2) The aerogel is transparent and it is easy to locate dust captured in the aerogel. 3) The aerogel is consists mainly pure silicate ( $\text{SiO}_2$ ) and it is robust material against space environment. In 1997, the aerogel dust collectors were aboard the space shuttle (Fig.2). Details of the flight experiment are reported by Kitazawa *et al.*, [2], and NASDA and NASA [3].

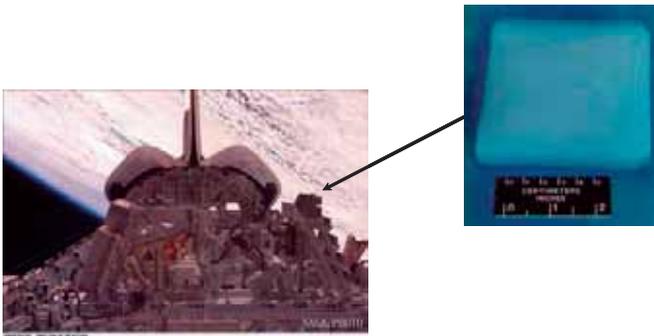


Fig.2 Aerogel Dust Collectors on the Space Shuttle (STS-85), 1997 (Kitazawa *et al.*,[2]).

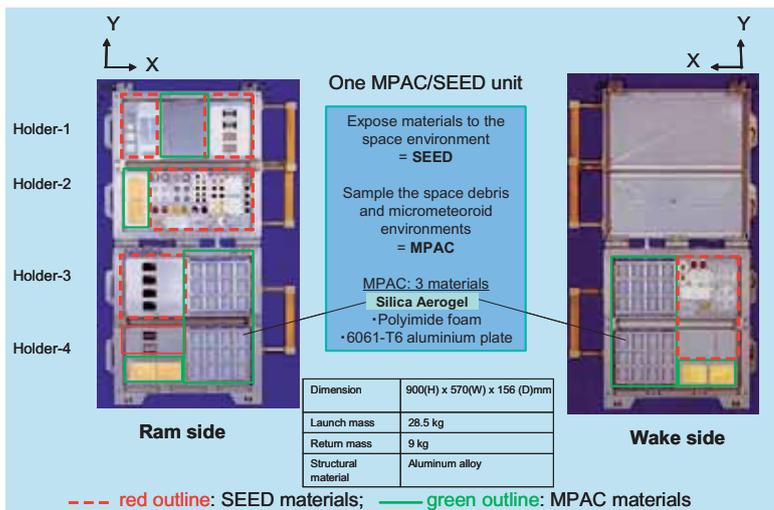


Fig.3 Locations of MPAC Equipments

For the SM/MPAC, another low density material is also used. The material is the polyimide foam with polyimide film. Objectives of the material are 1) Estimation of impact flux, and 2) Capturing dust particles fragments. Bulk density of the polyimide foam is  $0.011 \text{ g/cm}^3$  and the density is lower than the

aerogel. But the pore size of the foam is several ten micrometers and is very larger than the aerogel pore size which is a few to several nanometers. Although the large pore size is not suitable intact capturing of dust particles, but the low density portion is enough to capture fragments of dust particles. And the cost of the foam is very lower than that of aerogel and the handling of the foam is very easy. In addition, the polyimide film (thickness:  $12.5 \mu\text{m}$ ), which is covered on the exposed surface of the polyimide foam, is sensitive to dust impact and it is useful for the estimation of the impact flux of dust particles. The polished metal plates (6061-T6 Aluminum plate) are used for detail estimation of impact flux, estimation of impact energy, and analysis of residual material (if possible). AU (gold) plates will be used for JEM (Japanese Experiment Module “KIBO”)/MPAC. Fig.3 and Table 1 show dimensions and locations of SM/MPAC equipments.

Table 1 Dimensions of MPAC Equipments

Material	Ram side		Wake side	
	Tiles	Exposed Area of One Tile/Plate	Tiles	Exposed Area of One Tile/Plate
Aerogel	24	$37 \times 37 \text{ mm}$ (thickness 15 mm)	24	$37 \times 37 \text{ mm}$ (thickness 15 mm)
Polyimide Foam	4	two tiles: $50 \times 78.5 \text{ mm}^*$ (thickness 30 mm) two tiles: $50 \times 63 \text{ mm}$ (thickness 7 mm)	2	two tiles: $50 \times 78.5 \text{ mm}^*$
6061-T6 Aluminium Plate	1	$13.6 \times 15.25 \text{ mm}$ (thickness 2 mm)	-	-

\*the same tiles have both ram- and wake-exposed surfaces.

## 2.2 Hypervelocity Impact Experiments

Detailed understanding of hypervelocity impact-induced features on MPAC dust collectors is help to get information of characterization of the dust particles environment (ex. mass, velocity, material of dust particles). We performed hypervelocity impact experiments on MPAC equipment materials, mainly aerogels and metal plates. In following sections, we mention the experiments

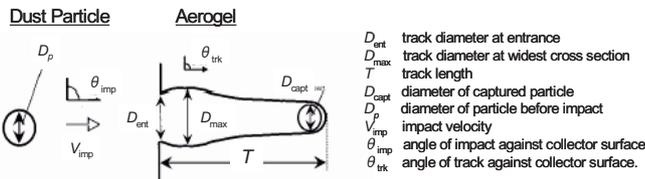
### 2.2.1 Hypervelocity Impact Experiments on Aerogel

Laboratory hypervelocity impact experiments were conducted to verify the performance of aerogel dust collectors to derive the relationships of various parameters characterizing the projectile with morphology of tracks left by the penetrating projectile in the aerogel pad. Aerogel collectors were impacted at velocities ranging from 1 to 14 km/s with projectiles of aluminum oxide, olivine, or sodalime glass, with diameters ranging from 10 to  $400 \mu\text{m}$ . Table 2 shows the summary of the experimental condition, and Fig.4 shows measurement parameters. Data from laboratory experiments used in the MPAC study comprised 149 hypervelocity impact data points, among which 141 were from the plasma-gun of the Hypervelocity Impact Facilities (HIF) of the Space Power Institute, Auburn University, 4 from the two-stage light-gas gun of the Institute of Space and Astronautical Science (ISAS/JAXA), JAPAN, and the remaining 4 from the electro-thermal gun of IHI Corporation., JAPAN. The ranges of impact velocity covered by the three data sets were 3 - 14 km/s with the plasma-gun, 1 - 5 km/s with the light-gas gun, and 1 - 2 km/s with the electro-thermal gun. As the results of the hypervelocity

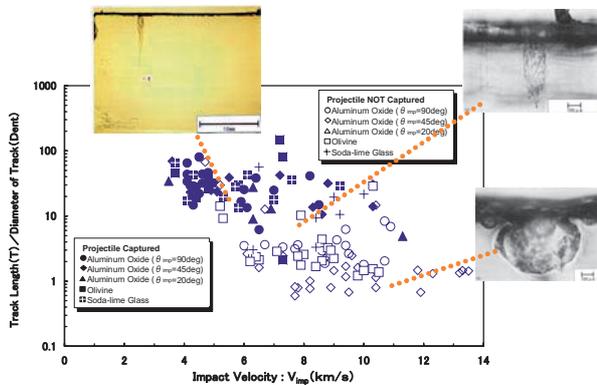
impact experiments, shapes and dimensions of the penetration tracks left in the aerogel collector were correlated with the impact parameters, and the results permitted derivation of a series of equations relating the track dimensions incoming projectile size, impact energy, and other projectile parameters. In addition, a simplified model, similar to meteor-entry phenomena, was used to predict the trends in experimental penetration track lengths and the diameters of captured projectiles. Details of experiments are described in Kitazawa *et al.*[4]. In here, we introduce typical experimental results, which bring useful information for the design of dust collectors and for the PFA.

