2010 Beijing Orbital Debris Mitigation Workshop
18-19 October, 2010, Beihang University

中国航天 中国空间技术研究院 China Academy of Space Technology(CAST)

M/OD Hypervelocity Impacts and Protection Research in CAST

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China Academy of Space Technology(CAST)

- Founded in February 20, 1968 ;
- The first president: Chien Hsuch-Sen;
- The largest space technology research center in China
- The largest Spacecraft development, production base in China.
- April 24, 1970 : Chinese first artificial Earth satellite – DFH-1;
- October 2003: manned spacecraft – Shenzhou-5;
- October 24, 2007: Chinese first lunar detector – Chang'E-1 ;
- September 25, 2008: the first Extravehicular activity – Shenzhou-7.
- October 1, 2010, the second lunar detector Chang'E-2

- Beijing Institute of Spacecraft Environment Engineering
- The Spacecraft Environment Engineering department of CAST.

Outline

§1 Space Debris Environment and Its Risks

§2 Space Debris Modeling

§3 Orbital Debris impact Risk Assessment in CAST

§4 HVI Testing and M/OD Protection in CAST

§5 Orbital Debris Mitigation in CAST

§ 1

Space Debris Environment and Its Risks

Orbital debris :
Humankind digs his own grave !

Space debris are all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional.

Obtial debris is the only man-made Space environment.

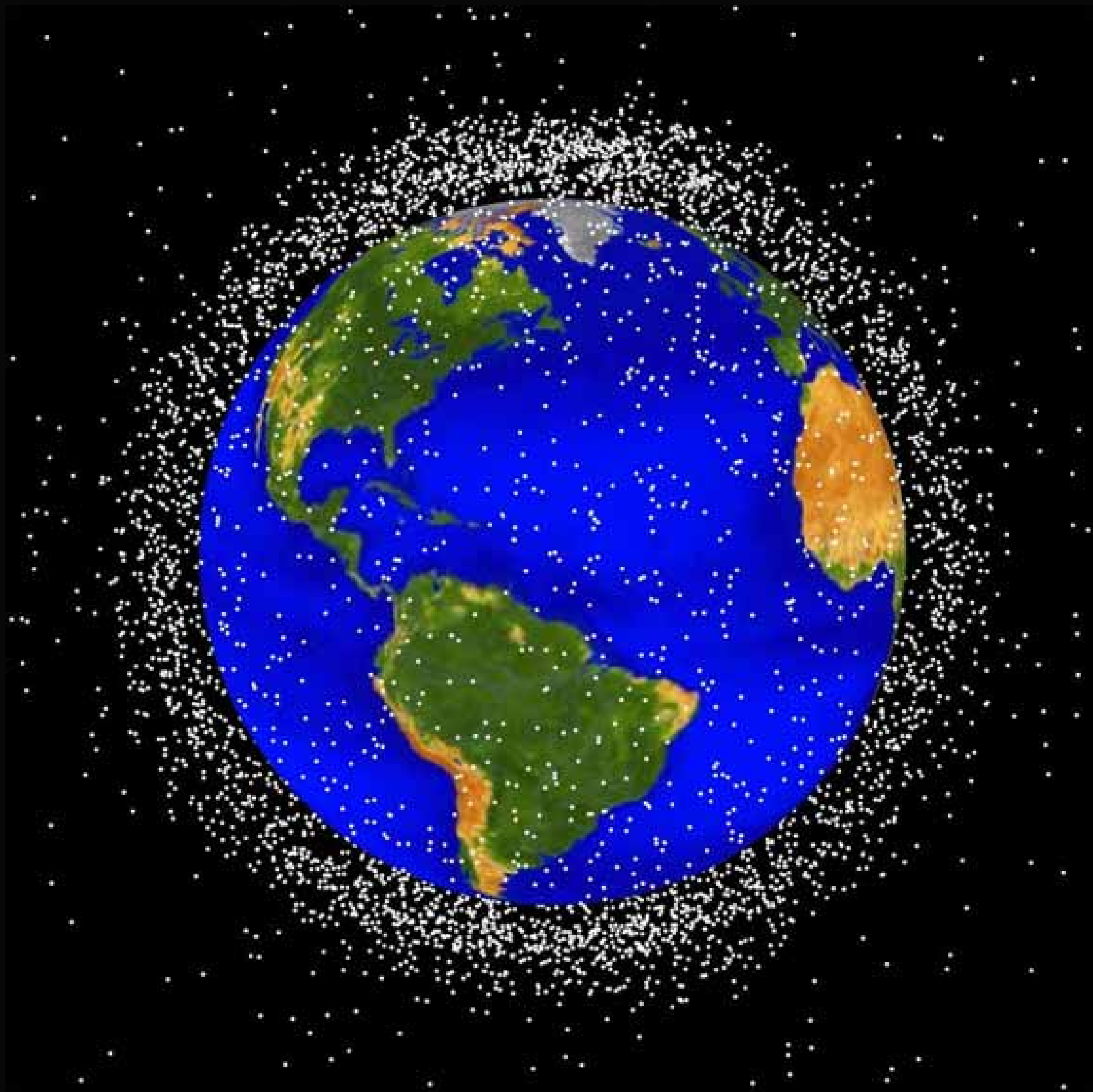
The past 50 years of space exploration has unfortunately generated a lot of junk that threatens the reliability of spacecraft.

The Space Debris Environment in 2010

- More than 5000 satellite launches since 1957 till the end of October 2010;
- 245 on-orbit break-ups led to 12,500 objects in the US Space Surveillance catalog;
- catalog size threshold ⇨ 10cm;
- mass on orbit ⇨ 6,000 tons;
- catalog orbit distributions:
  - low Earth orbits ⇨ 73%;
  - near-geostationary orbits ⇨ 8%;
  - highly eccentric orbits ⇨ 10%;
  - other orbits (incl. GNSS) ⇨ 9%
- catalog composition ⇨ 7% operational satellites,
  - About 800 operational satellites;
  - 380 active spacecraft on the GEO;

catalog composition ⇨ 40% non-operational but intact objects, and 53% fragments .

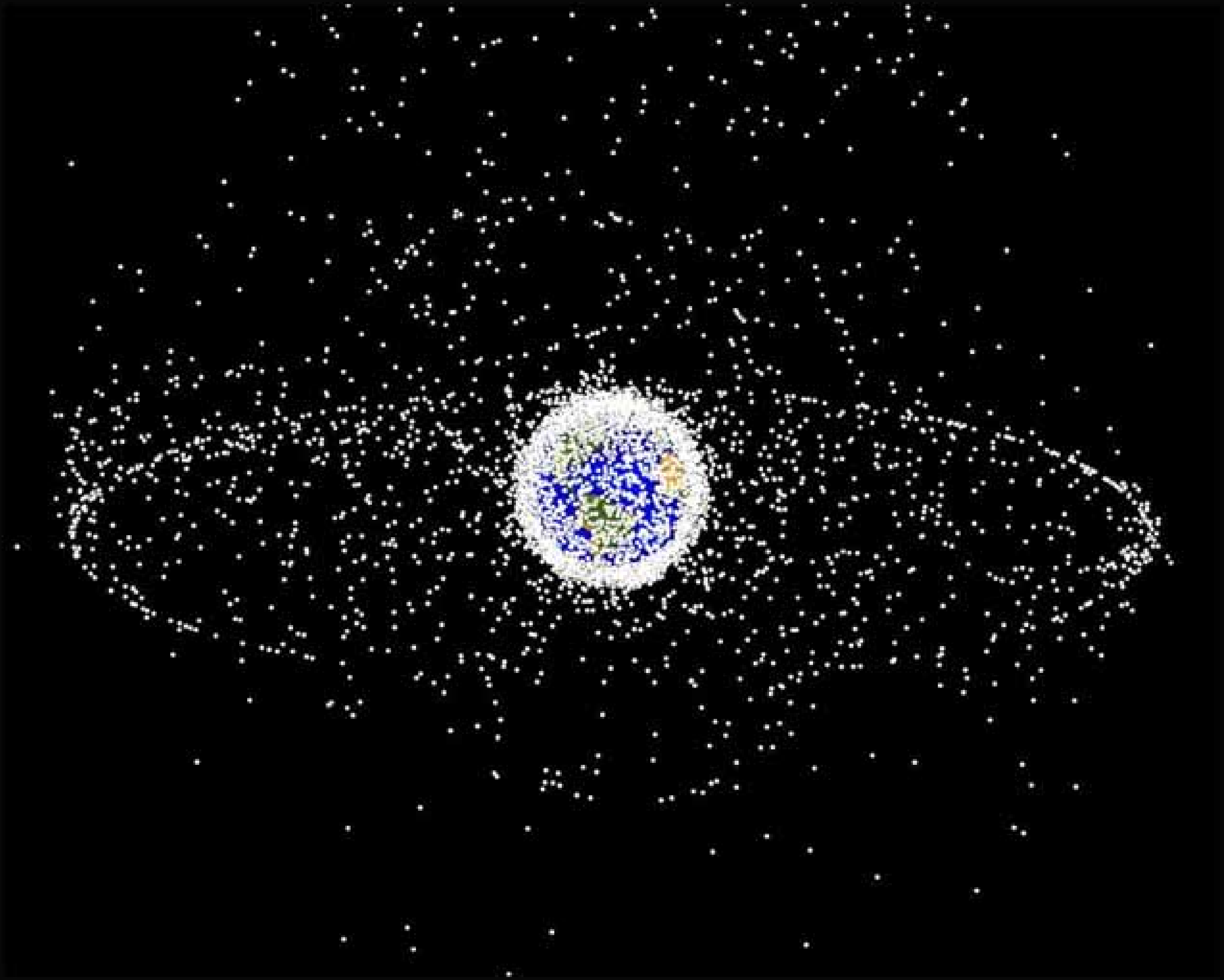
Orbital Debris Graphics



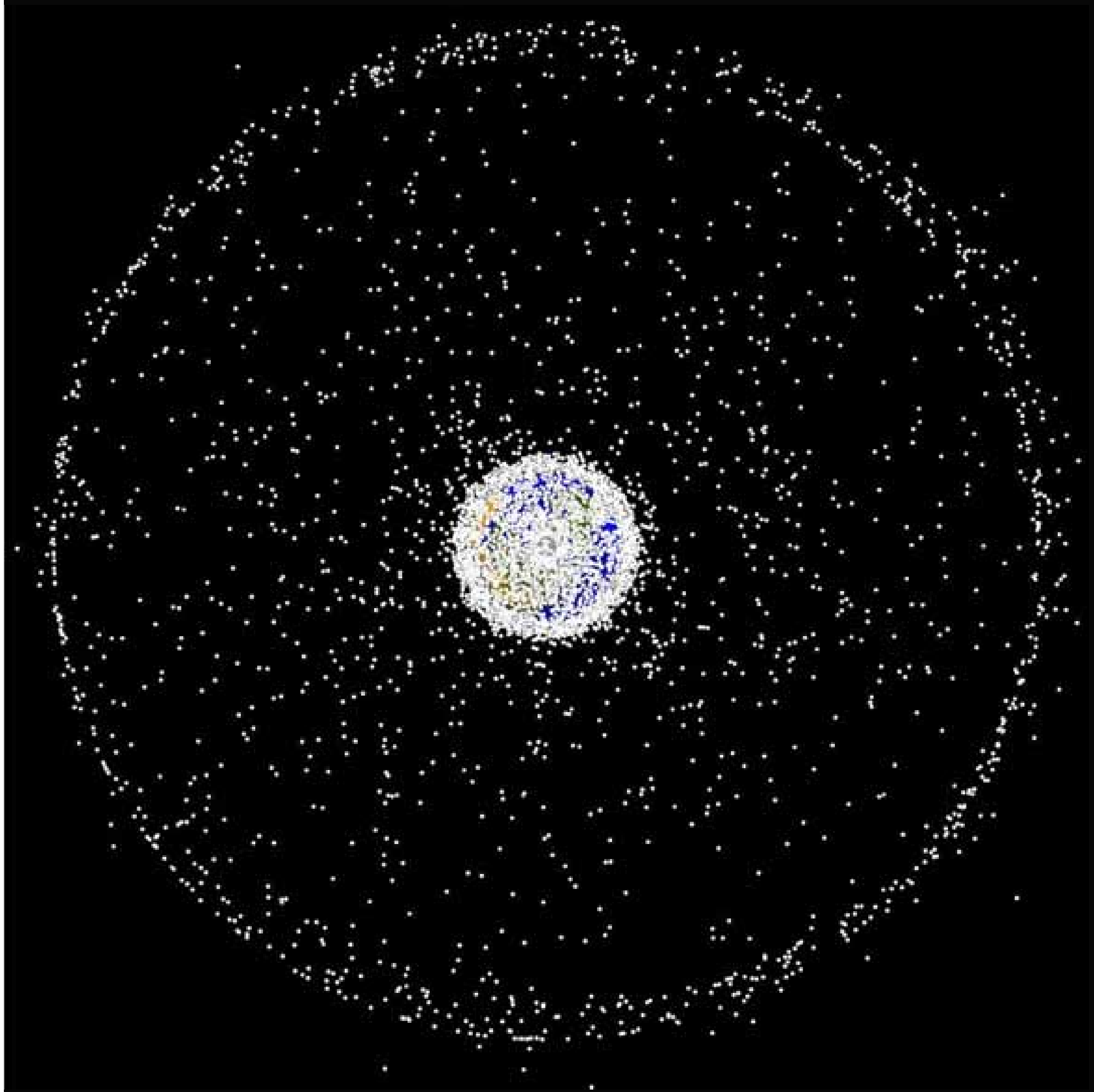
LEO images

LEO stands for low Earth orbit and is the region of space within 2,000 km of the Earth's surface. It is the most concentrated area for orbital debris.

GEO equatorial images



The GEO images are images generated from a distant oblique vantage point to provide a good view of the object population in the geosynchronous region (around 35,785 km altitude). Note the larger population of objects over the northern hemisphere is due mostly to Russian objects in high-inclination, high-eccentricity orbits.



GEO Polar images

The GEO Polar images are generated from a vantage point above the north pole, showing the concentrations of objects in LEO and in the geosynchronous region.

SATELLITE BOX SCORE
(as of 06 October 2010, cataloged by the U.S. SPACE SURVEILLANCE NETWORK)

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	98	3395	3493
CIS	1406	4600	6006
ESA	39	44	83
FRANCE	49	426	475
INDIA	41	133	174
JAPAN	113	76	189
USA	1124	3701	4825
OTHER	479	115	594
TOTAL	3349	12490	15839

Table 1. Top 10 Breakups, May 2010

Common Name	Year of Breakup	Altitude of Breakup	Cataloged Debris*	Debris in Orbit*	Cause of Breakup
Cosmos 2251	2009	790 km	1267	1215	Accidental Collision
STEP 2 Rocket Body	1996	625 km	713	63	Accidental Explosion
Iridium 33	2009	790 km	521	498	Accidental Collision
Cosmos 2421	2008	410 km	509	18	Unknown
SPOT 1 Rocket Body	1986	805 km	492	33	Accidental Explosion
OV 2-1 / LCS 2 Rocket Body	1965	740 km	473	36	Accidental Explosion
Nimbus 4 Rocket Body	1970	1075 km	374	248	Accidental Explosion
TES Rocket Body	2001	670 km	370	116	Accidental Explosion
CBERS 1 Rocket Body	2000	740 km	343	189	Accidental Explosion
			Total: 7903	**Total: 5172**	

* As of May 2010

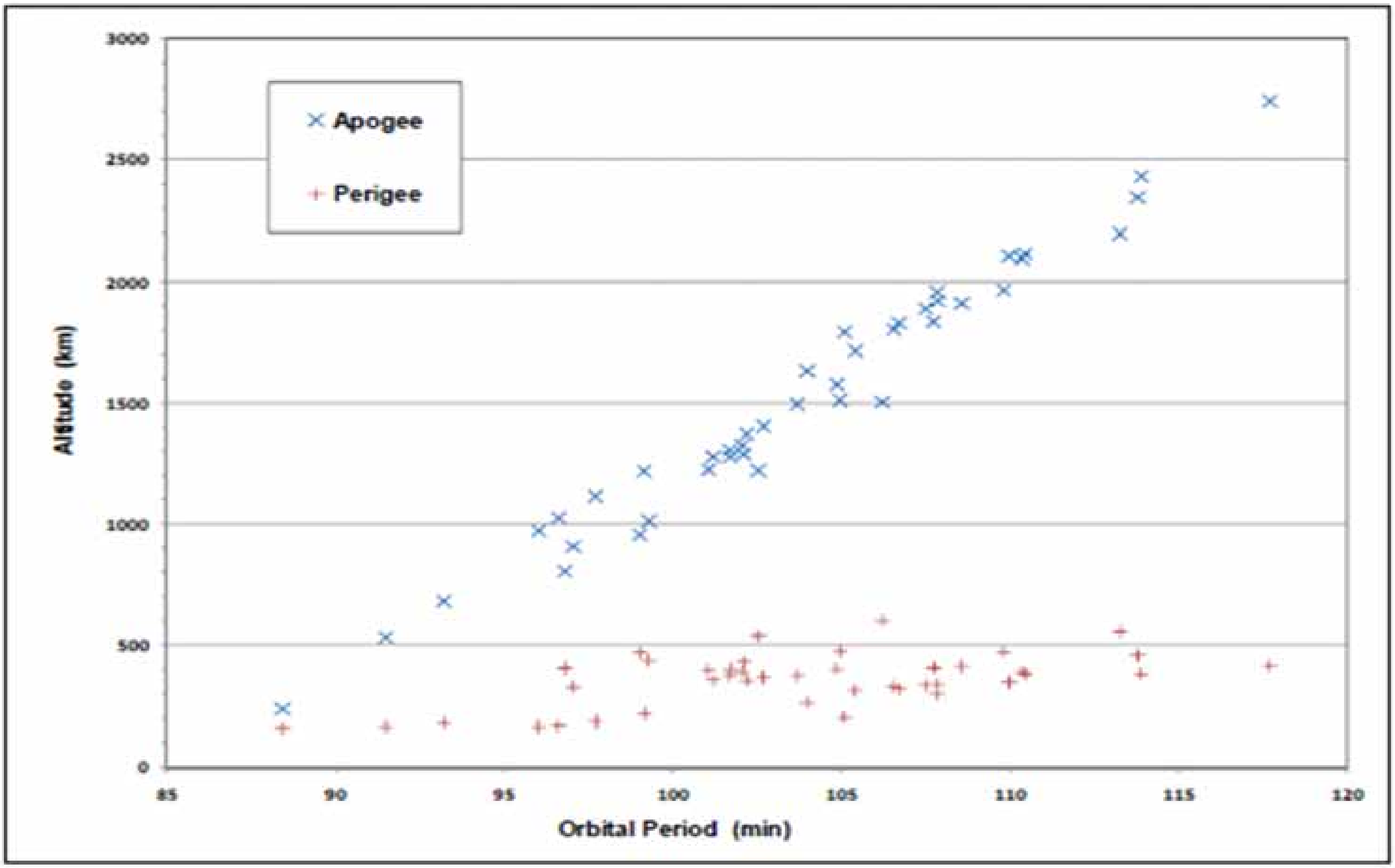


Figure 2. Distribution of Breeze-M tank debris on 9 July 2010.