**Table 2 Summary of the Experimental Condition**

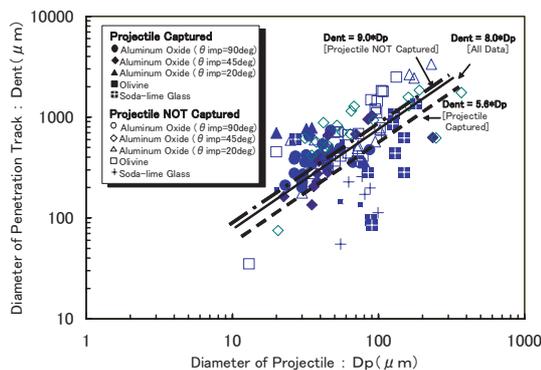
Category	Item	Value	Unit
Environment Projectile	vacuum level	$10^{-5}$ or $10^{-1}$	torr
	temperature	room temperature	
	diameter	10-400	$\mu\text{m}$
Impact condition	material	$\text{Al}_2\text{O}_3$ , olivine, glass	
	velocity	1-14	km/s
	angle	90, 45, 20	degree



**Fig.4 Measurement Parameters of the Hypervelocity Experiments on Aerogel Dust Collectors (Kitazawa *et al.*,[4])**



**Fig.5 Relation of aspect ratio of the tracks ( $T/D_{ent}$ ) with impact velocity (Kitazawa *et al.*,[4])**



**Fig.6 Relation between track diameter at the aerogel surface,  $D_{ent}$ , and projectile diameter,  $D_p$ . (Kitazawa *et al.*,[4])**

Fig.5 shows relation of aspect ratio of the tracks ( $T/D_{ent}$ ) with impact velocity. At impact velocities below 6 km/s the projectiles were captured without fragmentation by the aerogel collector and, in many instances, without complete ablation even at 12 km/s. Fig.6 Relation between track diameter at the aerogel surface,  $D_{ent}$ , and projectile diameter,  $D_p$ .

The main results obtained are summarized as follows:

1) The silica-aerogel collector (density:  $0.03 \text{ g/cm}^3$ ) is feasible for the intact capturing of dust particles. It can capture projectiles without appreciable damage at impact velocities less than 6 km/s, and even has the capability to capture some part of projectiles at velocities as great as 12 km/s.

Projectiles can be captured under the following condition,

$$D_p \leq 1.2 \cdot 10^7 / \delta v_{imp}^2, \quad \dots (1)$$

where  $D_p$  is the projectile diameter,  $\delta$  is the projectile density and  $v_{imp}$  is the impact velocity of the projectile.

2) Dimensions and features of penetration tracks caused by projectiles impacts are correlated with projectile size and impact velocity. The aspect ratio ( $T/D_{ent}$ ) and track features correspond to the impact velocity of the projectile, where  $T$  is the track length, and  $D_{ent}$  is the track diameter. At velocities lower than about 5 km/s,  $T/D_{ent}$  is greater than 10, and the tracks are "carrot-shaped". The characteristics of the track change, depending on the impact velocity range. At impact velocities less than about 3-4 km/s, many branches around the track and the bottom of the track are observed, and are similar in shape to the appearance of aerogel pricked by a needle. At impact velocities greater than 3-4 km/s, there are few main branches around the "trunk" of the track between the surface of the aerogel and the bottom of the track, but there are small branches or cracks surrounding the bottom of the track and just before the bottom, and the shape of the end of the track often fits the captured projectile shape. Above about 5 km/s, the aspect ratio  $T/D_{ent}$  decrease with increasing velocity. Particularly at 12 - 13 km/s these quantities assume very small values, and the spindle-shaped or crater-shaped track becomes dominant. When  $T/D_{ent} \geq 10$ , the track is spindle-shaped and sometimes has several branches at the bottom of the track. In some cases, fragmented projectiles are found in each branch. When  $T/D_{ent} < 10$ , the track is crater-shaped and the tracks have few projectile fragments.

Figure 11 shows  $D_{ent}$ , which increases with projectile size. The relation between  $D_{ent}$  and  $D_p$  obtained by the least squares fit is represented by

$$D_{ent} = 8.0 D_p, \quad \dots (2)$$

and the correlation coefficient ( $r$ ) of the equation is 0.6.

Also indicated are the best-fit lines for data from tracks both with and without residue. Dent for tracks which have projectile residues are the following;

$$D_{ent} = 5.6 D_p, \quad \dots (3)$$

while, Dent of tracks which have no projectile residues are the following;

$$D_{ent} = 9.0D_p \quad \dots (4)$$

The track angle measured from the surface of the aerogel ( $\theta_{trk}$ ) gives information on impact angle ( $\theta_{imp}$ ) for  $T/D_{ent} \leq 10$ .

3) Projectiles captures in aerogel and those before impact are almost the same in chemical content, although captured projectiles have a partial 'cover' of molten aerogel. Even when no captured projectile can be found in aerogel with an optical microscope, chemical components of the projectile are sometimes detected on the inner wall of the penetration track.

Those correlations suggest that it is possible to estimate projectile impact parameters from penetration track observations when post-flight analysis of the dust collectors is performed.

4) A simplified model can predict penetration track lengths and diameters of captured projectiles. This model assumes that a projectile penetrating into an aerogel suffers dynamic drag and ablation from the aerogel in a similar way to that of a meteoroid penetrating the atmosphere.

The velocity  $v(t)$  and mass  $m(t)$  of a projectile are represented by the following equations,

$$m(t) \frac{dv(t)}{dt} = -\Gamma S(t) \rho v(t)^2 - T_s S(t) \quad \dots (5)$$

$$\frac{dm(t)}{dt} = -A \frac{S(t) \rho v(t)^3}{2Q} \quad \dots (6)$$

where  $t$  is time,  $\Gamma$  is drag coefficient,  $S(t)$  is midsectional area of the projectile,  $\rho$  is density of the aerogel,  $T_s$  is tensile strength of the aerogel,  $A$  is heat-transfer coefficient (equal to or less than unity) and  $Q$  is latent heat of vaporization or fusion of the projectile. The second term on the right-hand side of equation (16) represents the effects of tensile strength of the aerogel. The length of the penetration track ( $T$ ) is given by the following equation.

$$T = \int_0^{t_e} v(t) dt \quad \dots (7)$$

where  $t_e$  is time at which  $v(t) = 0$ , and  $t_e$  is estimated by

$$\frac{1}{2} m(te) v(te)^2 / S \leq K_c^2 (1 - \nu^2) / E \quad \dots (8)$$

where  $K_c$  is fracture toughness of the aerogel,  $\nu$  is Poisson's ratio of the aerogel and  $E$  is Young's modulus of the aerogel.

The method is an appropriate analytical treatment of hypervelocity impacts of projectiles on aerogel.

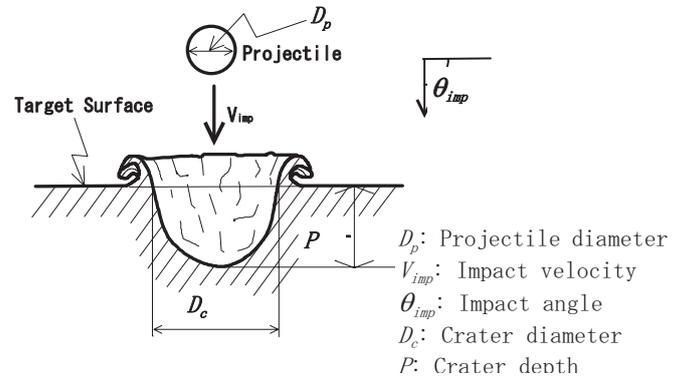
## 2.2.2 Hypervelocity Impact Experiments on Metal Plates

Details of experiments are reported in Kitazawa *et al.*[5]. All hypervelocity impact experiments were carried out using the plasma gun at Auburn University - A square shaped target was used for this study (Al: 10cm x 10 cm x 2mm, Au: 10cm x 10cm x 1mm). Table 3 shows the experimental condition and Fig.7 shows measurement parameters. Crater diameter ( $D_c$ ) and crater depth ( $P$ ) were measured using a laser microscope (Lasertec 1LM21) with accuracy of  $\pm 0.1 \mu\text{m}$ .  $D_c$  and  $P$  measurements refer to the initial target surface as reference datum (Fig. 7). Detail morphological fixtures of craters were observed with a Scanning Electron Microscope (SEM), and identification of projectile specific elements of residual materials in craters was performed using an SEM Energy Dispersive X-ray (SEM-EDX) analyzer (Elinox ERA-8000 with EDAX DX-4).

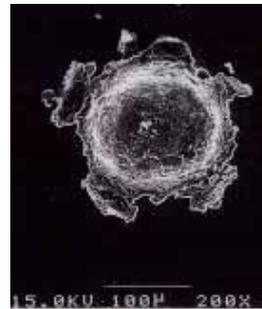
**Table 3 Experimental Condition**

Category of Conditions	Item	Value	Unit
Environment	Vacuum Level	$10^{-3}$	Pa
	Temperature	Room Temp.	
Projectile	Diameter	5 - 135	$\mu\text{m}$
	Material	$\text{Al}_2\text{O}_3$ ,	
Impact Condition	Velocity	3 - 10	km/s
	Angle	90	Deg.

(vertical to the target surface)



**Fig. 7 Measurement parameters of projectiles and craters**



**Fig. 8 SEM image of the crater on the Al plate. Projectile material is  $\text{Al}_2\text{O}_3$ , projectile diameter ( $D_p$ ) is 34 x 48  $\mu\text{m}$ , impact velocity ( $V_{imp}$ ) is 6.3 km/s, crater diameter ( $D_c$ ) is 135  $\mu\text{m}$ , crater depth ( $P$ ) is 48  $\mu\text{m}$ .**

Fig. 8 and Fig. 9 show examples of craters on Al plate and Au plate respectively. Most craters were round in shape and possessed raised rims. The greater part of the impacting projectile can still be found. In Fig.10 and Fig. 11, the projectile material can be found at the wall

and on the bottom of the crater, and it also can be found as ejecta around the crater. Especially, in case of the Au plate, a large amount of the projectile residual can be seen on the bottom of the craters. It seems that the amount of residual in craters on the Au plate is relatively greater than that on the Al plate.



(a) SEM image of the crater on the Au plate.



(b) EDX mapping image. Light dots show Al components of the same area of the SEM image.

**Fig. 9 SEM image and EDX element mapping image of the crater on the Au plate. Projectile material is  $Al_2O_3$ , projectile diameter ( $D_p$ ) is 45  $\mu m$ , impact velocity ( $V_{imp}$ ) is 4.2 km/s, crater diameter ( $D_c$ ) is 66  $\mu m$ , crater depth ( $P$ ) is 25  $\mu m$ .**

Mizutani [6] reviewed the previous semi-empirical equations for various material combination of targets and projectiles, and he suggests a relationship of projectile kinetic energy ( $E$ ) and crater diameter ( $D_c$ ) as follows;

$$D_c \propto E^{1/3} \quad \dots (9)$$

Fig. 10 shows the crater diameter ( $D_c$ ), as a function of the 1/3 power of projectile kinetic energy. The best-fit relationship between  $D_c$  ( $\mu m$ ) and  $E(J)$  are described as the following equations.

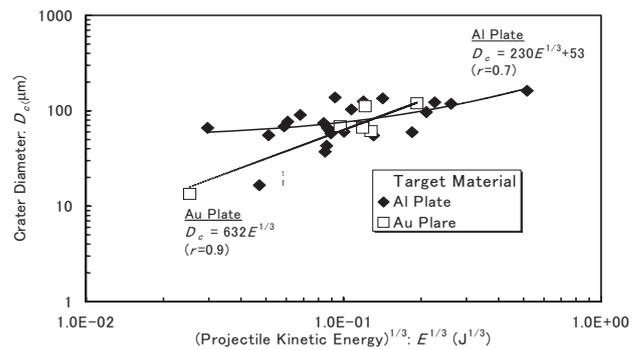
$$Al: D_c = 230E^{1/3} + 53 \quad \dots (10)$$

with a correlation coefficient of 0.7.

$$Au: D_c = 623E^{1/3} \quad \dots (11)$$

with a correlation coefficient of 0.9.

The diameter of a crater ( $D_c$ ) is correlated with projectile kinetic energy ( $E$ ) as shown in Fig. 10. Therefore, it is thought possible to presume the kinetic energy of a projectile from the diameter of a crater.