42 debris which had been identified by 9 July, 2010 for Russian Launched Breeze-M tank.

The Space Debris Environment in 2010

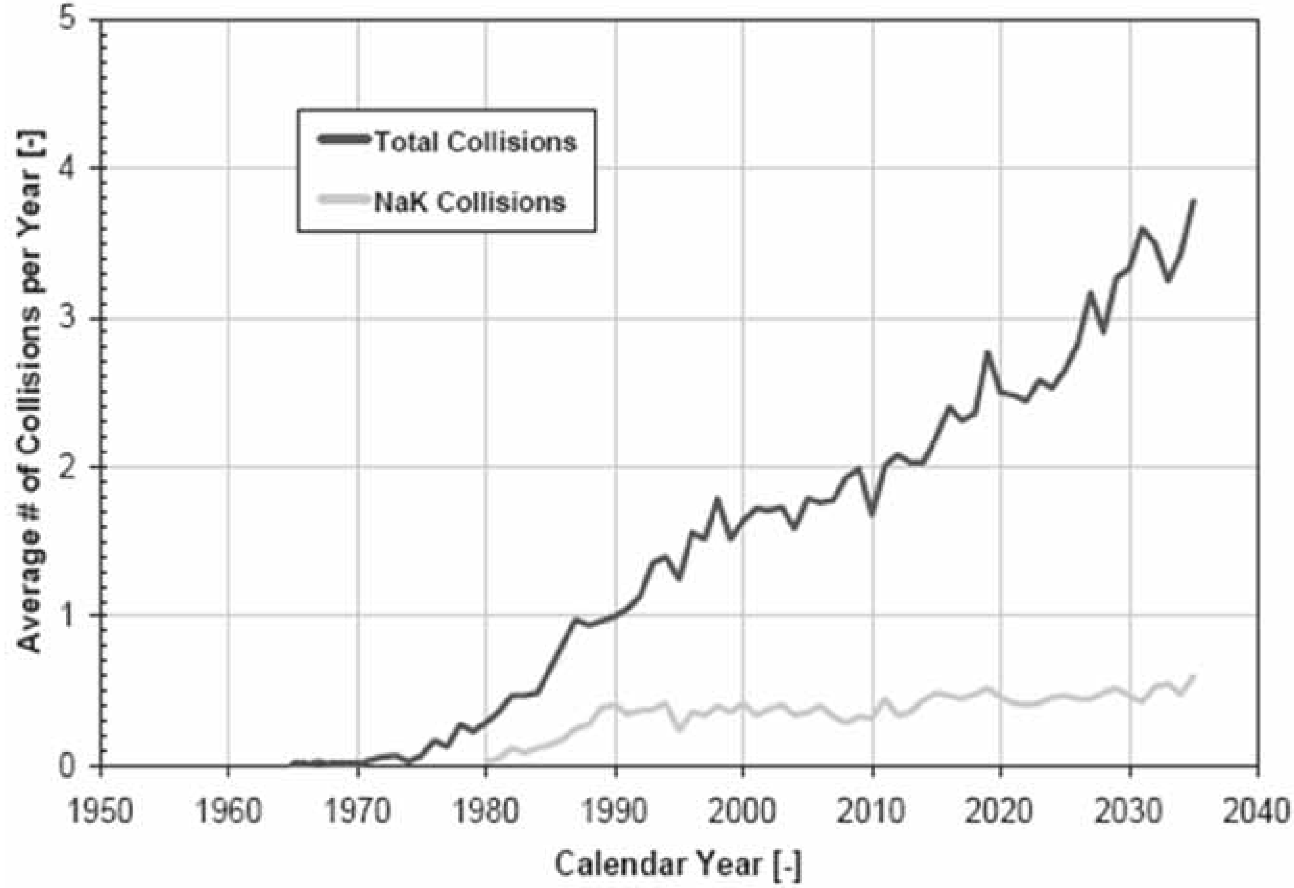
- **Large debris：size diameter≥10cm**
  - can be tracked using ground-based radars and optical telescopes
  - It can not be defended
  - the probability of collision is very low,
  - It would cause catastrophic failure of spacecraft,
  - spacecraft must maneuverable avoidance Collision
  - up to September 30, 2010, ~12,490

The Space Debris Environment in 2010

- hazardous debris :size diameter 1cm～10cm, called "hazardous orbital debris"
  - can not be tracked using ground-based radars and optical telescopes
  - It can not be defended
  - the probability of collision is low,
  - it would cause significant damage.
  - spacecraft must maneuverable avoidance Collision
  - more than ~500,000

The Space Debris Environment in 2010

- Small debris ： size diameter <1cm
  - size >1mm,~180 million, > 0.1mm 20,000 million
  - can not be tracked ground based,
  - The probability of collision is high
  - it would cause significant damage. The damage could functionally compromise the vehicle, or worse, result in catastrophic failure.
  - Spacecraft must be designed to withstand hypervelocity impacts by these small, untraceable particles



Collision Number per year of operational spacecraft with space debris large than 1cm

Space objects larger than 10cm in the coming 200 years

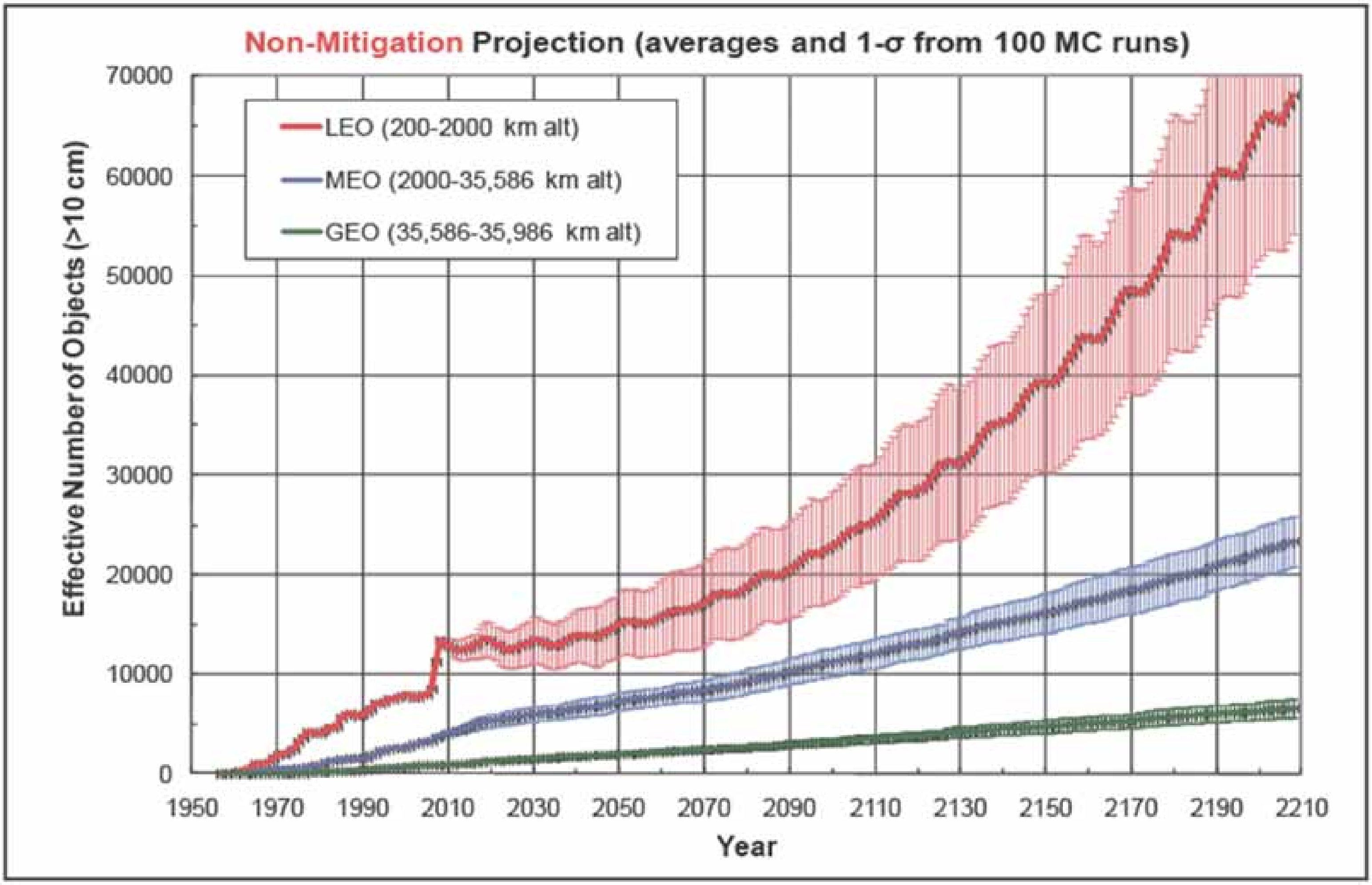
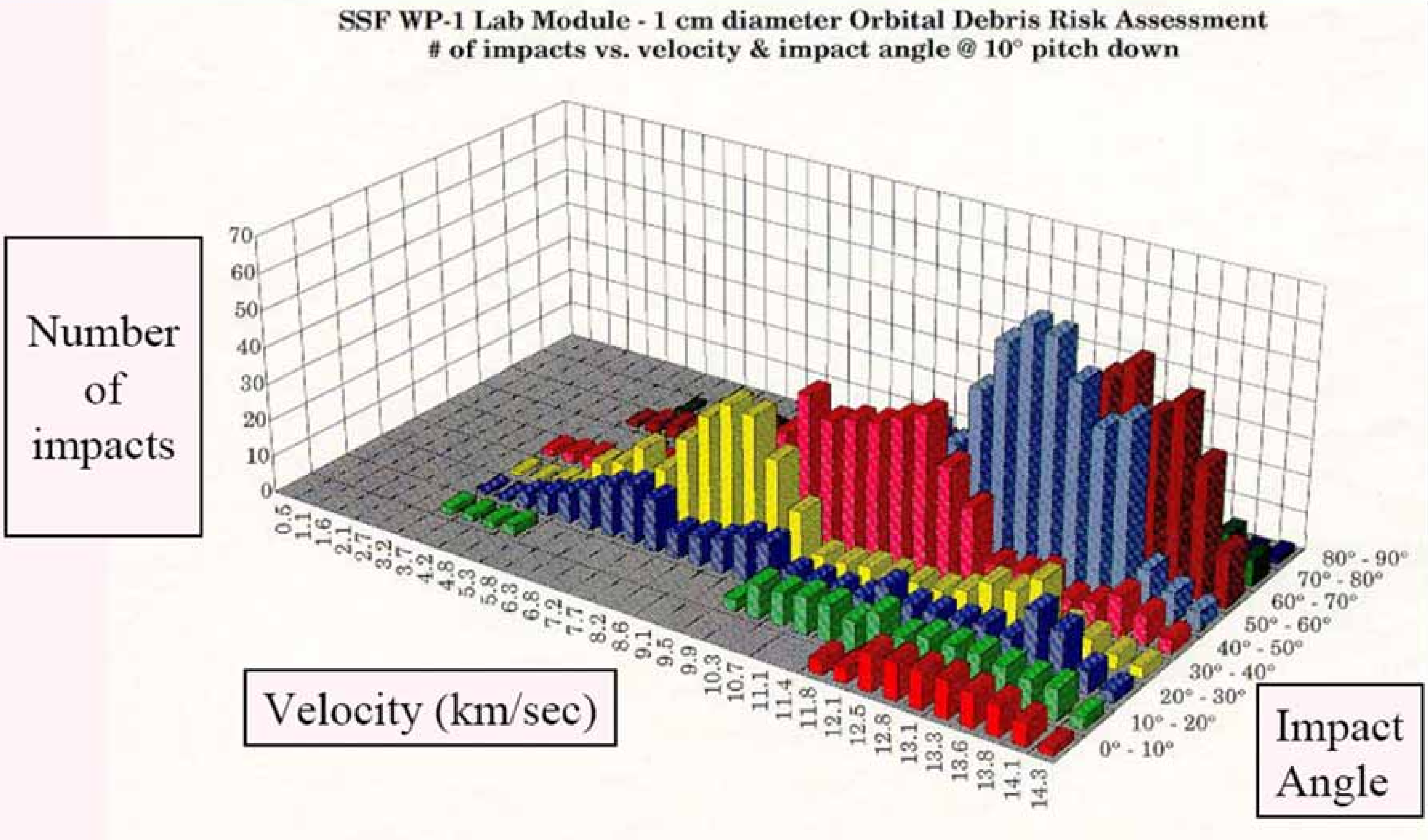


Figure 1. Updated (includes Fengyun-1C ASAT and Iridium/Cosmos collisions) projection of the runaway growth of >10 cm resident space objects if postmission disposal measures are not implemented. Figure includes 1 σ uncertainties.

Orbital Debris Quarterly News 2010(1)

Typical Orbital Debris Impact Distribution Versus Velocity and Obliquity



Joel Williamsen, Conference, Colorado Springs, CO, 2001.11

Table 1. Collision Avoidance Maneuvers in 2009

Spacecraft	Maneuver Date	Object Avoided
TDRS 3	27 Janaury	Proton rocket body
ISS	22 March	CZ-4 rocket body debris
Cloudsat	23 April	Cosmos 2251 debris
EO-1	11 May	Zenit rocket body debris
ISS	17 July	Proton rocket body debris
Space Shuttle	10 September	ISS debris
PARASOL (France)*	29 September	Fengyun-1C debris
Aqua	25 November	Fengyun-1C debris
Landsat 7	11 December	Formosat 3D

* Operating in NASA-led Earth observation network

ISS Performs First Collision Avoidance Maneuver

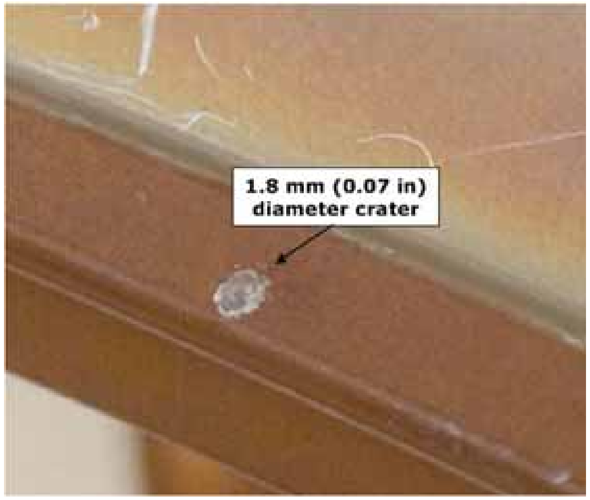
The International Space Station (ISS) conducted its first collision avoidance maneuver on October 26, 1999, to ensure no possible contact with a derelict Pegasus upper stage (1998-046K, U.S. Satellite Number 25422).