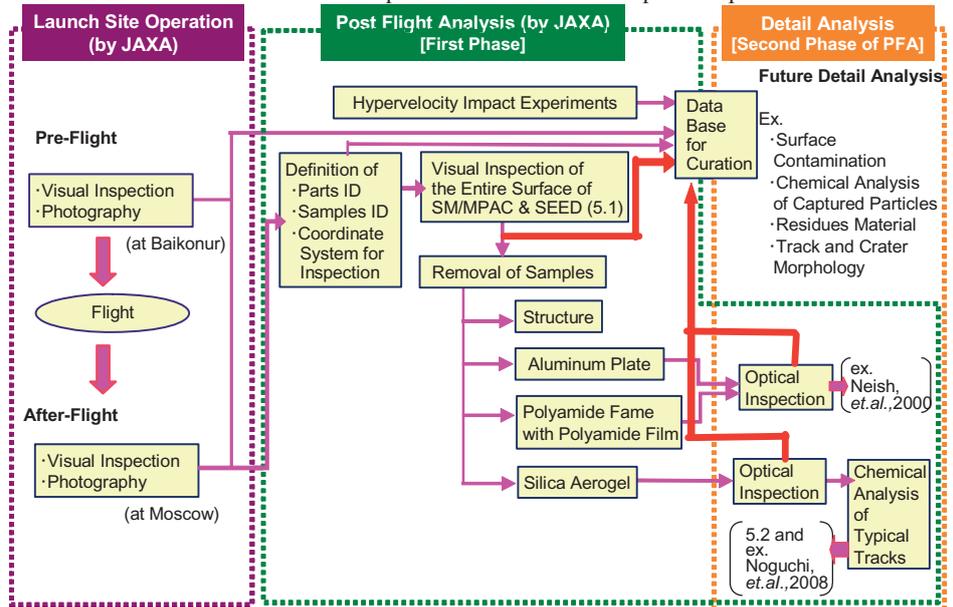


**Fig. 10 Relationship between crater diameter ( $D_c$ ) and the 1/3 power of projectile kinetic energy.**

### 2.3 Post Flight Analysis (PFA)

The procedure of the pre-flight inspection, the post flight analysis, and detail analysis of SM/MPAC(&SEED) is described in Fig.11. Before the flight, the preflight inspection was performed on whole SM/MPAC&SEED structures and on each samples at the Baikonur Cosmodrome, and the inspection was consists of the visual inspection and the photographic survey using a camera (PENTAX 67II) with lenses (9 0mm F2.8 and Macro 100 mm F4). After the flight, the same inspection was performed at the S.P.Korolev Rocket and Space Corporation (RSC) “Energia” in Moscow. We did after-flight inspection SM1, SM2, and SM3 individually, just after retrieves of the sample holders. Objectives of those inspections were recording of the surface condition at just before the launch and at the just after the flight. The inspection results were used for quick comparison between the pre-flight and the post flight and are used for the baseline data of surface conditions of each SM/MPAC&SEED. Those data will be included for the data base for the curation.

The PFA is divided in two phases. Main purpose of the first phase is making data base for curation and detail analysis of several typical impact features. The data base includes visual inspection results on the entire surface of SM/MPAC&SEED and MPAC samplers. Details of the inspection procedures



**Fig. 11 Procedure of PFA (Post Flight Analysis)**

described in the section 2.3.1. In addition, inspection data and discussion of dust impacts on the 6061-T6 Al plate and polyimide foams are reviewed in Neish, *et al.*[7] and Neish, *et al.*[8]. In here, we mentioned the visual inspection of the entire surface of SM/MPAC&SEED and the inspection and analysis on aerogels.

**2.3.1 Inspection Procedures**

**(1) Visual inspection of the entire surface of SM/MPAC&SEED**

Visual inspection of the entire surface and creation of basic data sets for curation were carried out according to the following procedures. 1) Each surface of the SM/MPAC&SEED structure (includes MPAC's samples and SEED's environment monitor samples) was scanned with the aid of an 8x optical microscope. 2) When an impact-like feature was detected, the ID of the impacted part and the X and Y coordinates of the impact were recorded with accuracy of 0.1mm. 3) Dimensions of the feature were measured, and photographs and/or sketches were made of the feature with the aid of a 50-175x CCD (Charge-Coupled Device) optical scope ((KEYENCE VH-Z25 (CCD fiber scope lens) and VH-6300 (Image recorder and device controller)). 4) A morphological assessment of the feature was made (impact-induced or not).

**(2) Silica Aerogel Inspection**

After removal of all aerogel tiles from the frame, silica aerogel tiles (exposed area: 37mm x 37mm per tile) were inspected as follows: 1) Each tile was scanned individually with the aid of a 150x CCD optical scope. 2) When an impact feature was located, its X and Y coordinates were recorded and photographs and/or sketches of the feature were made. 3) Morphological parameters of the track were measured, and particle remnants were searched for. When typical tracks were found, aerogels were sliced with a microtome into thin, small pieces of between 1 and 3 mm thickness. After the slicing of aerogels, the following procedures were performed. 4) Optical microscope images and SEM images of selected typical tracks were obtained. 5) EDS, X-ray diffraction and Raman spectroscopic analyses were carried out to determine the chemical composition of residues left in the tracks. [Details of 4) and 5) are described in Noguchi, *et al.*[9].]

**2.3.2 Inspection results**

**(1) Visual inspection of the entire surface of SM/MPAC&SEED**

Visual inspection of SM/MPAC&SEED was conducted on all sample holders. Data sets of impact features were compiled for curation (Fig. 12). Morphological judgment placed the feature in one of three categories. Class I (the first quality level): hypervelocity impact-induced features which meet all of three criteria (<1> the feature has a crater-like rim and/or central peak, <2> the feature has radial cracks and/or ejecta, <3> the feature has a shape similar to those induced by hypervelocity impact experiments.). Class II (the second quality level): probably hypervelocity impact-induced features

which meet one or two of the criteria. Class III: not hypervelocity impact-induced features. The number of impact-induced features was almost directly related to the exposure period (Fig. 13). The impact rate was almost constant, with the sum of Class I and Class II events about 15 impacts per year.

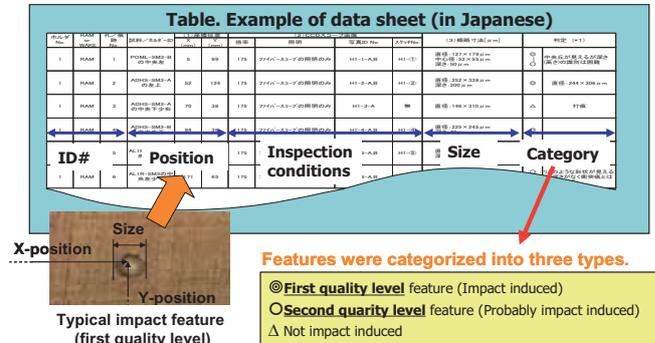
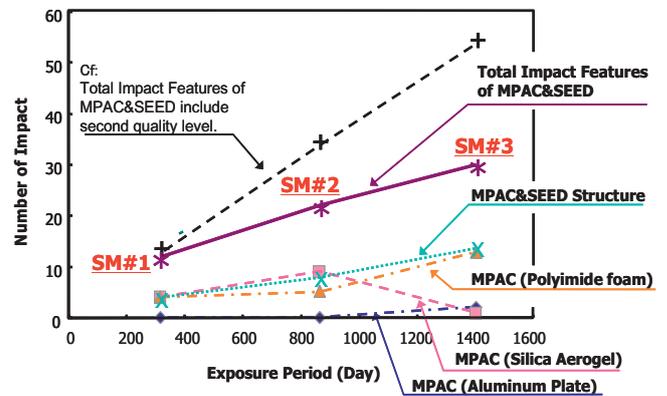


Fig.12 An example of data record format.



**(2) Silica Aerogel Inspection**

**1) Surface alterations of silica aerogel**

Fig. 14 shows surfaces of retrieved aerogels. The aerogel surfaces on the WAKE side are yellowish and have countless fine cracks. SM3/MPAC and SM2/MPAC display more pronounced yellow discoloration and more fine cracks than SM1/MPAC. The appearance of the surface of the aerogel near the cracks is similar to that produced by the deposition of metal vapor with a thickness on the order of one μm. In contrast, the RAM sides became whitened and a maximum of about seventy very minute tracks ( $D_{ent} < 20\mu m$ , and  $T < 300\mu m$ ) per aerogel were detected in SM1/MPAC. Moreover, in SM2 and SM3, about a thousand foreign bodies were found in each aerogel (milk-white ellipses, average diameter about 100 μm) instead of minute tracks. Similar shapes are produced when atomized organic solvent hits the aerogel. EDS detected carbon in addition to the Si and O that are the main ingredients of the aerogel. Details of the surface alterations are discussed by Noguchi, *et al.*[9].

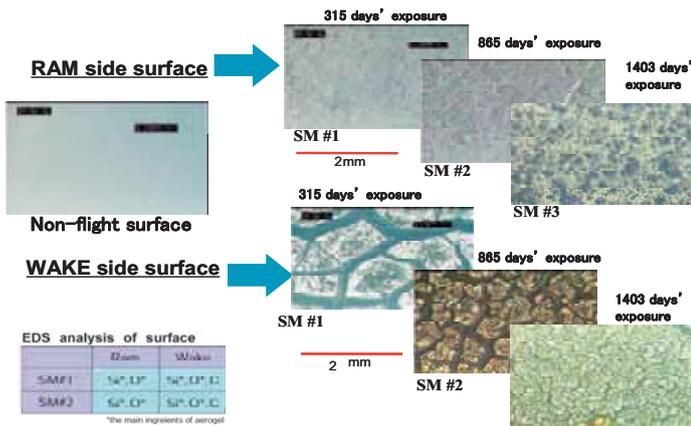


Fig. 14 Surface alterations of exposed aerogel.

2) Typical tracks in silica aerogels

Fig. 15 shows comparisons of two impacts with hypervelocity impact experiment results (Kitazawa, *et al.*, [5]). Regardless of surface alterations of the aerogel, tracks from experimental hypervelocity impacts are quite similar to those seen in flight experiments.

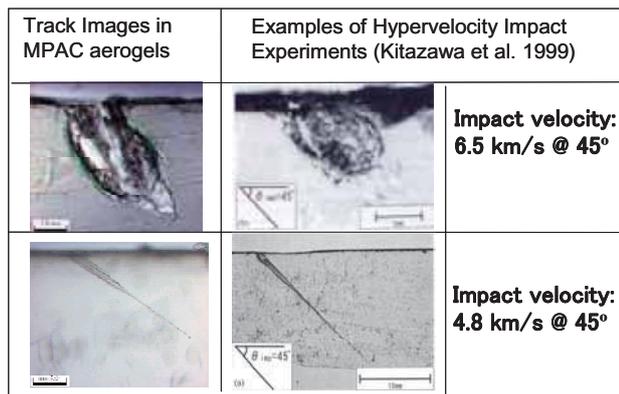


Fig.15 Comparison of tracks in MPAC aerogels with experimental hypervelocity impact tracks.

3) Captured particles

Combined SEM, transmission electron microscope (TEM), micro Raman spectroscopy, and synchrotron radiation X-ray diffraction analyses revealed that captured particles are space debris, secondary debris, and a micrometeoroid, respectively. Details are discussed in Noguchi, *et al.* [9].

4) Estimated impact flux on silica aerogel

We compared calculated impact fluxes of the three environment models with the impact fluxes on aerogels. Fig. 16 shows a comparison of the impact flux estimated from inspection of the aerogel and calculated results from MASTER-2001, MASTER-2005 and ORDEM 2000 (Fukushige *et al.* [10]). Particle diameter  $d$  was estimated using a linear relationship between  $d$  and  $Dent$ , which shown in Fig.6 and equations (2) – (4). By the surface alteration of aerogels, it is difficult to inspect small tracks and it was not able to estimate the fluxes of diameter  $>10 \mu m$  of SM2 aerogels and SM3 aerogels.

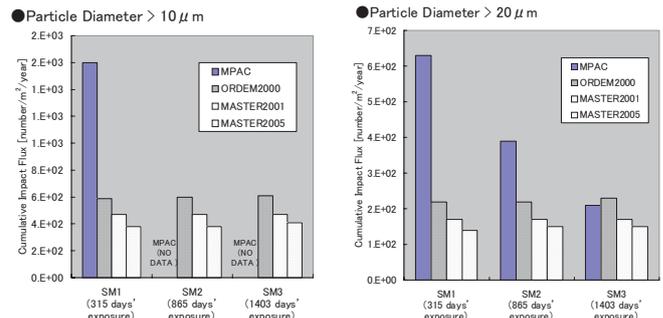


Fig.16 Comparison with impact flux of MPAC aerogels and calculated results of three models (Left: Particle diameter  $>10 \mu m$ , Right Particle diameter  $>20 \mu m$ )

In Fig.16, impact fluxes of aerogels are seemed to be in inversion portion to the exposure period and the fluxes are greater than model results.

3. Discussion

3.1 Entire Surface of MPAC&SEED

A database of impact-like features and part IDs of all MPAC&SEEDs are available for curation. The database also includes detailed inspection results for MPAC samples. The sample curation system and sample distribution plan will be discussed in the next step. In Fig. 4, the number of impact-induced features was almost directly related to exposure period and the impact rate was almost constant. These data show that during the exposure period of MPAC&SEED (October 15, 2001 - August 19, 2005), there was no noteworthy change in the dust flux environment.

3.2 Silica Aerogel Inspection

3.2.1 Surface alterations of silica aerogel

In a previous aerogel experiment in space (Kitazawa, *et al.*, 1998), no noteworthy surface alterations were reported. In contrast, the surface alterations of MPAC’s aerogels are quite remarkable, and seem to be the result of the deposition of carbon-containing particles (whether gas, liquid or solid) over the entire aerogel surface. Problems in the operation of space stations such as MIR and ISS are strongly related to the gas-particle environment that forms around the station, which can contaminate external surfaces. The attitude control thrusters widely used on space stations contribute significantly to the formation of a gas-particle environment [11]. The effects of contaminants emitted from the thrusters of the ISS, Soyuz and Progress are under discussion. Detail analysis results on the surfaces of aerogels are reported by Noguchi, *et al.* [9].