ISS started the Zarya module's propulsion system 18 hours before the conjunction would occur. Instead of a miss distance of less than one kilometer, ISS and the Pegasus stage passed at a safe separation of more than 140

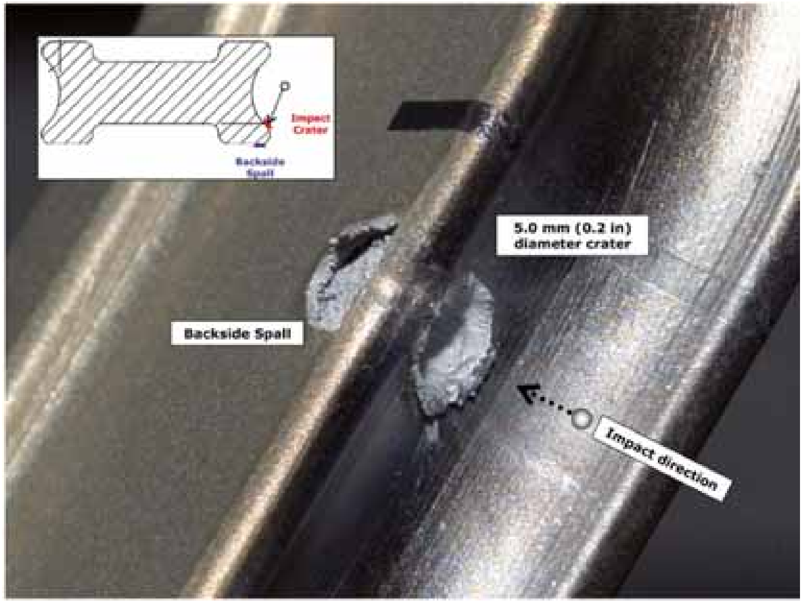
So far, 10 times of maneuver

2008 Debris Impacts on ISS

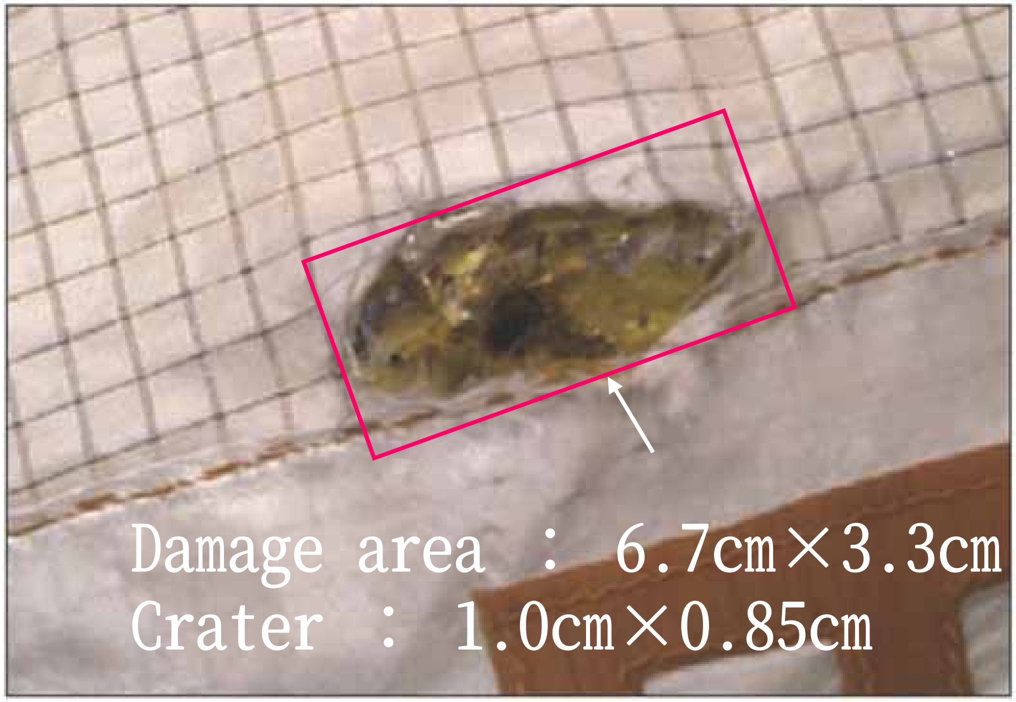
- During the STS-122 mission to ISS in February 2008, a crew member discovered a small impact crater (~2 mm diameter) on the US airlock hand rail. This ragged feature might have been the source for cuts found on some EVA suit gloves.



- During the STS-123 mission to ISS in March 2008, a larger 5 mm diameter impact crater was observed on an EVA tool which had been externally stored.



Damage to International Space Station



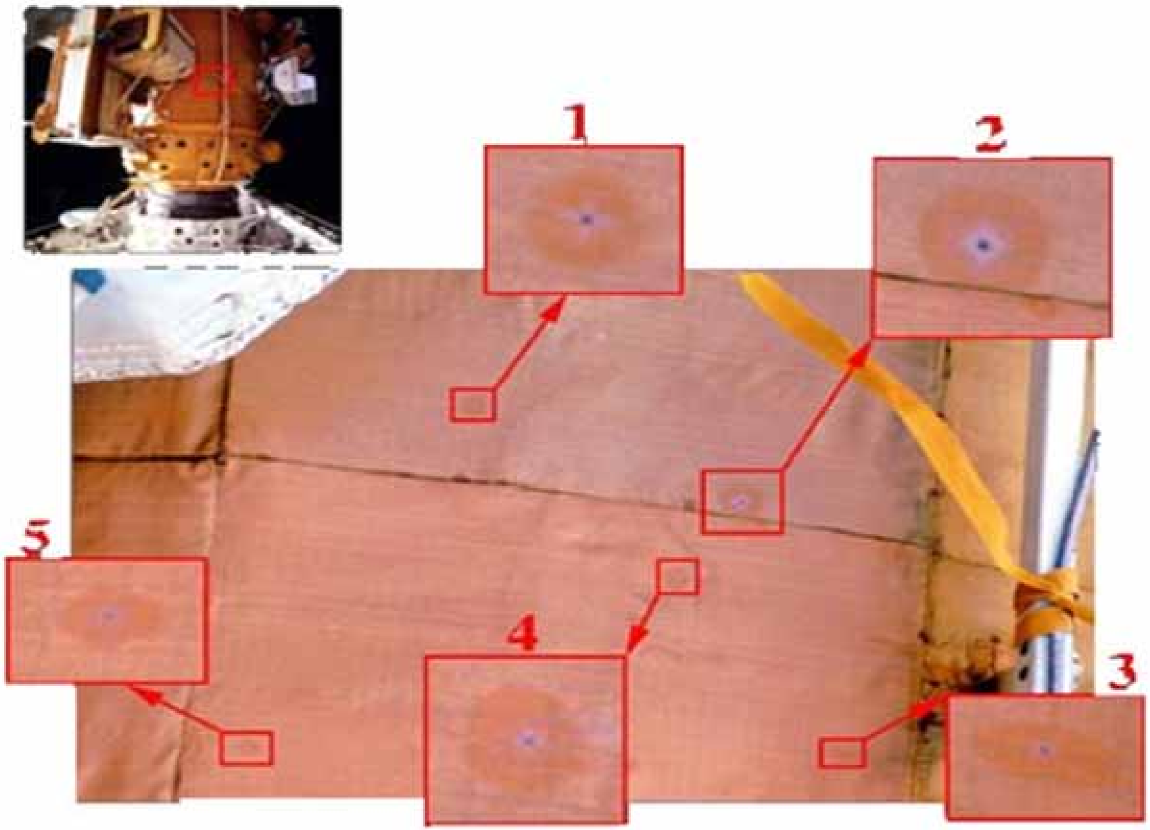
Damage to thermal blanket of FGB(Zarya Control Module)

Based on ground test results, it is believed that the likely particle size causing the damage was:

Projectile: 0.2 cm to 0.3 cm;

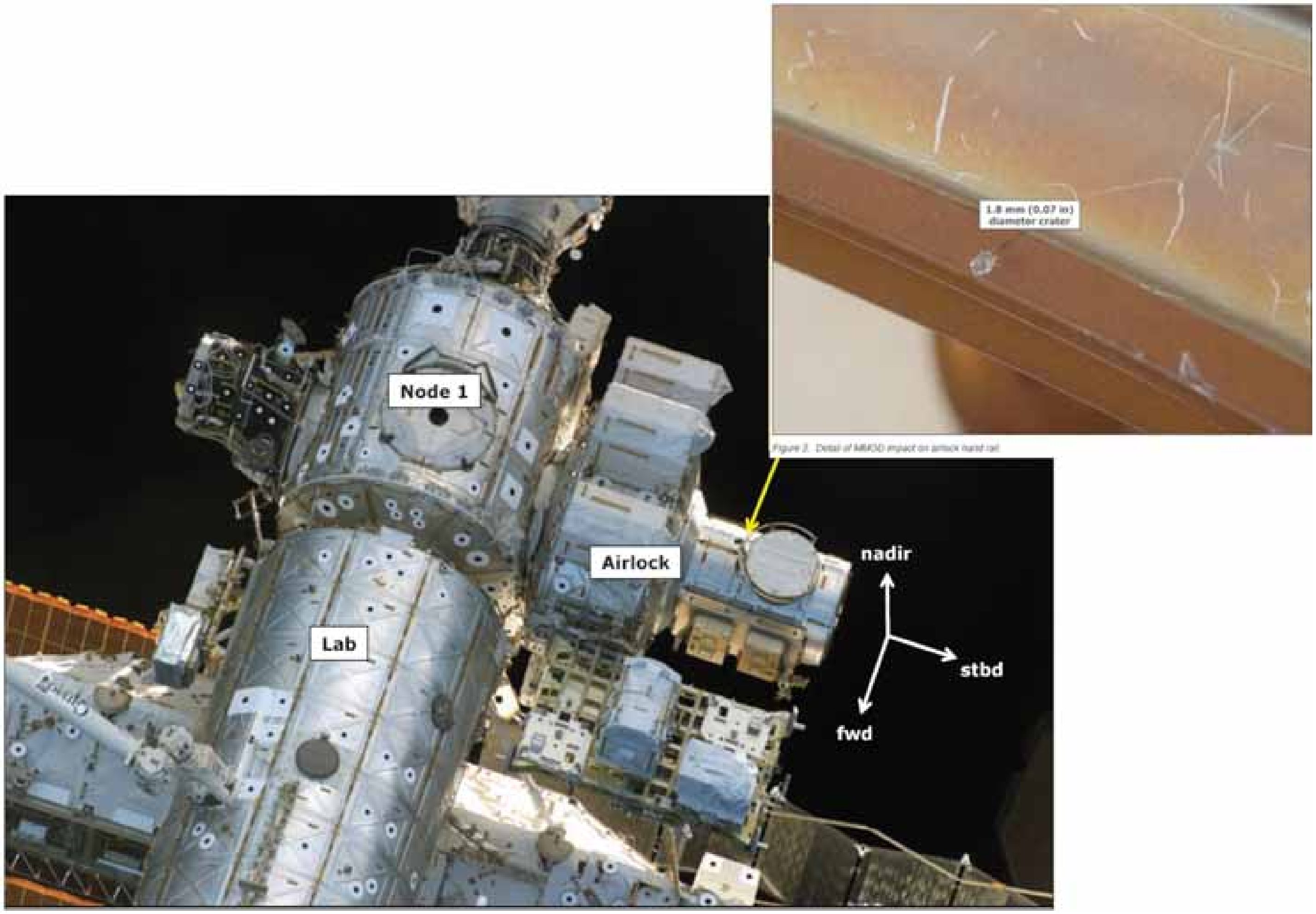
Impact angle: 75 °

Damage to Space Station



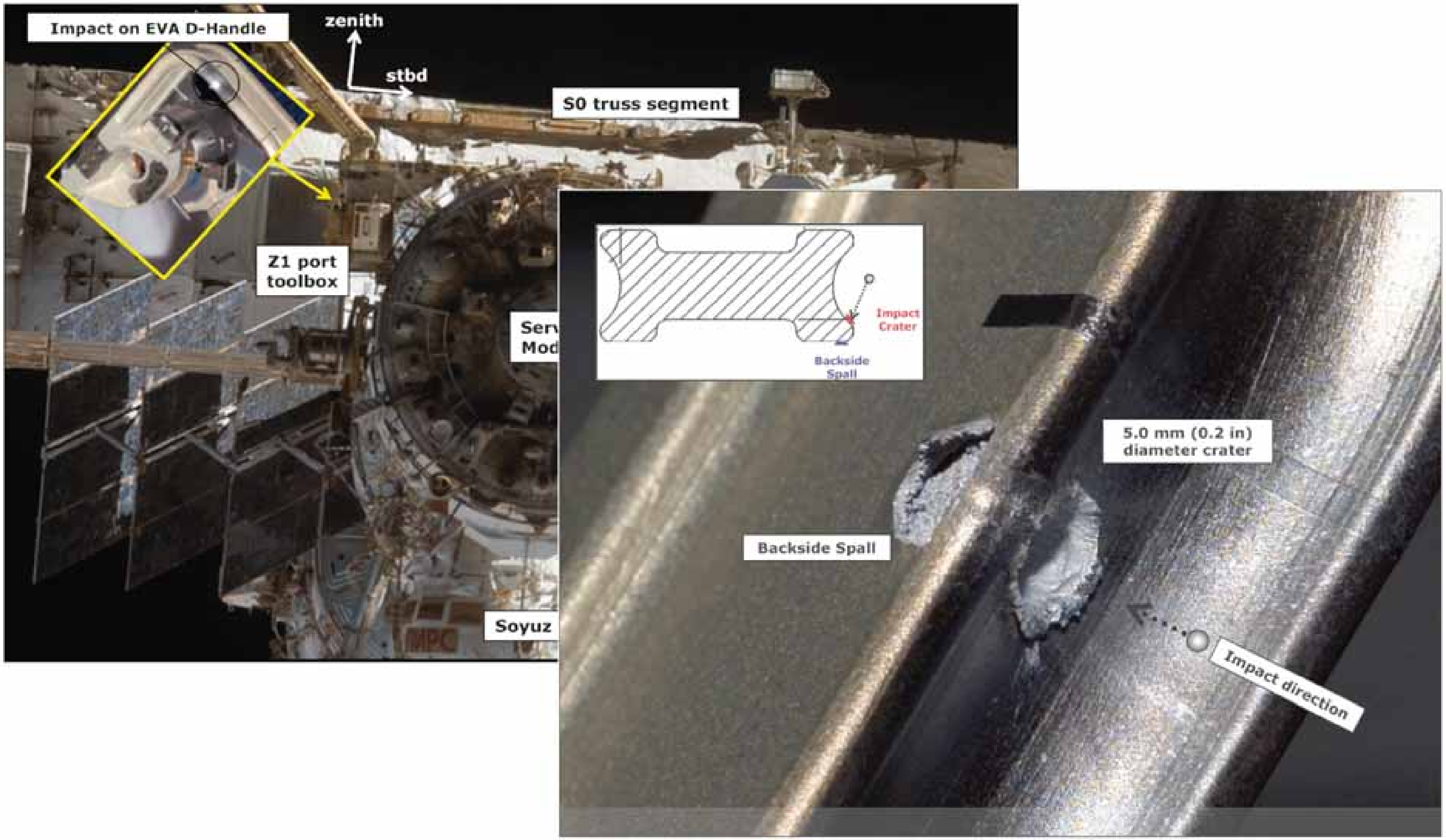
Thermal blanket (MIR)

Damage to Space Station



Detail of MMOD impact on airlock hand rail (ISS)

Damage to Space Station



Detail of MMOD impact on EVA D-Handle (ISS)

Table Damage to porthole of space shuttle

Mission	Time	altitude(km)	Days	Impact number	Results
STS-87	1997.11	285	16	176	Two glass replaced
STS-89	1998.1	280-390	16	115	Four glass replaced
STS-95	1998.10	574	9	73	Five glass replaced
STS-88	1998.12	390	12	40	Three glass replaced
STS-92	2000.10	335-446	13	38	Three thermal plate replaced
STS-97	2000.12	335-446	11	30	Two glass replaced
STS-114	--	--	--	14	One glass replaced

Our ability to safely use outer space in the long term is not guaranteed:

Multiplication of government and private space operators:

- 9 nations operate launch systems (over 60 launches in 2010);
- More than 50 states and regional organizations operate satellites in Earth orbit.
- An increasing number of very large and small private companies operate commercial satellite systems.
- Increased crowding in low earth orbit as well as in the geostationary orbit creates new challenges.
- Managing the orbital and spectral resources will require a new discipline and possibly new international mechanisms to ensure a sustainable use of outer space.

The key question is therefore :

Are space activities in Earth orbit sustainable over the long term?