3.2.2 Typical tracks in silica aerogels

Regardless of any surface alterations of the aerogels, the shape of penetration tracks, which are presumed to have been formed by hypervelocity collisions with dust particles, are in good agreement with track shapes observed in hypervelocity impact experiments (Kitazawa, *et al.* [4]). Therefore, it is possible to estimate the impact parameters of the dust particles, such as their diameter, impact velocity, impact direction, etc., from the results of the hypervelocity impact experiment. The

typical carrot-shape tracks captured dust particles and the chemical analysis on the particles were performed by Noguchi, *et al.* [9].

### 3.2.3 Estimated impact flux on silica aerogel

Flux values estimated from inspection of the aerogels shown in Fig.16 are contradictory to the inspection results on the entire surface of MPAC&SEED (See, 3.2.1). Surface alterations of aerogels induce the difficulties of surface inspection of aerogels. As the results, it is thought that it seems seemingly that flux is decreasing by the alterations. It assumes that there is no remarkable change, the inspection result of SM1 should be trusted and the flux value is five to 100 times higher than calculated fluxes by the models. The causes of elevated flux levels may be; 1) model uncertainties, 2) elevated flux values from dust swarms (dust clouds), 3) contaminants emitted from the ISS, Soyuz, Progress or the Shuttle, 4) secondary debris. It is thought that at least the flux of the smallest particles (less than 10  $\mu\text{m}$ ) is affected by contaminants.

## 4. Summary

### 4.1 Development of Dust collectors

Based on the SOCCER heritage, dust collectors were developed for focus on measurement of micro debris. Aerogel is selected for the dust capturing material, and as the auxiliary material, the polyimide foam with polyimide film is selected. The polished metal plates (6061-T6 Aluminum plate) are used for detail estimation of impact flux, estimation of impact energy, and analysis of residual material (if possible). In addition, AU (gold) plates will be used for JEM/MPAC.

### 4.2 Hypervelocity Impact experiments

Laboratory hypervelocity impact experiments were conducted to verify the performance of dust collectors. The shapes and dimensions of the penetration tracks left in the aerogel collector were correlated with the impact parameters, and the results permitted derivation of a series of equations relating the track dimensions to incoming projectile size, impact energy and other projectile parameters. A simplified model, similar to meteor entry-phenomena, was used to predict the trends in experimental penetration track lengths and the diameters of captured projectiles. The diameter of a crater is correlated with projectile kinetic energy. Experimental results helped the design of dust collectors and will give useful information for the PFA.

### 4.3 Post Flight Analysis

Main purpose of the first phase of the PFA is making data base for the curation for sample users and detail analysis of several typical impact features. The data base includes visual inspection results on the entire surface of SM/MPAC&SEED and MPAC samplers. Those data will be included for the data base for the curation. Detail analysis of several typical impact features suggest MPAC samples captured many space materials (meteoroids, space debris, secondary debris and contamination materials). Surface alteration of aerogels, which were caused by contamination probably, causes the difficulty for the surface inspection, and more sophisticated inspection

methods should be developed.

## References

- [1] A. Fujiwara: Comet coma sample return intact captures technology, SOCCER comet coma sample return, Proceedings of ISAS/NASA Joint Working Group Meeting, October 17 and 18, 1988, Institute of Space and Astronautical Science (1988).
- [2] Y. Kitazawa, K. Imagawa, Y. Okada, A. Fujiwara, T. Kadono, and R. Amagata: Hypervelocity impact tests and post-flight Analysis on MFD dust collectors, Proceedings of the 21<sup>st</sup> International Symposium on Space Technology and Science, 1842-1847 (1998).
- [3] NASDA: NASDA ESEM final report, Evaluation of Space Environment and Effects on Materials (ESEM), Archive System, NASA Langley Research Center, NASA Home Page, 1998, <http://setas-www.larc.nasa.gov/esem/AOE.html>, (1998).
- [4] Y. Kitazawa, A. Fujiwara, T. Kadono, K. Imagawa, Y. Okada and K. Uematsu; Hypervelocity impact experiments on aerogel dust-collector, Journal of Geophysical Research, Vol. 104 E9, 22035-22052, (1999).
- [5] Y. Kitazawa, K. Kawachi, K. Fukasawa, Y. Yamaura, T. Miyadera, R. Nakamura, K. Imagawa, C. Kamakura, Y. Nakayama, and Y. Tachi; MPAC; Passive measurement experiment of dust particles on ISS, Proceedings of the 22nd International Symposium on Space Technology and Science, 2077-2082, (2000).
- [6] H. Mizutani: Science of craters (Kure-ta no kagaku), UP Earth Science, Tokyo-daigaku syuppan-kai, Tokyo, 102-120, 1980, text in Japanese.
- [7] M. J. Neish, K. Imagawa, T. Inoue, J. Ishizawa, Y. Kitazawa, Y. Yamaura, A. Murakami and Y. Ochi; Microparticle capture on the international space station using aerogel and polyimide foam: Proceeding of 9th International Symposium on Materials in a Space Environment, Noordwijk, The Netherlands, 16-20 June 2003, ESA SP-540, pp.431-435,(2003).
- [8] M. J. Neish, Y. Kitazawa, T. Noguchi, T. Inoue, K. Imagawa, T. Goka, Y. Ochi; Passive measurement of dust particles on the ISS using MPAC: Experiment summary, particle fluxes and chemical analysis, Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005, ESA SP-587, pp.221-226,(2005)
- [9] T. Noguchi, T. Nakamura, Y. Kitazawa, R. Yamanaka, Y. Kimoto, M. Suzuki: Internal investigation of silica aerogel equipped on SM/MPAC & SEED recovered from the ISS in 2003, 2004, AND 2005., Proceedings of the International Symposium on "SM/MPAC&SEED Experiment.", Tsukuba, Japan, March 10-11, 2008, JAXA-SP (in printing), (2008).
- [10] S. Fukushima, Y. Akahoshi, Y. Kitazawa, T. Goka: Comparison of debris environment models; ORDEM2000, MASTER2001 and MASTER2005, IHI Engineering Review Vol.40, No. 1, 31-41, (2008).
- [11] S. Rebrov and Y. Gerasimov: Investigation of the Contamination Properties of Bipropellant Thrusters, 35th AIAA Thermophysics Conference, 11-14 June 2001, Anaheim, CA, AIAA 2001-2818, (2001).

**Publication list**

- T. Noguchi, T. Nakamura, Y. Kitazawa, R. Yamanaka, Y. Kimoto, M. Suzuki: Internal investigation of silica aerogel equipped on SM/MPAC & SEED recovered from the ISS in 2003, 2004, AND 2005., Proceedings of the International Symposium on "SM/MPAC&SEED Experiment.", March 10-11, 2008, Tsukuba, Japan, JAXA-SP (in printing) (2008)
- Y. Kitazawa, S. Fukushige, M. Uchino, Y. Akahoshi, T. Goka, A. Sakurai, T. Yasaka, K. Funakoshi, T. Hanada, H. Matsumoto, T. Noguchi, R. Yamanaka, Y. Kimoto, and M. Suzuki: Current Problems of Debris Environment Models and Related Studies of JAXA, E European Geosciences Union, General Assembly 2007 Vienna, Austria, 13-18 April 2008, CD-ROM (EGU2008 EGU2008-A-01753) (Abstract) (2008).
- Y. Kitazawa, S. Fukushige, M. Uchino, Y. Akahoshi, T. Goka, A. Sakurai, T. Yasaka, K. Funakoshi, T. Hanada, H. Matsumoto, T. Noguchi, R. Yamanaka, Y. Kimoto, and M. Suzuki: Current Problems of Debris Environment Models and Related Studies of JAXA, Proceedings of the JAXA 3<sup>rd</sup> Space Debris Workshop, Tokyo, Japan, 21-22 January, 2008, JAXA-SP-TBD (in printing) (2008).
- S. Fukushige, Y. Akahoshi, Y. Kitazawa, and T. Goka; Comparison of Debris Environment Models; ORDEM2000, MASTER2001 and MASTER2005 - Status Report of the Candidate of an ISO's Standard Entitled 'Process-based Implementation of Meteoroid and Debris Environment Models' -, the 58th Meeting of the Aeroballistic Range Association, Aeroballistic Range Association, Las Cruces, New Mexico, U.S.A., 17-20 September, 2007, (CD-ROM) (2007).
- Y. Kitazawa, T. Noguchi, M.J. Neish, I. Yamagata, Y. Kimoto, J. Ishizawa, A. Fujiwara, M. Suzuki, Y. Yamaura, and S. Yamane; Passive Measurement of Dust Particles on the ISS (MPAC): Status report of the post flight analysis, European Geosciences Union, General Assembly 2007 Vienna, Austria, 15-20 April 2007, CD-ROM (EGU2007-A-01406) (Abstract) (2007)
- Y. Kitazawa, M. J. Neish, T. Noguchi, I. Yamagata, Y. Kimoto, J. Ishizawa, A. Fujiwara, M. Suzuki, Y. Yamaura, Y. Watanabe, and S. Yamane; Passive measurement of dust particles on the ISS (MPAC): Third report on aerogel dust collectors, the 57th Meeting of the Aeroballistic Range Association, Venice, Italy, 18-22 September, 2006 CD-ROM (2007)
- Y. Kitazawa, M. J. Neish, T. Noguchi, I. Yamagata, Y. Kimoto, J. Ishizawa, M. Suzuki, and A. Fujiwara: Preliminary analysis report on SM/MPAC, Proceedings of 2<sup>nd</sup> Symposium on "SM/MPAC&SEED EXPERIMENT", 21-24, February 21, 2006, Tsukuba, Japan, JAXA-SP-06-021, ISSN1349-113X (2007) (in Japanese)
- Y. Kitazawa, M. J. Neish, T. Noguchi, I. Yamagata, Y. Kimoto, J. Ishizawa, A. Fujiwara, and M. Suzuki: Dust capturing experiment on the international space station (MPAC), Proceedings of the 3<sup>rd</sup> Space Environment Symposium, December 14 - 15, 2006, Tsukuba, Japan (2006) (in Japanese)
- Y. Kitazawa, M. J. Neish, T. Noguchi, I. Yamagata, Y. Kimoto, J. Ishizawa, A. Fujiwara, and M. Suzuki: Dust capturing experiment on the international space station (MPAC), Proceedings of the 22<sup>nd</sup> Space Structure and Material Symposium, December 8 - 9, 2006, Sagami-hara, Japan (2006) (in Japanese)
- Y. Kitazawa, M. J. Neish, T. Inoue, J. Ishizawa, A. Fujiwara, K. Imagawa, Y. Yamaura, S. Yamane, and S. Nakazato; Passive measurement of dust particles on the ISS (MPAC): Second report on aerogel dust collectors, Preprints of the 25th International Symposium on Space Technology and Science, (CD-ROM), Kanazawa, Japan, 30 May - 6 June 2006, (2006)
- T. Noguchi, Y. Kitazawa, M. J. Neish, I. Yamagata, Y. Kimoto, J. Ishizawa, M. Suzuki, A. Fujiwara, Y. Yamaura, and S. Yamane; Passive measurement of dust particles on the ISS (MPAC): Third report on aerogel dust collectors, European Geosciences Union, General Assembly 2006 Vienna, Austria, 02 - 07 April 2006 (Abstract) (2006).
- Y. Kitazawa, M. J. Neish, T. Noguchi, I. Yamagata, Y. Kimoto, J. Ishizawa, A. Fujiwara, and M. Suzuki: The dust capturing Experiment on the international space station (MPAC), Proceedings of the annual meetings of the Japan Institute of Metals (JIM), 161, March 21- 23, 2006, Waseda University, Tokyo, Japan. (2006). (in Japanese)
- Y. Kitazawa, M. J. Neish, T. Noguchi, I. Yamagata, Y. Kimoto, J. Ishizawa, A. Fujiwara, and M. Suzuki: The dust capturing Experiment on the international space station (MPAC), Proceedings of the JAXA 2<sup>nd</sup> Space Debris Workshop, 78-90, December 8 - 9, 2005, Chofu, Tokyo, Japan. (2005). (in Japanese)
- M. J. Neish, Y. Kitazawa, T. Noguchi, T. Inoue, K. Imagawa, T. Goka, and Y. Ochi: Passive measurement of dust particles on the ISS using MPAC: Experiment summary, particle fluxes and chemical analysis, Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005, ESA SP-587 (2005).
- Y. Kitazawa: Space development and space dust, Proceedings of the Rotary International District 2750 (Minato-ku Rotary Club) 2004-2005, 32-34, (2005)
- Y. Kitazawa, T. Noguchi, M. J. Neish, T. Inoue, J. Ishizawa, A. Fujiwara, K. Imagawa, Y. Yamaura, Y. Watanabe, and A. Murakami: First year mission results of passive measurement experiment of dust particles on ISS (MPAC), Preprints of the 24th International Symposium on Space Technology and Science, Miyazaki, Japan, 30 May to 6 June 2004 (CD-ROM), (2004).
- Y. Kitazawa, M. J. Neish, T. Inoue, K. Imagawa, A. Fujiwara: First year mission results of passive measurement experiment of dust particles on ISS (MPAC), the 35th COSPAR Assembly, Paris, France, 17-25 July 2004, (Abstract) (2004).
- M. J. Neish, K. Imagawa, T. Inoue, J. Ishizawa, Y. Kitazawa, Y. Yamaura, A. Murakami and Y. Ochi, Microparticle capture on the International Space Station using aerogel and polyimide foam; Proceeding of the 9th International Symposium on Materials in a Space Environment, Noordwijk, The Netherlands, 16-20 June 2003, ESA SP-540, 431-435 (2003).
- NASDA: MFD /ESEM final report, NASDA-TMR-000011, ISSN1345-7888 (2001). (in Japanese)
- Y. Kitazawa, K. Kawachi, K. Fukasawa, Y. Yamaura, T. Miyadera, R. Nakamura, K. Imagawa, C. Kamakura, Y. Nakayama, and Y. Tachi: MPAC: Passive measurement