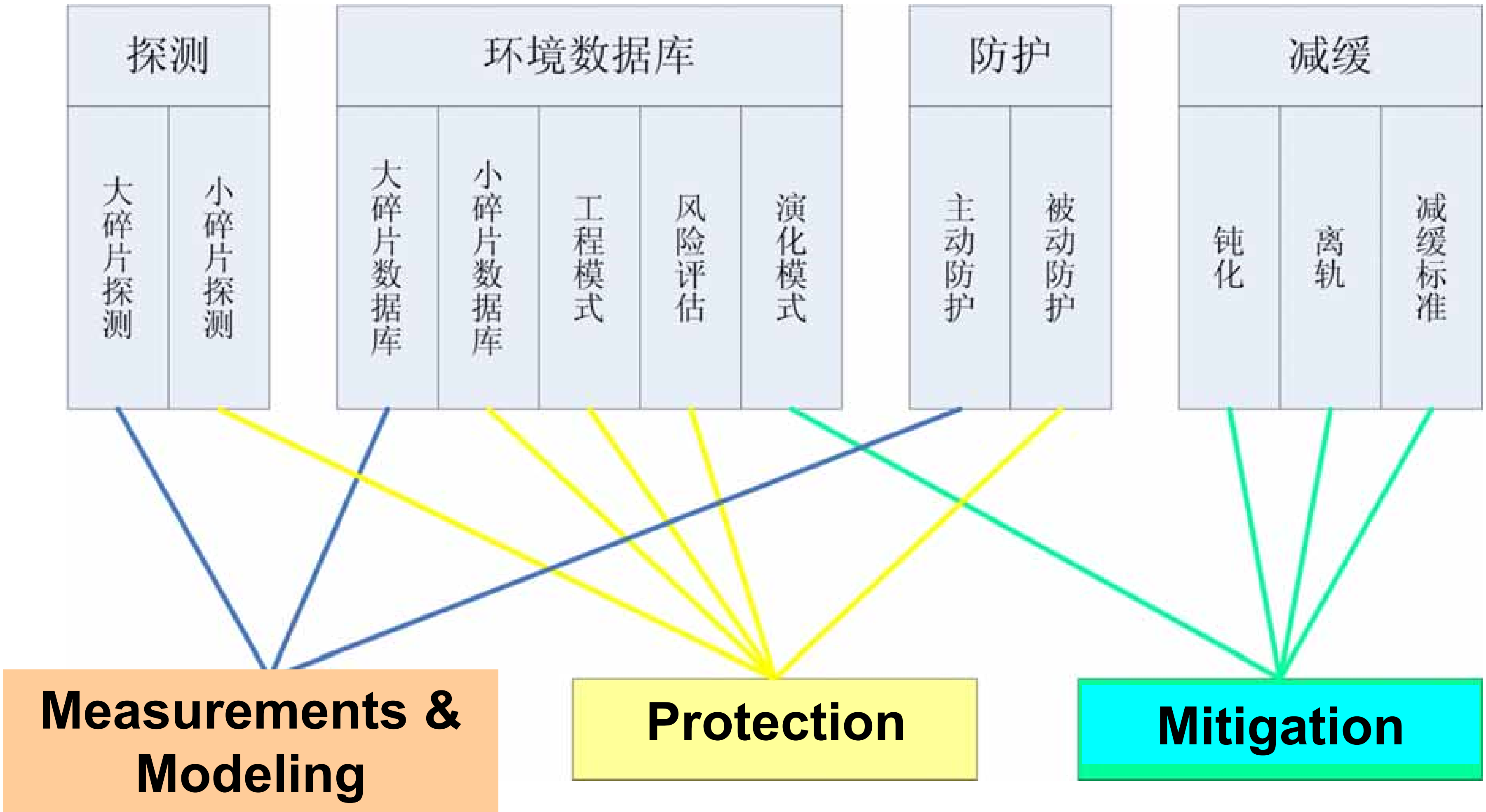
- Space Security is fragile.
- Ensuring secured and sustainable access to, and use of outer space is a major issue for all, national governments and commercial operators.
- Recent events have shown that the issue is not a theoretical one.

The Inter-Agency Space Debris Coordination Committee (IADC) is an international forum of governmental bodies for the coordination of activities related to the issues of man-made and natural debris in space.

IADC cannot stay for ever with recommendations but should prepare space laws and stronger solutions

Orbital Debris research is divided into the following broad research efforts:

3 projects



§ 2
Space Debris Modeling

2.1 Orbital Debris Measurements

- **1 Ground-based observations**
  - **(1) Orbital Debris Radar Measurements**
    (2) Orbital Debris Optical Measurements
- **2 Space-based observations**
  - **In-Situ Measurements And Retrieved Surfaces**

2.2 Orbital Debris Modeling

- NASA scientists continue to develop and upgrade orbital debris models to describe and characterize the current and future debris environment. Engineering models, such as ORDEM2000, can be used for debris impact risk assessments for spacecraft and satellites, including the International Space Station and the Space Shuttle. Whereas, evolutionary models, such as LEGEND, are designed to predict the future debris environment. They are reliable tools to study how the future debris environment reacts to various mitigation practices.

(1)Orbital Debris Engineering Models ----ORDEM2000

- The NASA Orbital Debris Program Office at JSC has developed a computer-based orbital debris engineering model, ORDEM2000. The model describes the orbital debris environment in the low Earth orbit region between 200 and 2,000 km altitude. The model is appropriate for those engineering solutions requiring knowledge and estimates of the orbital debris environment (debris spatial density, flux, etc.). ORDEM2000 can also be used as a benchmark for ground-based debris measurements and observations.

Orbital Debris Engineering Models----ORDEM2000

Incorporated in the model is a large set of observational data (both in-situ and ground-based), covering the object size range from 10 μm to 10 m and employing a new analytical technique utilizing a maximum likelihood estimator to convert observations into debris population probability distribution functions. These functions then form the basis of debris populations. ORDEM2000 uses a finite element model to process the debris populations to form the debris environment. A more capable input and output structure and a user-friendly graphical user interface are also implemented in the model. ORDEM2000 has been subjected to a significant verification and validation effort. Currently, ORDEM2000 runs on Windows 95/98/2000/NT/XP computers.

ORDEM2010

- The multi-year development of the NASA Orbital Debris Engineering Model 2010 (ORDEM2010) has passed a significant milestone with the release of the Beta version for testing. Like its predecessors in the ORDEM series of engineering models, ORDEM2010 is an empirically derived model that includes assessments of the orbital debris environment as a function of altitude, latitude, and debris size. It provides a state-of-the-art description of the environment, in terms of debris flux onto spacecraft surfaces or the debris detection rate observed by ground-based sensors. The ORDEM2010 model represents a major improvement over the existing ORDEM2000, with significant advances in several fundamental areas.

ORDEM2010

- The resulting debris population in the 10 μm to 10 cm size range serves as an input to the ORDEM2010 model. The GEO debris population, included in an ORDEM model for the first time, also is derived from NASA debris environment models and by slight extrapolation of GEO measurement data to smaller sizes with the NASA Standard Breakup Model.
- other quantities for the first time in an ORDEM model. The first is material density for debris smaller than 10 cm. These objects include non-breakup debris for which the compounds are known (e.g., sodium potassium droplets), and breakup fragments, for which low-, medium-, or high-density (i.e., plastics, aluminum, steel) are assigned based on noted ground collision test results. The second, newly included quantity is the population error, which includes measurement, future projection, and modeling uncertainties. Population errors are converted to flux errors in the final calculations of the spacecraft mode.

MASTER series

- MASTER series
- MASTER 2006
- development of MASTER-2009

(2)Orbital Debris **Evolutionary Models** --LEGEND

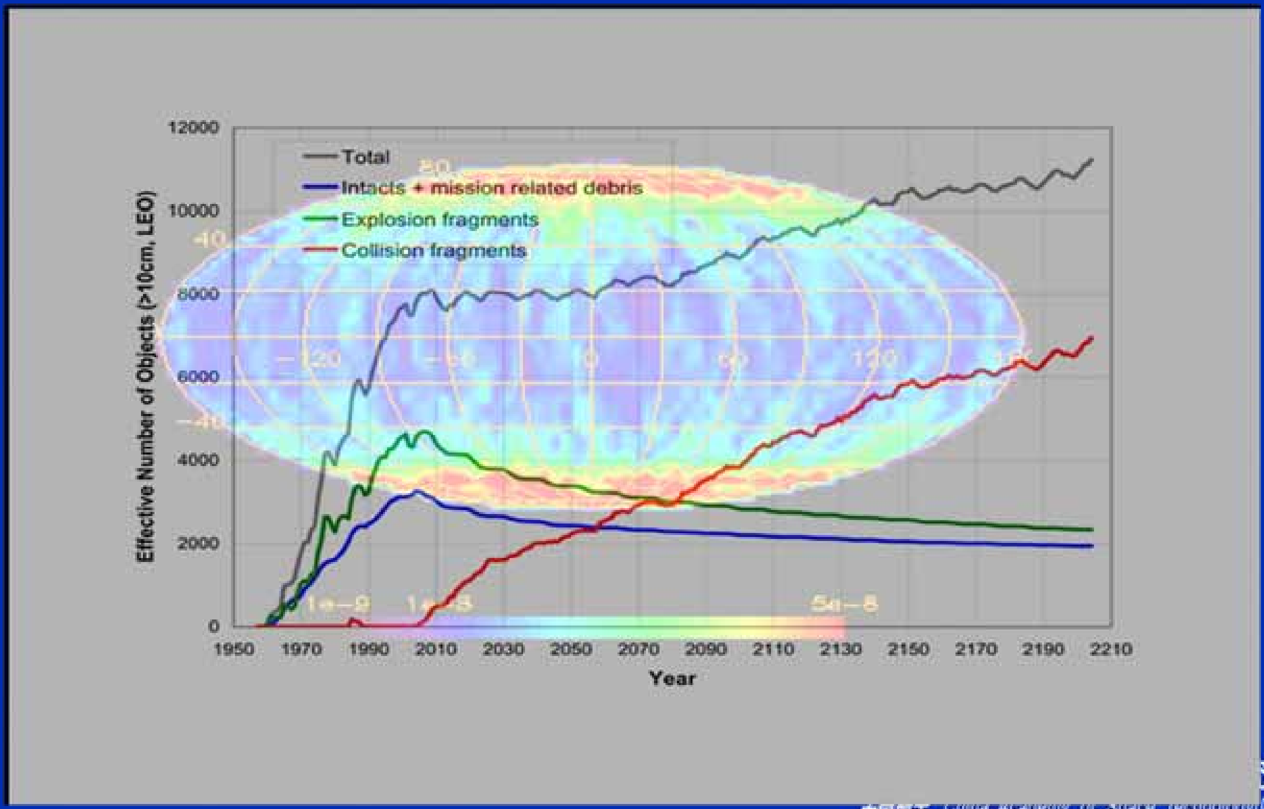
LEGEND is a full-scale, three-dimensional, debris evolutionary model that is the NASA Orbital Debris Program Office developed primary model for study of the long-term debris environment. It covers the near-Earth space between 200 and 50,000 km altitude, including low Earth orbit (LEO), medium Earth orbit (MEO), and geosynchronous orbit (GEO) regions. The model provides debris characteristics (number, type, size distribution, spatial density distribution, velocity distribution, flux, etc.) as functions of time, altitude, longitude, and latitude. In addition, LEGEND includes both historical simulation and future projection components. Populations included in the model are active and spent satellites, rocket bodies, breakup fragments, mission-related debris, and Sodium-Potassium (NaK) droplets, making it possible for the minimum size (diameter) threshold in the model to be as small as 1 mm.

Orbital Debris **Evolutionary Models**--LEGEND

- The main function of the LEGEND future projection component is to provide an understanding of how the orbital debris environment evolves in the future. It is also a reliable tool to examine how various mitigation practices may help protect the environment. A key element in the LEGEND future projection component is a three-dimensional evaluation model that provides a fast and accurate way to estimate future on-orbit collisions from LEO to GEO. Since no assumptions regarding the right ascensions of the ascending node and arguments of perigee of objects involved are required, this probability model captures the collision characteristics in real three-dimensional physical space. It is a critical component of a true three-dimensional debris evolutionary model.

Orbital Debris **Evolutionary Models**--LEGEND

- The typical projection period in LEGEND is 100 years. Due to uncertainties involved in the process (e.g., future launch traffic, solar activity, explosions, collisions), conclusions are usually drawn based on averaged results from 100 Monte Carlo simulations.



§ 3

Orbital Debris impact Risk Assessment in CAST

§ 3 Orbital Debris impact Risk Assessment in CAST

3.1 Methodology

3.2 Impact Risk Assessment Codes:

- 3.2.1 BUMPER: NASA, JAXA
- 3.3.2 ESABASE/DEBRIS: ESA
- 3.2.3 COLLO, BUFFER, PSC: ROSCOSMOS
- 3.2.4 MDPANTO: DLR
- 3.2.5 SHIELD: BNSC
- **3.2.6 MODAOST: CAST**

3.1 **Methodology**

The standard M/OD risk assessment methodology for spacecraft is illustrated in Fig 1.

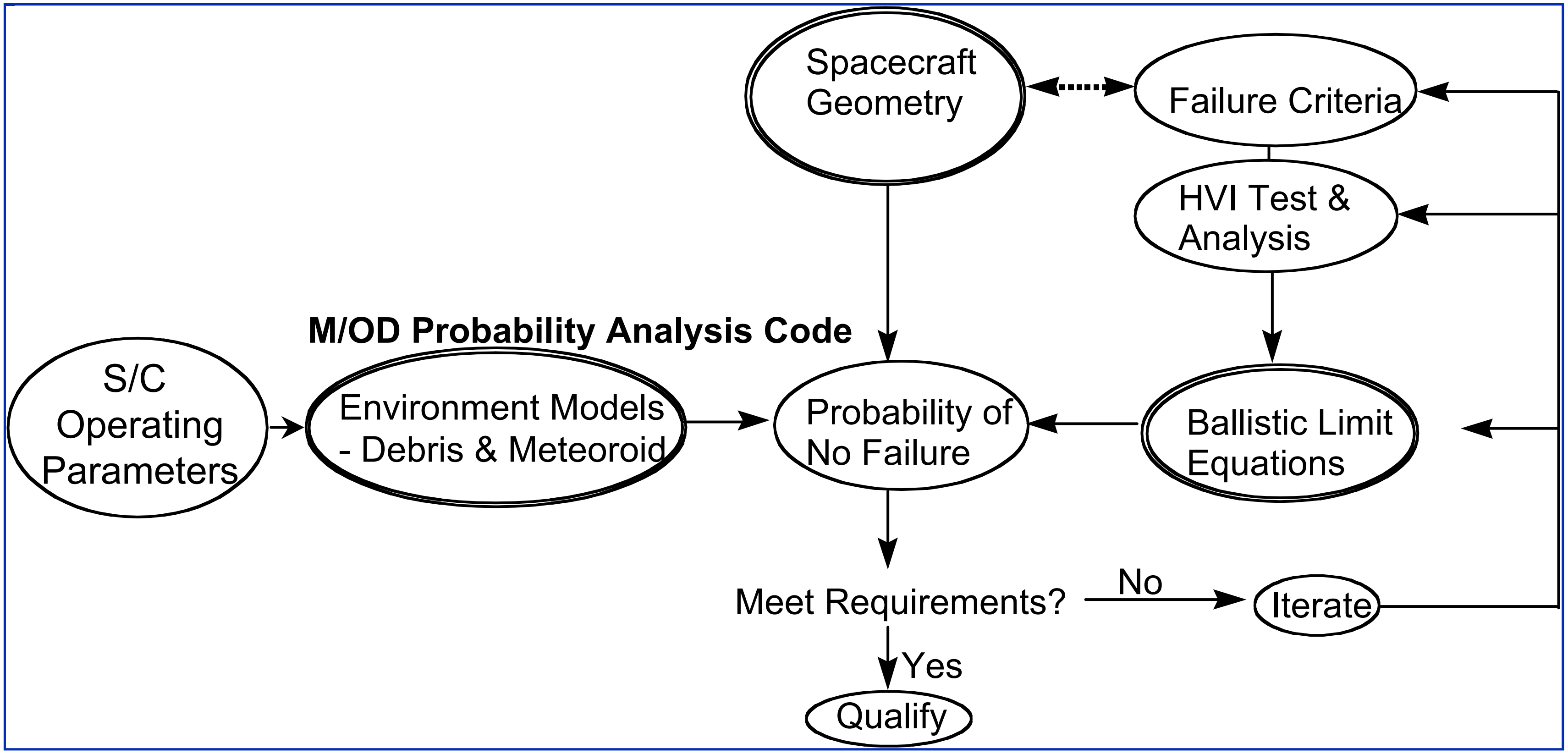


Figure 1 Standard Process for Assessing Spacecraft Meteoroid/Orbital Debris Risks

3.1 **Methodology**

The procedure for assessing and reducing spacecraft risks from M/OD impact is an iterative one. Specific steps in the procedure are listed below:

Step 1:

Identify spacecraft components/subsystems:

The M/OD analyst must know many details of the spacecraft design, operation, failure modes and effects, to properly perform a spacecraft M/OD risk assessment. The Spacecraft geometry should be well known, including materials and allocation of critical subsystems. The systems and components that are exposed to M/OD are identified and their criticality for the mission is assessed.

3.1 **Methodology**

Step 2、Assess HVI damage modes：

Hazards to be assessed in the M/OD risk assessment are defined for each exposed system and component.

Step 3、Determine failure criteria:

A very clear failure criterion is defined from the many potential hypervelocity impact damage modes for each spacecraft system. The Protection Manual (PM) defines many potential damage modes for different spacecraft systems. The failure mode is explicitly defined for each ballistic limit equation.

3.1 **Methodology**

Step 4、 Perform HVI test/analysis to anchor and verify the ballistic limit equations and to define “ballistic limits”:

Step 5、 Conduct probability analysis of failure due to meteoroid/orbital debris:

The probability of M/OD failure is assessed using the spacecraft geometry, ballistic limit equations and M/OD environment models.

3.1 Methodology

Step 6、 Compare M/OD analysis results with goal or requirement:

The analysis results (PNP or PNF) are compared to the goal or requirement for the spacecraft system or component, which is defined by the reliability and/or safety community. If PNF is greater than the required survival probability, than the analysis can be considered complete, otherwise the analysis continues with step 7.

3.1 **Methodology**

Step 7、 Consider updates to design, operations, analysis, test, or failure criteria:

If the analysis results do not meet the requirements, iteration of the analysis is necessary. Revising analysis assumptions in terms of failure criteria and/or improved spacecraft modelling is typically the least expensive option, as it has the least effect on the spacecraft design. Additional testing may be necessary to validate the ballistic limit equations. It is often possible to remove engineering conservatism in the BLEs after additional testing is conducted. Other options include changes to the spacecraft design.

3.1 Methodology

Step 8、 Update/Iterate as necessary to meet requirement:

Typically, many updates to a spacecraft's M/OD risk assessment are necessary to reflect changes in the spacecraft, BLEs, and M/OD environment models. These updates are achieved after each iteration of the previous steps.

3.2 Impact Risk Assessment Codes:

Several statistical impact analysis tools have been developed for a detailed impact risk assessment of non-trackable particles. These tools allow a fully three-dimensional numerical analysis, including directional and geometrical effects and spacecraft shielding considerations. They normally support the application of different environment and particle/wall interaction models. The tools allow a 3-D display of the results.

3.2 Impact Risk Assessment Codes:

Typical user specified input parameters for these tools are:

1. the orbit and mission parameters,
2. spacecraft attitude, geometry and shielding,
3. the particle type, size, mass density and velocity range to be analysed,
4. the damage equations and related parameters to be applied.

3.2 Impact Risk Assessment Codes:

the number of impacts for the specified particle range,

1. the resulting number of damaging impacts (failures) taking into account the spacecraft shielding and damage assessment equations,
2. the mean particle impact velocity (amplitude and direction),
3. the numbers of craters of specified size,
4. the probability of no failure.

3.2 Impact Risk Assessment Codes:

Computer codes used by the PWG members to assess the risk from M/OD impacts include:

1. BUMPER: NASA, JAXA
2. ESABASE/DEBRIS: ESA
3. COLLO, BUFFER, PSC: ROSCOSMOS
4. MDPANTO: DLR
5. SHIELD: BNSC
6. MODAOST: CAST

3.2 Impact Risk Assessment Codes:

MODAOST: CAST

Procedure:

Both of the space debris environment models and the meteoroid model have been integrated in MODAOST.

The M/OD environment results should be given by filling the mission parameters and finite element model could be defined by the user or provided by older FE model samplings. [Zheng et al., 2005; Sun et al., 2007]

3.2 Impact Risk Assessment Codes:

MODAOST: CAST

Flux Models Implemented

Meteoroids:

•Model from [Gruen *et al*., 1985; Anderson (ed.), 1994]

Space Debris:

•NASA 91 [Anderson (ed.), 1994]
•ORDEM 96 [Kessler *et al*., 1996]
•ORDEM 2000 [Liou *et al*., 2002]

3.2 Impact Risk Assessment Codes:

MODAOST: CAST

Damage Equations Implemented：

Presently, damage equations for the following configurations are implemented:

- single wall [Cour-Palais]
- single bumper [Christiansen]
- stuffed whipple[Christiansen]
- multi-shock shield[Christiansen

3.2 Impact Risk Assessment Codes:

MODAOST: CAST

Special Features/Comments：

- Powerful ability of modelling complex spacecraft
- Easy achievement of the traditional FE model
- High-accuracy of handling complex structures (partly shadowing is considered)
- User-friendly interface

3.2 Impact Risk Assessment Codes:

Calibration Results

Calibration runs were performed by different agencies, using their codes. A summary of available results are presented in Table 1 for the cube.More detailed results for each face of the cube case, for each element of the space station case (cylinders and cube) are generally available. Detailed results for some of the codes are presented in [Version 4.0 of the IADC Protection Manual. Germany: 2009]

3.2 Impact Risk Assessment Codes:

Calibration Results

Table 1 **Calibration results for the cube**

		BUMPER	ESAB./ Debris	MDPANTO	COLLO	SHIELD	MODAOST
NASA 2000	d > 0.1 mm	2.131E+01	n.a.	2.139E+01			2.143E+01
	d > 1.0 cm	2.876E-06	n.a.	2.872E-06			2.873E-06
	p > 1.0 mm	3.528E-01	n.a.	3.360E-01			3.368E-01
	single	1.714E+00	n.a.	1.642E+00			1.639E+00
	double	2.373E-05	n.a.	2.257E-05			2.303E-05
Meteoroid	d > 0.1 mm	2.221E+01	2.12E+01	2.164E+01			2.164E+01
	d > 1.0 cm	1.398E-06	1.30E-06	1.360E-06			1.362E-06
	p > 1.0 mm	1.013E-01	8.30E-02	9.064E-02			8.812E-02
	single	6.804E-01	6.00E-01	6.204E-01			6.018E-01
	double	1.354E-05	1.20E-05	1.142E-05			1.142E-05

3.2 Impact Risk Assessment Codes:

Applications of Impact Risk Assessment Codes

Protection structures manned spacecraft. During preliminary design phase, MODAOST was used to assess the impact risk and the result was used to guide the protection design. PNP risk has been calculated many times in order to meet the requirement and two specific ballistic limited curves achieved by HVI tests have been integrated into MODASOT system.

3.2 Impact Risk Assessment Codes:

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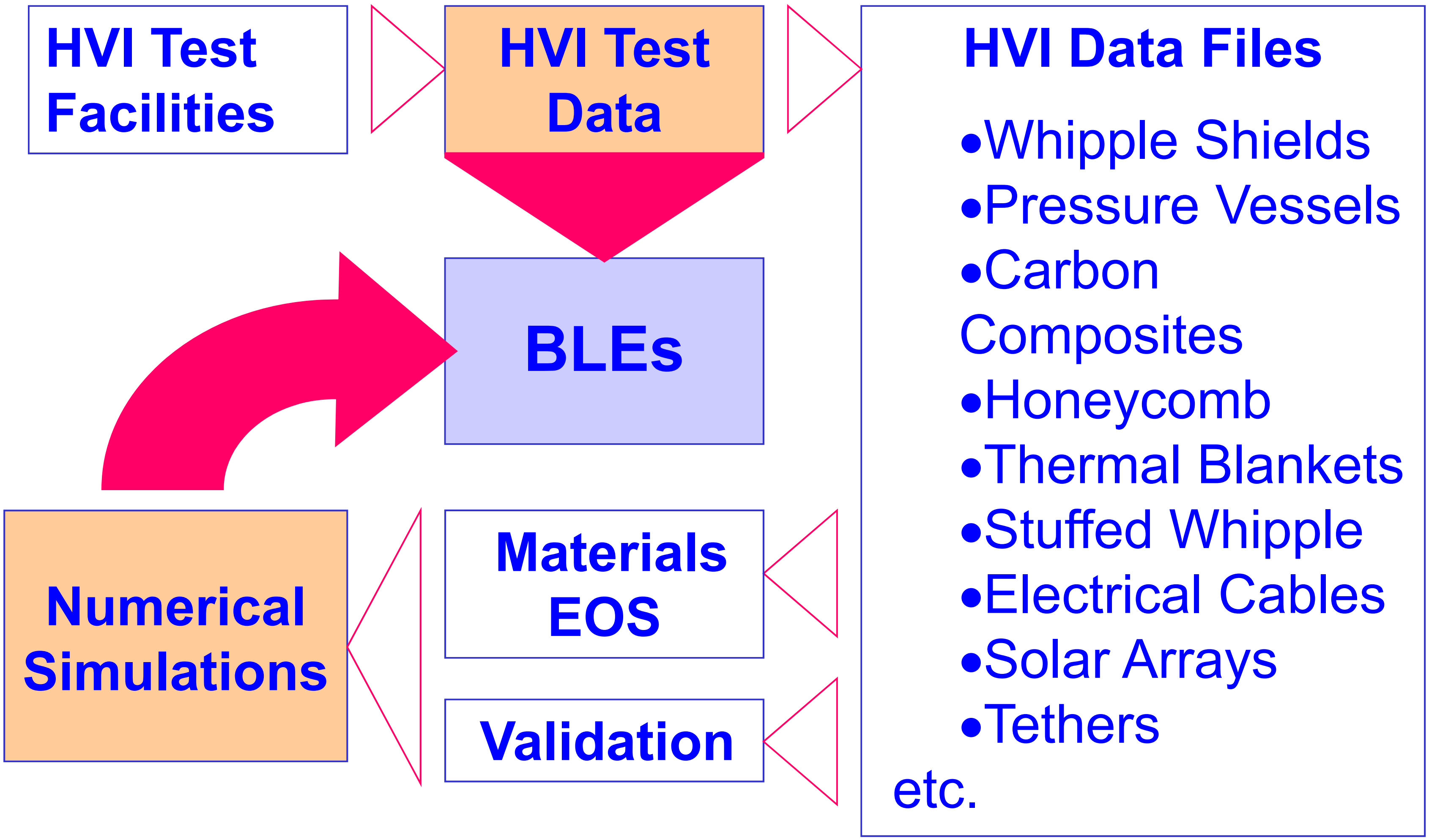
§ 4

HVI Testing and M/OD Protection in CAST

Why Hypervelocity Impact tests ?

- To design effective shielding for spacecraft and to evaluate the risk posed by debris and meteoroids, we must be able to perform tests in the laboratory. Hypervelocity Impact testing has some extreme requirements.
- HVI tests are necessary to:
  - obtain the reference points of BLEs within the testable range and their verification;
  - provide data for testing (verification, calibration) of the numerical codes (including models of materials behaviour under HVI conditions).

The role of HVI experiments



4.1 Hypervelocity Impact Testing Facilities in CAST

Two stage Ligth-Gas Gun

- **Caliber：Φ18**
- **Launch Speed：2-7km/s**
- **Projectile: aluminium alloy spheres and cylinders, 1-15mm in diameter, 0.0015-5g.**

Laser-drive flyer system

- Laser energy: 20J, pulse
- Launch Speed: 1-10km/s
- Projectile: metal foil,0.5-3mm in diameter, 3-25μs in thickness.

Staff ：9, include：1 Professor, 5 doctors, and graduated students

4.2 Hypervelocity impact (HVI) Research in CAST

1. Development of new shield with high protection performance
2. HVI characteristics of MLI
3. Ballistic limit Curve of porthole glass
4. Development of Debris cloud model
5. Ballistic limit Equations of protection shields
7. Hypervelocity launch technique (V>7km/s)
8. Shape effects of projectile in HVI
9. Development of Laser-driven flyer techniques
10. Velocity Measuring technique for micro-flyer
11. the hypervelocity impact cumulative effects of micro M/OD on the outer surfaces functional of materials of spacecraft

1. Develop new concept shield with high performance

Characters of previous study/research:

- More than two bumpers;
- New composite;
- Complex structure;
- High performance.

→

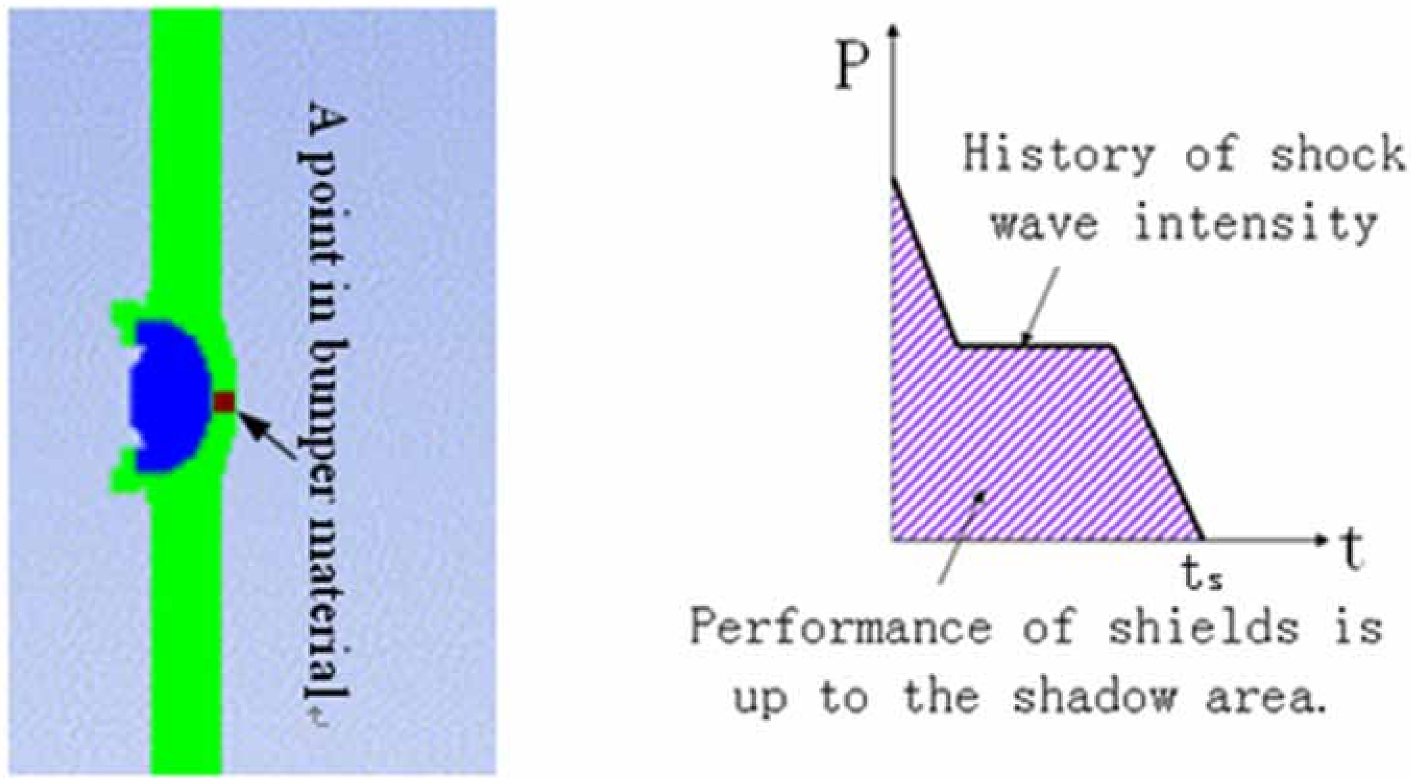
Application in our spacecraft:

- Can not get these new materials;
- Can not reduce its weight;
- Linkage is complicated.

Question:

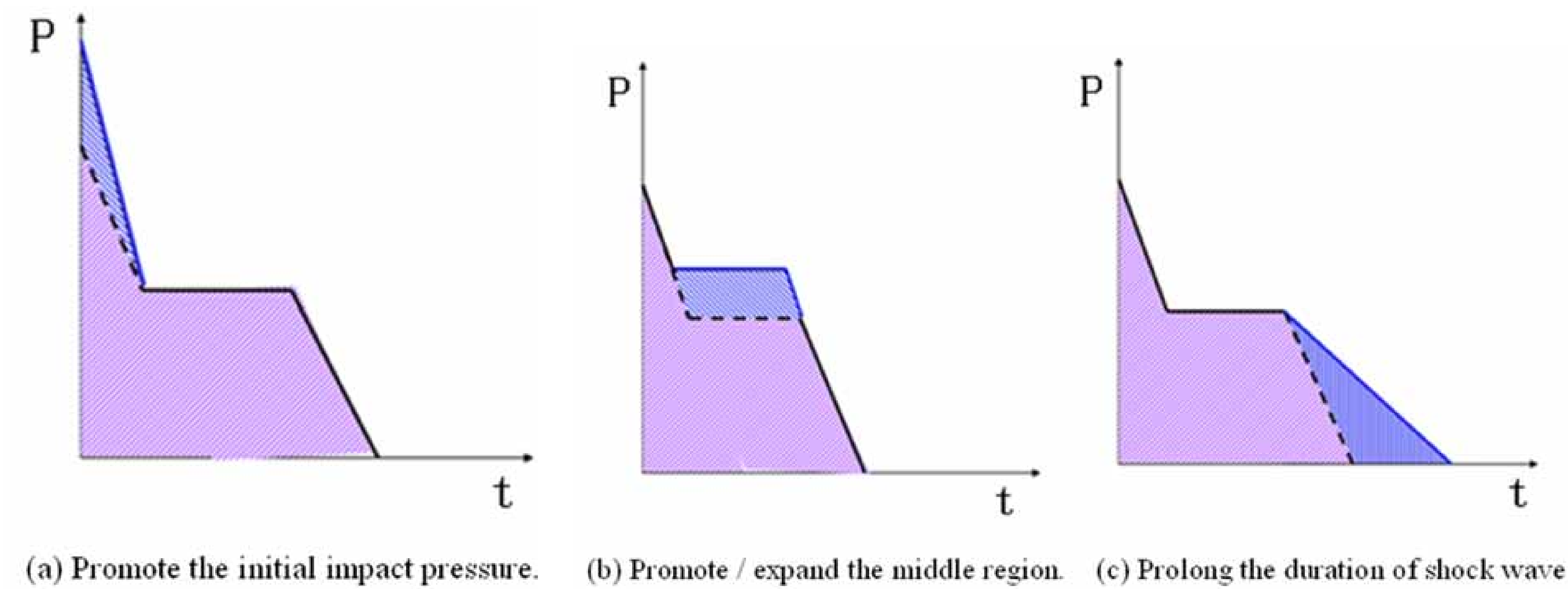
Is there a kind of simple shield with high performance?