- experiment of dust particles on ISS, Proceedings of the twenty-second international symposium on space technology and science, 2077-2082, (2000).
- Y. Kitazawa: Recent studies on dust particles in space – from a point of view of space experiment -, The Japan Society of Microgravity Application (JASMA) Journal, Vol.17, No.2, 104-113 (2000) (text in Japanese, abstract in English)
- Y. Kitazawa: Dust particles in space, NISSAN ARC Monthly, Vol.9, No.9 (2000) (in Japanese)
- Y. Kitazawa, A. Fujiwara, T. Kadono, K. Imagawa, C. Kamakura, Y. Okada and K. Uematsu; Hypervelocity impact experiments on aerogel dust-collector, Proceedings of the fall meeting of the Japanese Society for Planetary Sciences,305 (1999) (in Japanese)
- Y. Kitazawa, K. Kawachi, K. Ogiwara, T. Miyadera, R. Nakamura, K. Imagawa, C. Kamakura, Y. Nakayama, and Y. Tachi: Overview of dust capturing experiment (MPAC) on the international space station (ISS), Proceedings of the fall meeting of the Japanese Society for Planetary Sciences,306 (1999) (in Japanese)
- C. Kamakura, K. Imagawa, Y. Nakayama, Y. Tachi, K. Kawachi, Y. Kitazawa, K. Ogiwara, T. Miyadera and R. Nakamura: Overview of dust capturing experiment and space exposure experiment on the international space station (ISS), Proceedings of the 43<sup>rd</sup> Space Sciences and Technology Conference, October 20 -22, 1999, Kobe, Japan (1999) (in Japanese)
- Y. Kitazawa, A. Fujiwara, T. Kadono, K. Imagawa, Y. Okada and K. Uematsu; Hypervelocity impact experiments on aerogel dust-collector, Journal of Geophysical Research , Vol. 104 E9,22035-22052, (1999).
- Y. Kitazawa, R. Amagata, K. Kawachi, K. Fusegi, K. Imagawa and Y. Okada: Development of dust collector for the JEM exposed module, Proceedings of the 14<sup>th</sup> Space Station Conference, 105-106 (1998) (in Japanese)
- Y. Kitazawa, K. Imagawa, Y.Okada, A. Fujiwara, and T. Kadono: Hypervelocity impact Experiments on Aerogel Dust-Collector, Proceedings of Solar System Science Symposium, 53-56 (1998) (in Japanese)
- Y. Kitazawa, K. Imagawa, Y. Okada, A. Fujiwara, T. Kadono, and R. Amagata: Hypervelocity impact tests and post-flight analysis on MFD dust collectors, Proceedings of the 21st International Symposium on Space Technology and Science, 1842-1847 (1998)
- NASDA: NASDA ESEM Final Report, Evaluation of Space Environment and Effects on Materials (ESEM) Archive System, NASA Langley Research Center ,NASA Home Page,1998, <http://setas-www.larc.nasa.gov/esem/AOE.html>, (1998)
- H. Ohashi, Y. Kitazawa and H. Yano: In-situ measurement and capturing of meteoroid & space debris, of the Japanese Society for Planetary Sciences, Vol.6, No.7, 312-325 (1997) (in Japanese)
- H. Yano, Y. Kitazawa, S. Kibe, and K. Nogami: In-situ measurement and capturing of meteoroid & space debris using JEM exposed module, Proceedings of the 13<sup>th</sup> Space Station Conference, 1997 (in Japanese)
- M.J. Neish, S.P. Deshpande, S. Kibe, H. Yano, Y. Kitazawa, and S. Yamamoto: Micrometeoroid and space debris impacts on the Space Flyer Unit and hypervelocity impact calibration of its materials, Proc. Second European Conf. on Space Debris, ESA-SP-393, 177-182, (1997).
- M.J Neish, H. Yano, S. Kibe, S.P. Deshpande, Y. Kitazawa, and S. Yamamoto: Hypervelocity impact damage to Space Flyer Unit multi-layer insulation, Proceedings of the International Symposium. on Materials in Space Environment, Toulouse, France, (1997)
- M.J. Neish, S. Kibe, H. Yano and Y. Kitazawa: Impact calibration of SFU surfaces, Proceedings of the 17<sup>th</sup> Symposium on Shock Waves in Japan, 233-236, (1997)
- Y. Kitazawa, K. Imagawa, A. Fujiwara, and Y. Okada: Development of the MFD dust collector, Proceedings of the 17<sup>th</sup> Symposium on Shock Waves in Japan, 233-236, (1997) (in Japanese)
- H. Yoshida, H. Hoshi, K. Uematsu and Y. itazawa: A single, small particle launch system by electrothermal gun and microsabat, Review of Scientific Instruments Vol.68, No.1, Part 1, 178-183, (1997)
- Y. Kitazawa, K. Imagawa, A. Fujiwara, H. Yoshida, and K. Fusegi: Preliminary study on development of dust collector using low density material, the 20<sup>th</sup> International Symposium on Space Technology and Science (Abstract), (1996)
- Y. Kitazawa and K. Uemats: Micro-debris problems and its related studies, Proceedings of the 15<sup>th</sup> Symposium on Shock Waves in Japan, (1995) (in Japanese)
- Y. Kitazawa: Preliminary study of micro-debris measurement on the international space station, Proceedings of the 11<sup>th</sup> Space Station Conference, 73-74 (1995) (in Japanese)
- Y. Kitazawa, A. Fujiwara, H. Yoshida, and K. Uematsu: Preliminary study of dust impact onto low density material, International Astronomical Union (150th Colloquium) , (Abstract), (1995).
- Y. Kitazawa, K. Imagawa, A. Fujiwara, and Y. Okada: Development of dust collector using low density material, Proceedings of the fall meeting of the Japanese Society for Planetary Sciences (1995) (in Japanese)
- Y. Kitazawa and K. Uemats: Micro-debris problems and its related studies of IHI, Ishikawajima-Harima Engineering Review, Vol.35, No.2, 143-149, (1995) (text in Japanese, abstract in English)
- Y. Kitazawa: Preliminary study of the combined system of in-situ measurement with capturing of micro-debris, Proceedings of the 38<sup>th</sup> Space Sciences and Technology Conference (1994) (in Japanese)
- Y. Kitazawa, K. Uematsu, and H. Yoshida: Hypervelocity impact experiments on the multi-layer insulation (MLI), Proceedings of the 38<sup>th</sup> Space Sciences and Technology Conference (1994) (in Japanese)
- K. Uematsu, H. Yoshida and Y.Kitazawa: micro-debris impact experiments using ET-gun, Proceedings of the 37<sup>th</sup> Space Sciences and Technology Conference (1993) (in Japanese)
- The Japan Society for Aeronautical and Space Sciences (editor) : The report of the space debris study group (1993).
- K. Kimoto, H. Mori, K. Sato, Y. Kitazawa, and K. Miyoshi: Conceptual study of debris measurement/capturing experiment satellite, Proceedings of the future activity workshop/Lunar Base Workshop, Tsukuba, Japan (1992) (in Japanese)