Shock wave propagation in bumper:

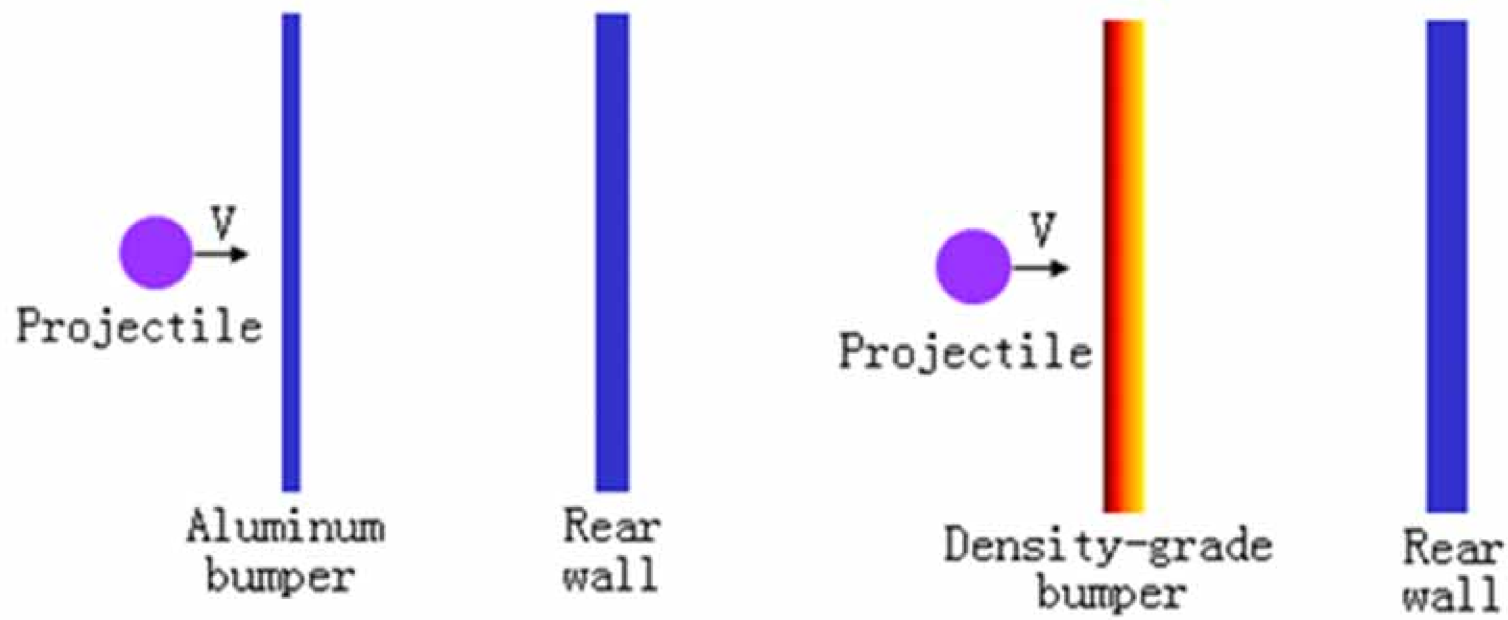


(a) A point in bumper material.   (b) History of shock wave intensity of the point.

How to increase the shadow area?



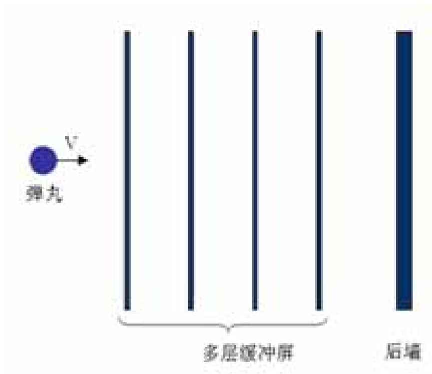
Three methods to increase the shadow area



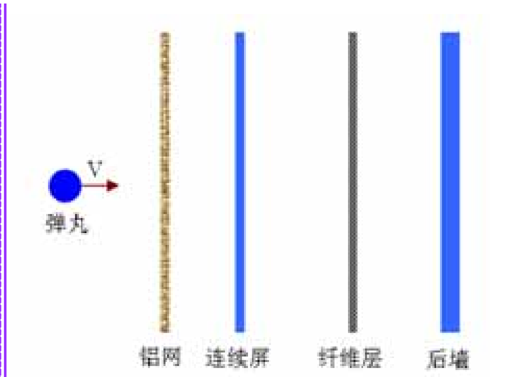
(a) Whipple Shield (b) Gong-Hou Shield

Fig. 1 The sketch of Whipple Shield and Gong-Hou Shield

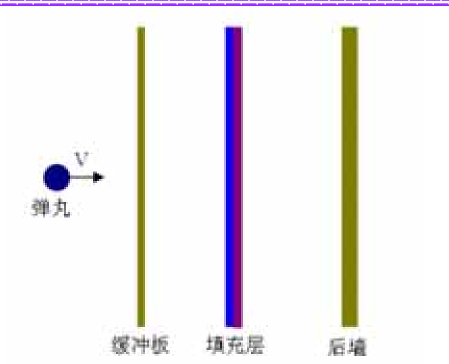
Comparison with other enhanced shields:



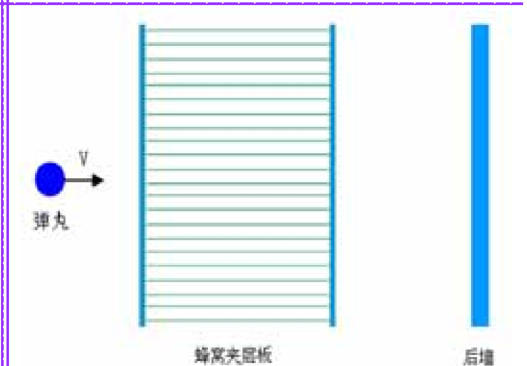
Multi-Shock Shield



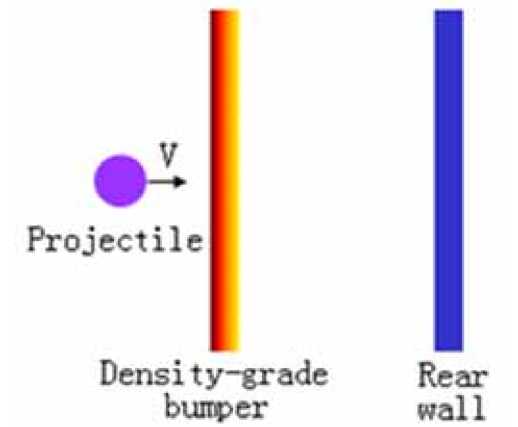
Mesh Double Bumper Shield



Stuffed Whipple Shield



Honeycomb Shield



Characters of Gong-Hou Shield：

- ✓Simple constructure；
- ✓Higher performance；
- ✓Routine materials；
- ✓Easy to be used and fixed.

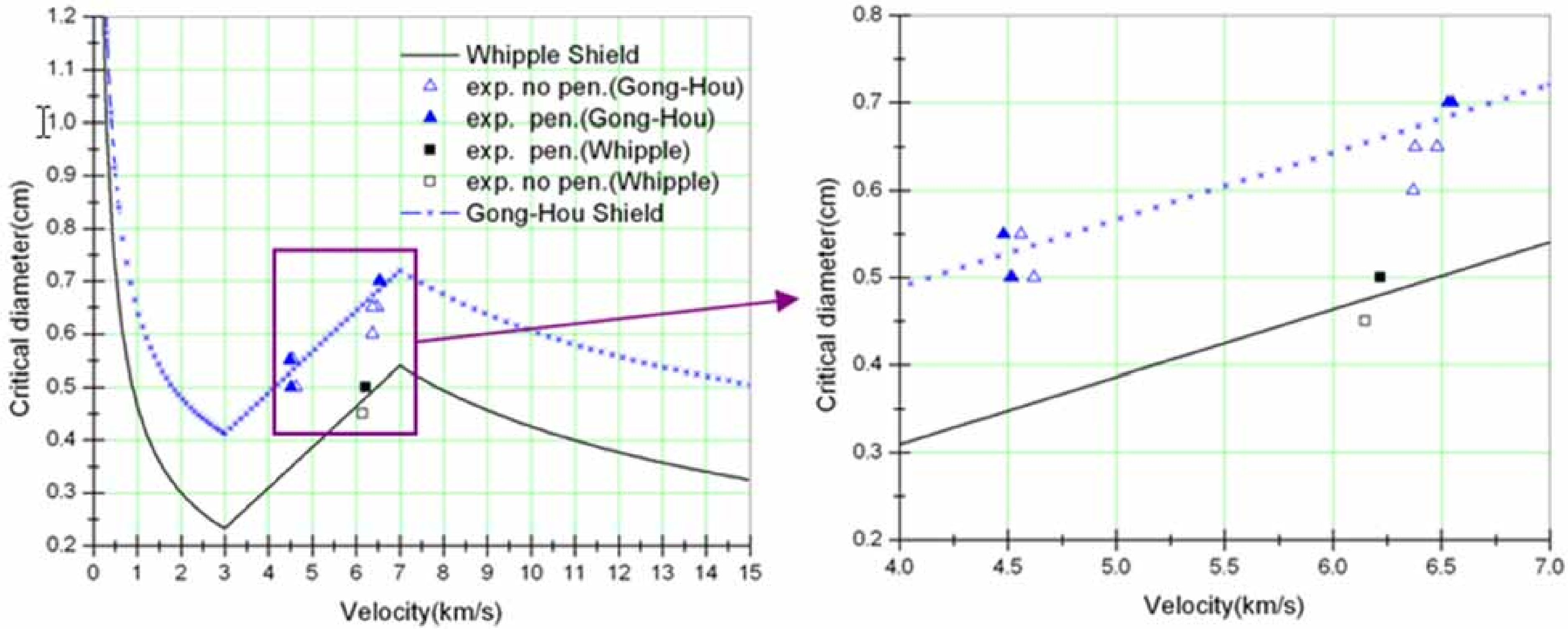
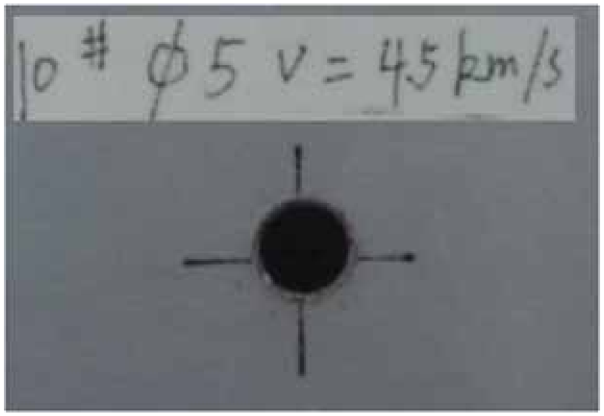
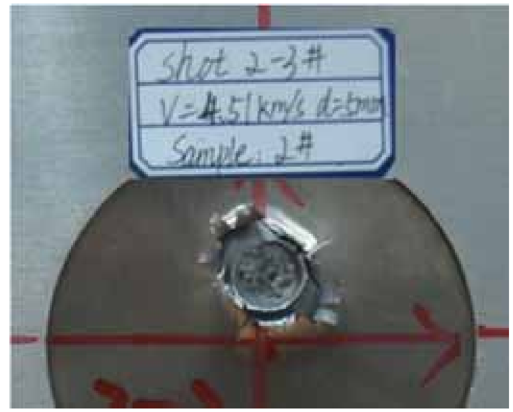


Fig. 4 Comparison between Gong-Hou Shield and Whipple Shield

The performance of Gong-Hou shield increases more than 50% at 6.4 km/s compared to Whipple shield. While at 4.5 km/s, the BL of Gong-Hou Shield increases 64%.

Image of specimens of Gong-Hou shield





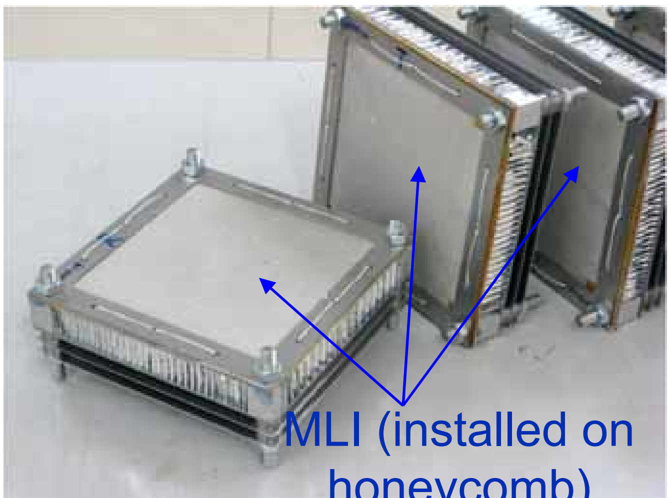
Penetration hole comparison between
Gong-Hou Shield and Whipple shield

（V=6.38km/s，d=6.5mm）

Shot 1-1#　V=6.37,　D=6.0mm

2. HVI characteristics of MLI

Multilayer Insulation Thermal Blanket (MLI） are widely used on spacecraft, which directly exposes to space environment. If it is impacted by space debris, part of its thermal protection will be lost. So it is urgent to study the HVI characteristics of MLI and promote its protection capacity against space debris.

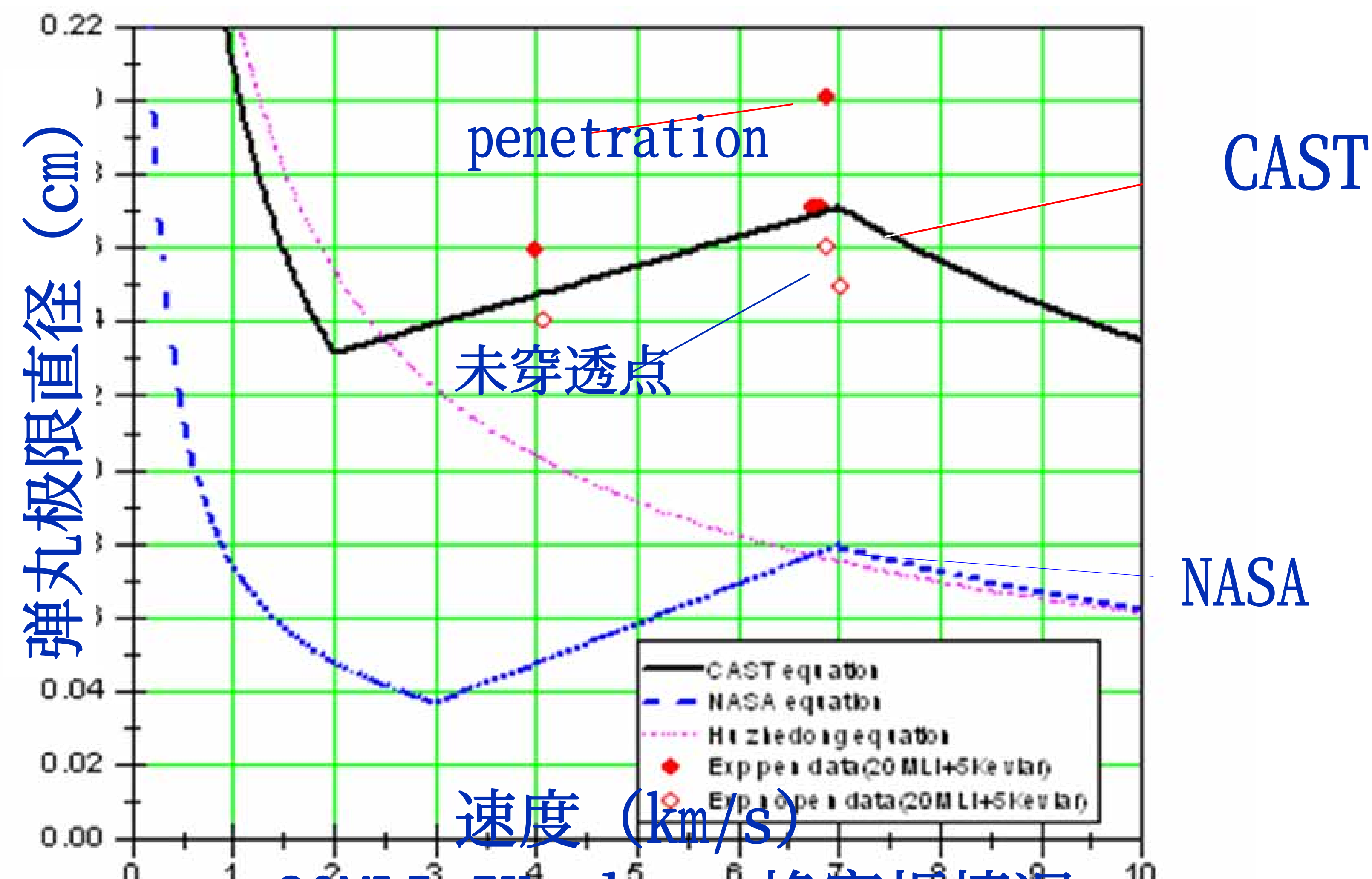


Specimen before experiment

Front: Φ4.8m

Back: Φ16.5mm hole

BLCs of honeycomb with enhanced MLI and routine MLI :



20MLI+5Kevlar +蜂窝板情况

Conclusion of HVI research on MLI:

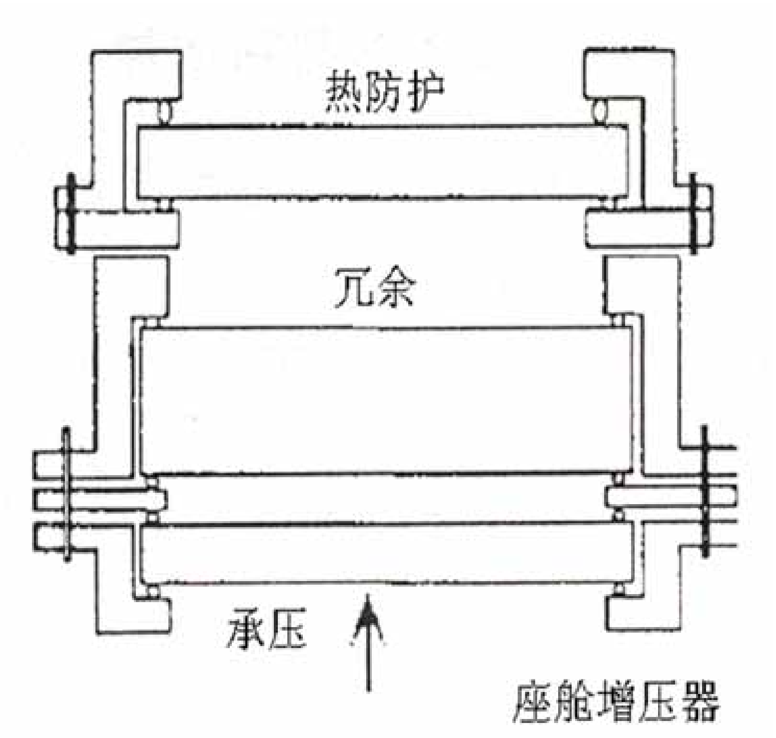
1. The experiments show that the performance of honeycomb covered with enhanced MLI increases 200% compared to the routine one.

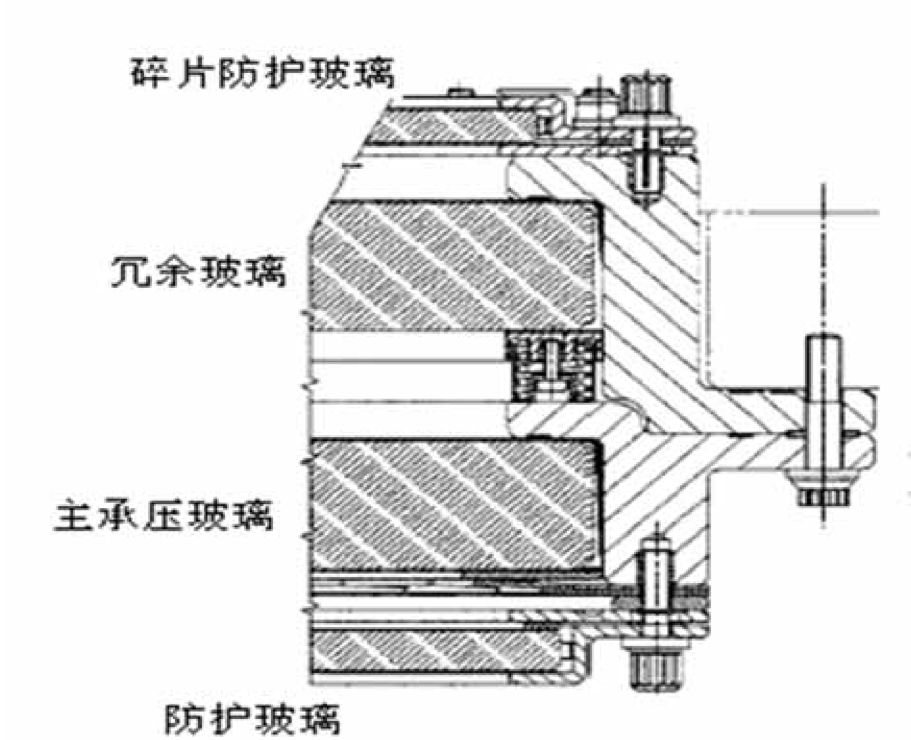
2. The BLE of honeycomb with enhanced MLI is obtained.

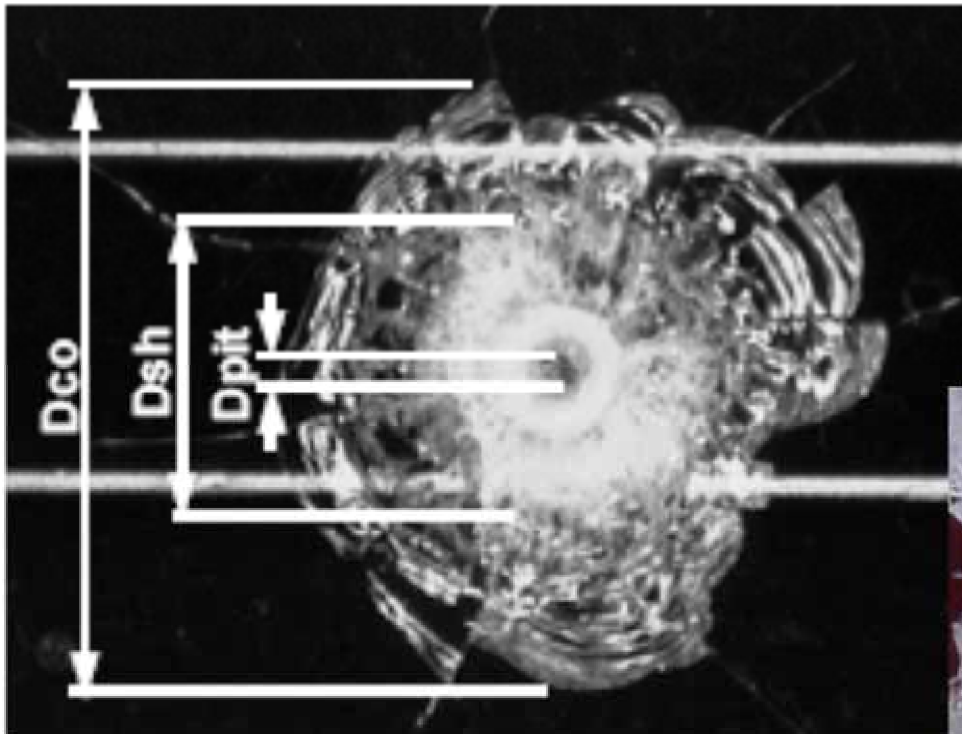
3. This kind of design is of important use in protection against space debris.

3. BLC of porthole glass

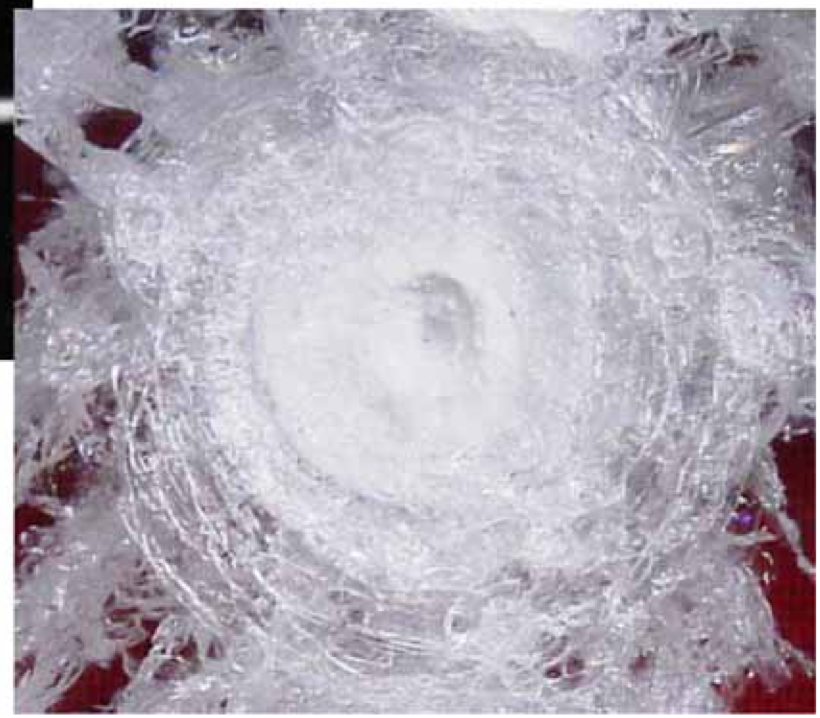
The sketch of porthole in spacecraft:



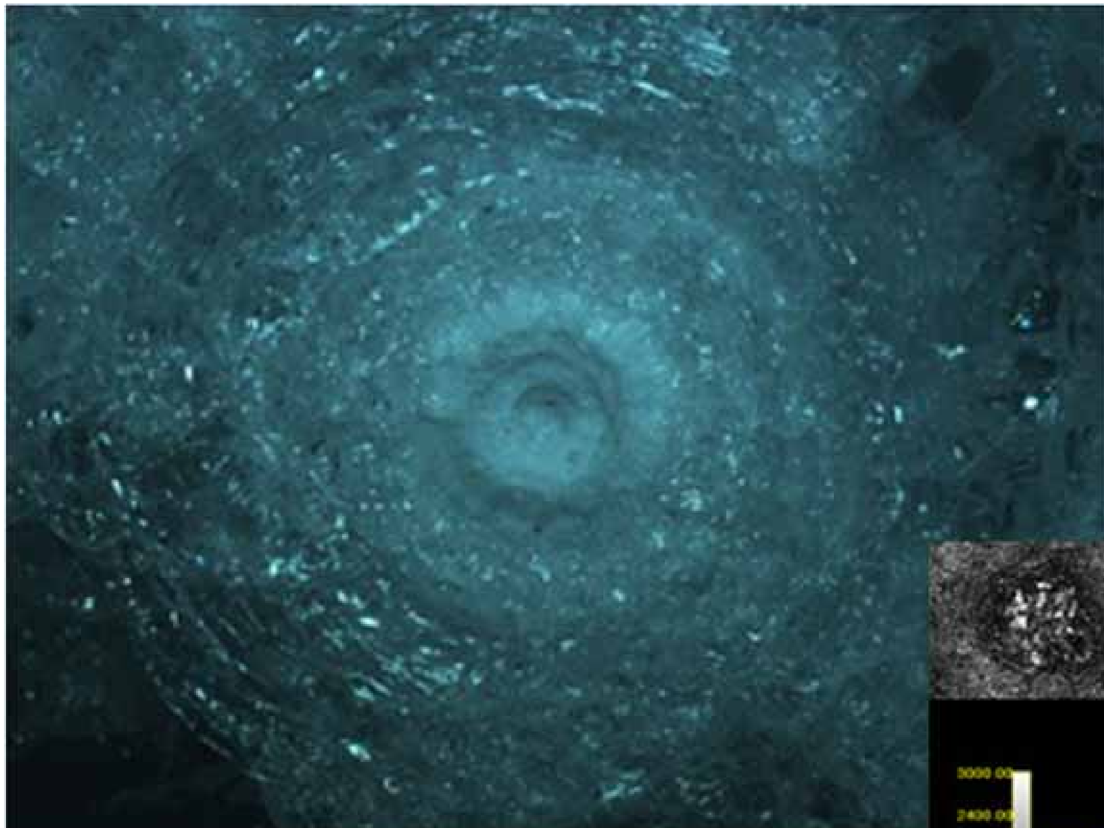


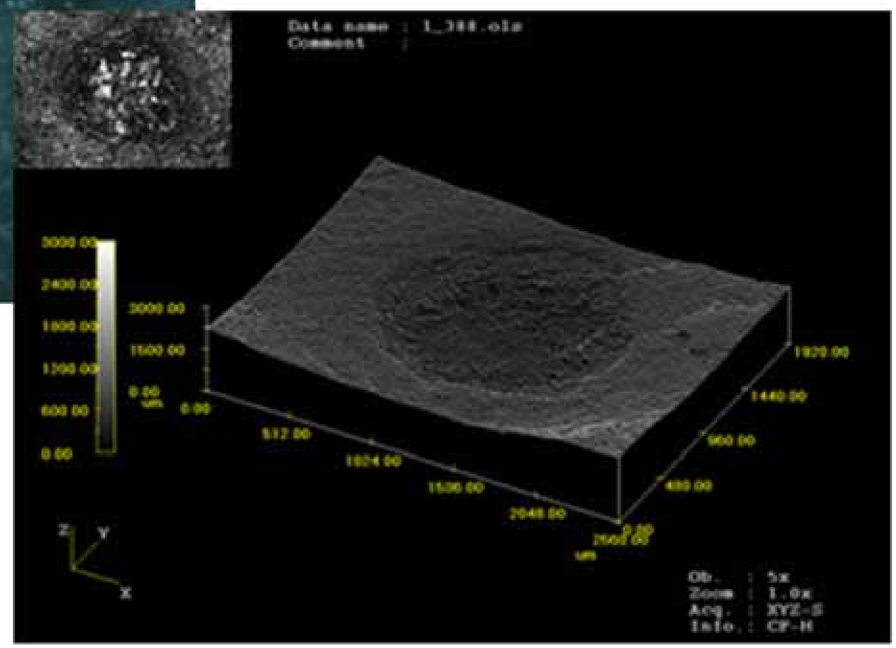


In-situ impact morphology on glass



Ground experiment result




Comment :
3000.00
2400.00
1800.00
1200.00
600.00
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2000.00
1500.00
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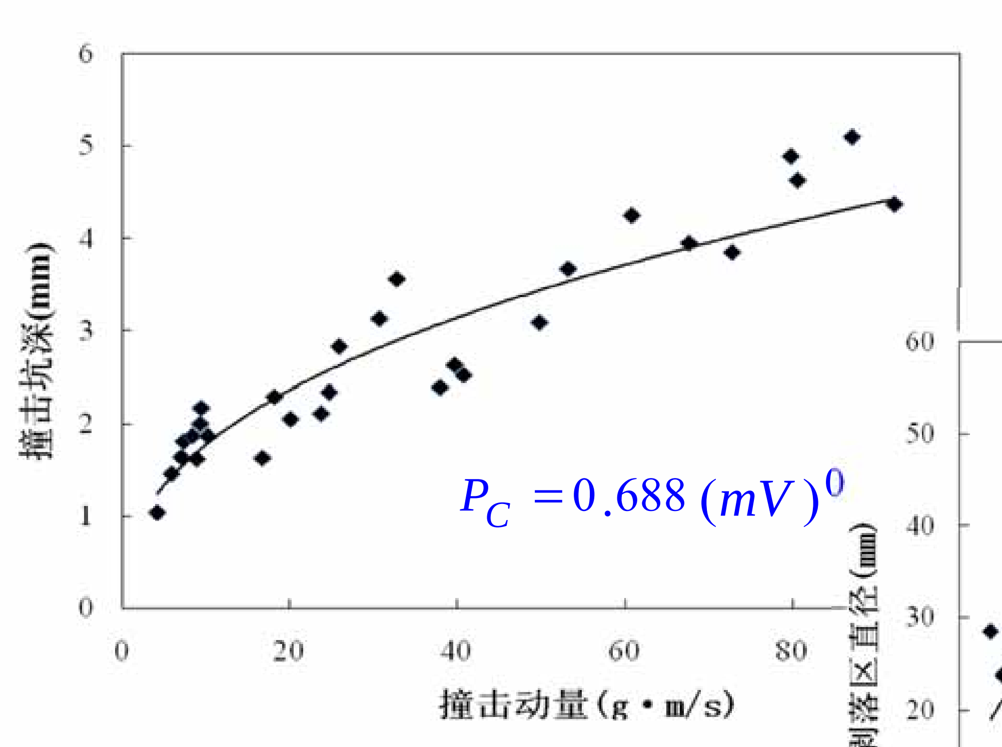
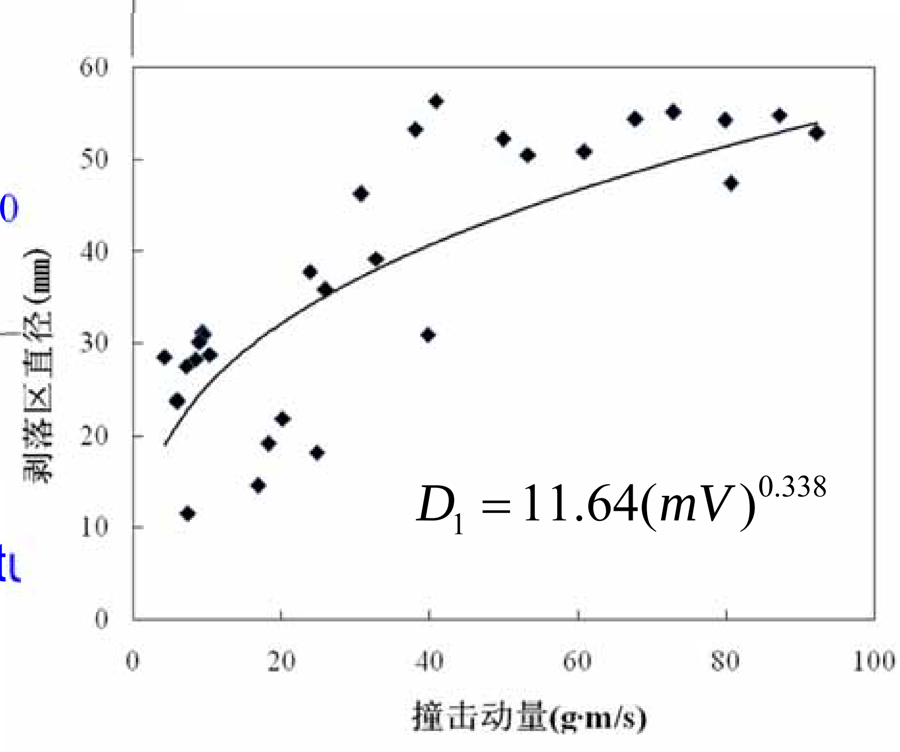
512.00
1024.00
1536.00
2048.00
um
1920.00
1440.00
960.00
480.00
Z
Y
X
Ob. : 5x
Zoom : 1.0x
Acq. : XYZ-S

撞击坑的三维形貌



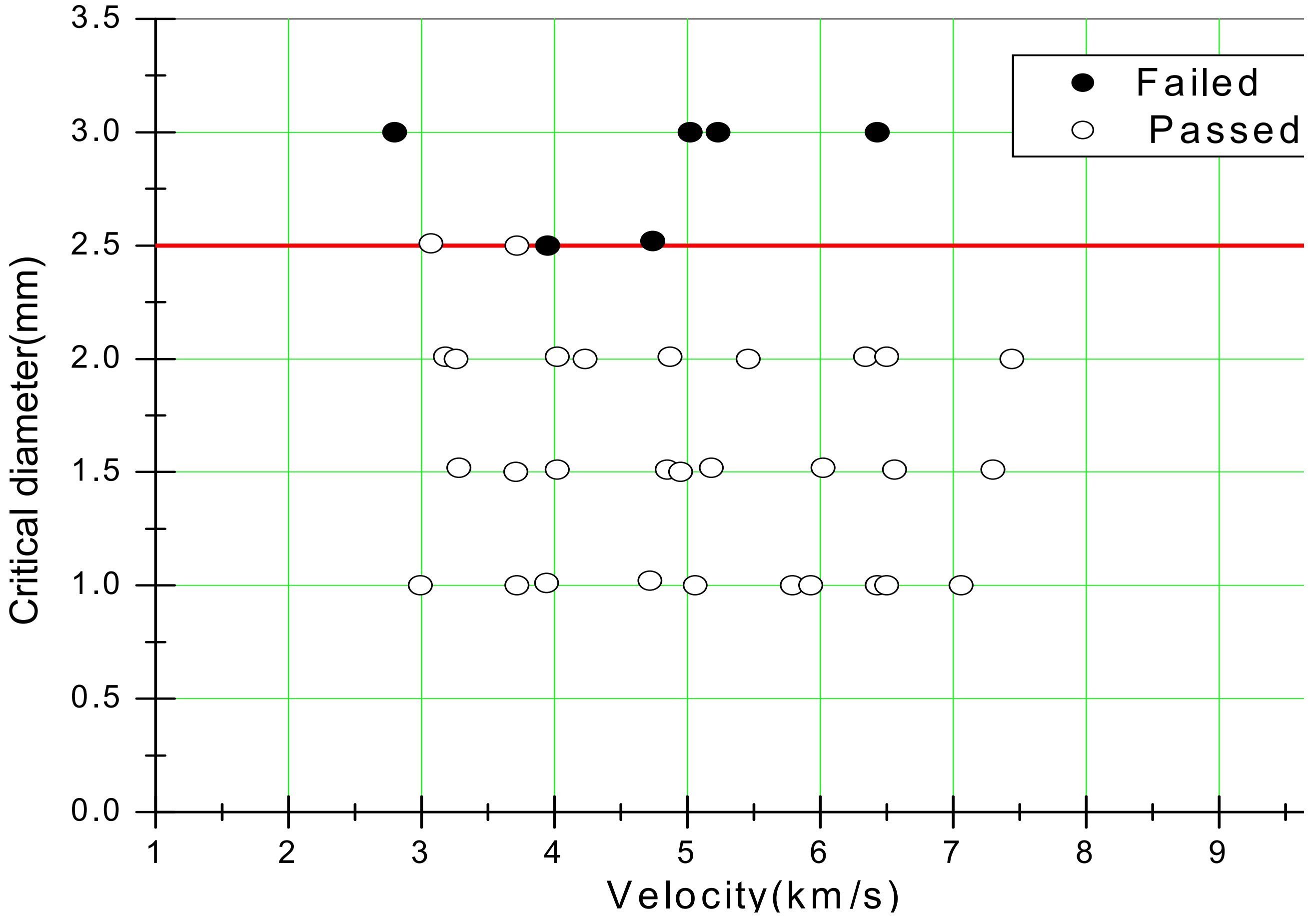
$P_C = 0.688\,(mV)^{0}$

Depth of crater versus momentu



$D_1 = 11.64(mV)^{0.338}$

Diameter of spallation versus momentum



BLC of porthole glass

Conclusion:

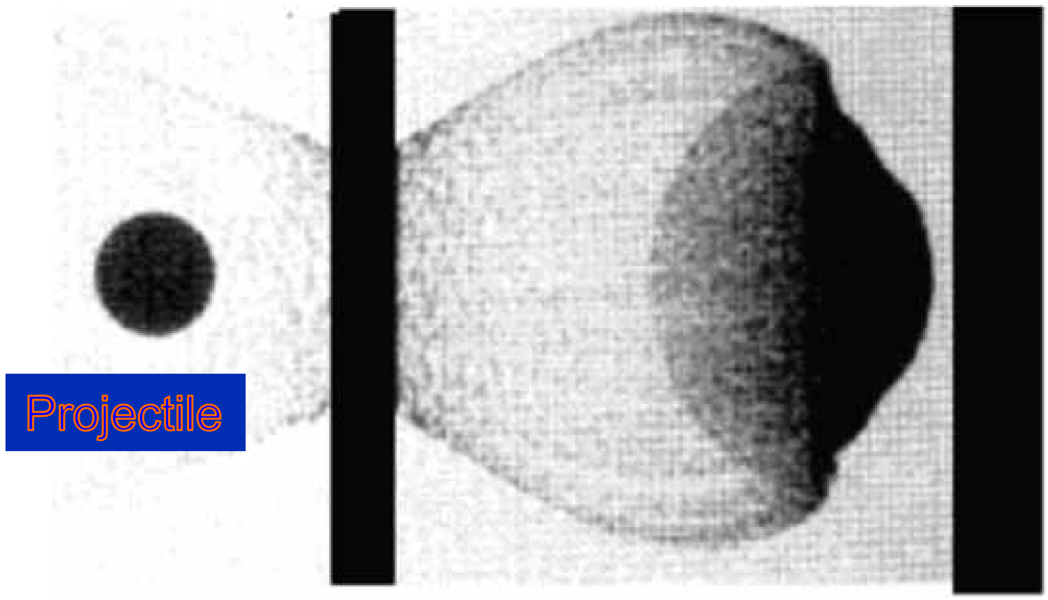
(1)The ballistic limit (BL) of fused quartz is 12mm when exposed to space debris. That is why the porthole glass of ISS and Space Shuttle was chosen to be 12mm.

(2)The BL shows that when the diameter of projectile is larger than 2.5mm, the 12mm glass can be penetrated, otherwise, it can’t. That mean the BL of 12mm glass is 2.5mm.

(3) The risk assessment show that, the impact possibility of space station by debris larger than 2.5mm is less than 1. So 12mm glass can enable to protect spacecraft.

4. Debris cloud model

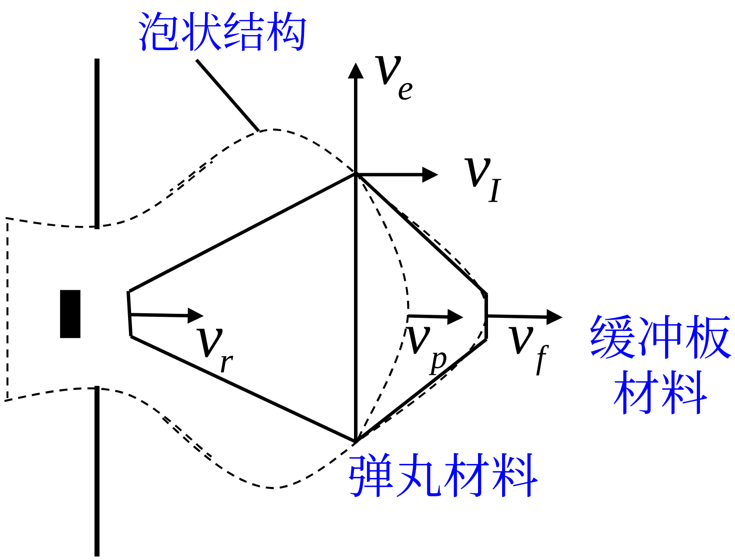
Classical morphology of debris cloud:



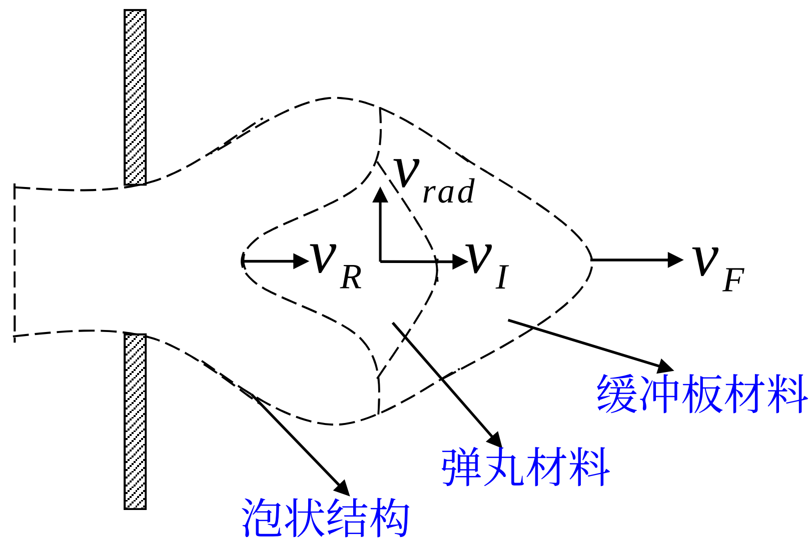
Bumper Debris cloud Rear wall

Debris cloud model is need to founded to analyze the characters of debris cloud and predict the damage of rear wall, so as to help to found ballistic limit equation of shield.

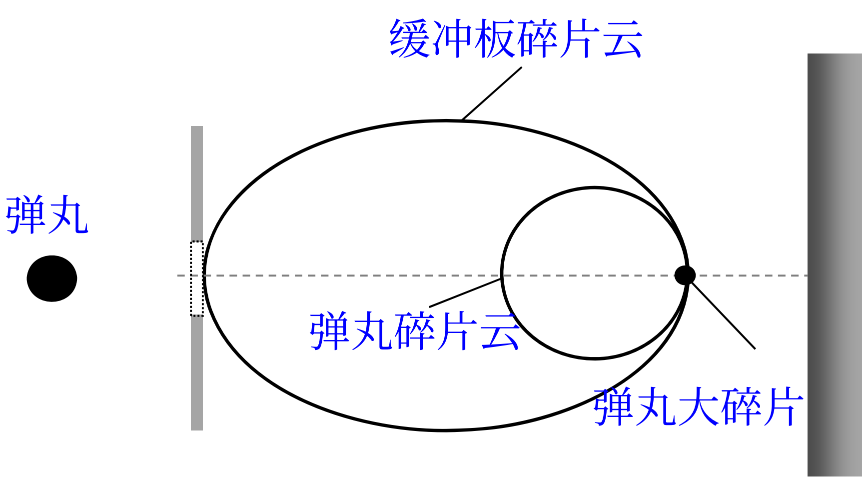
The existed models:



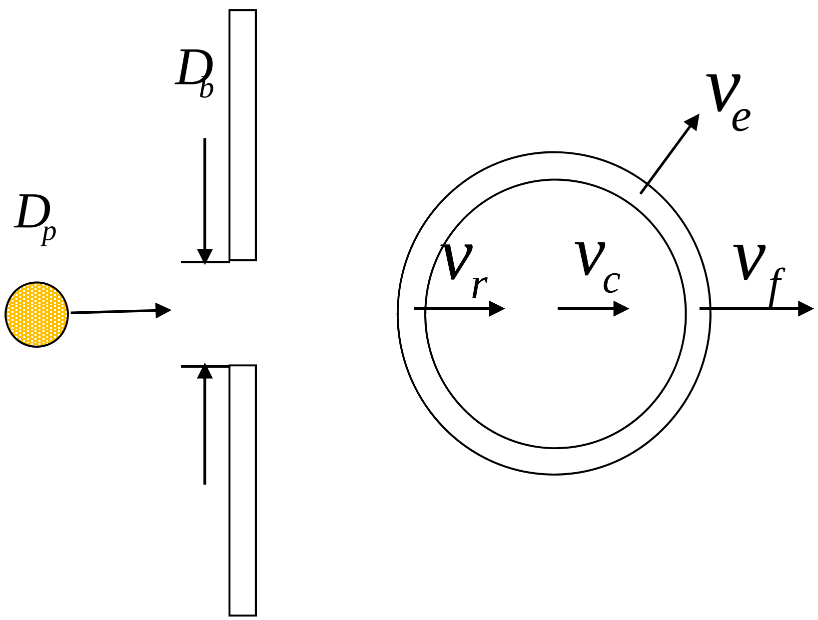
Piekutowski model



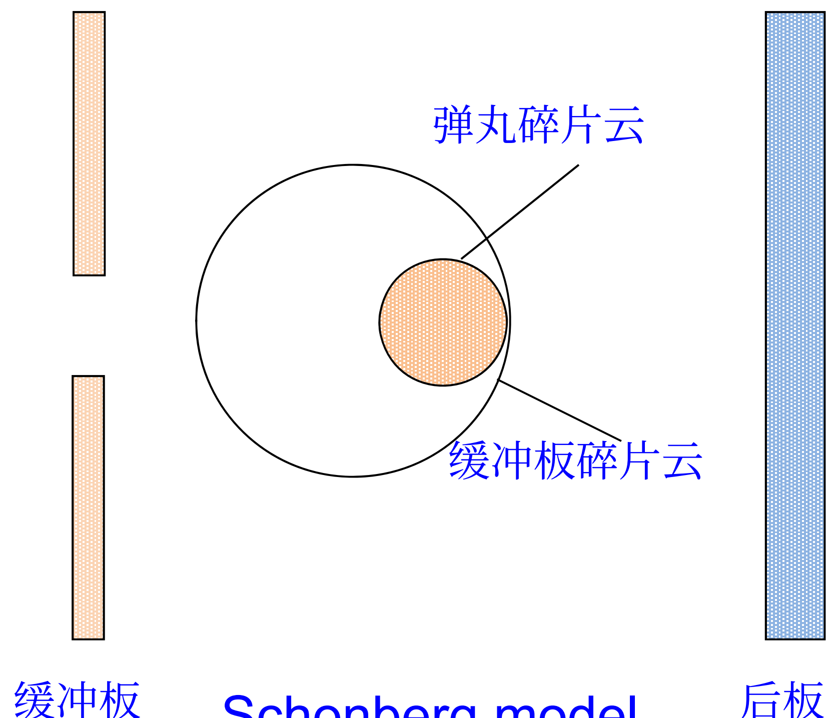
First-principle model



Schäfer model

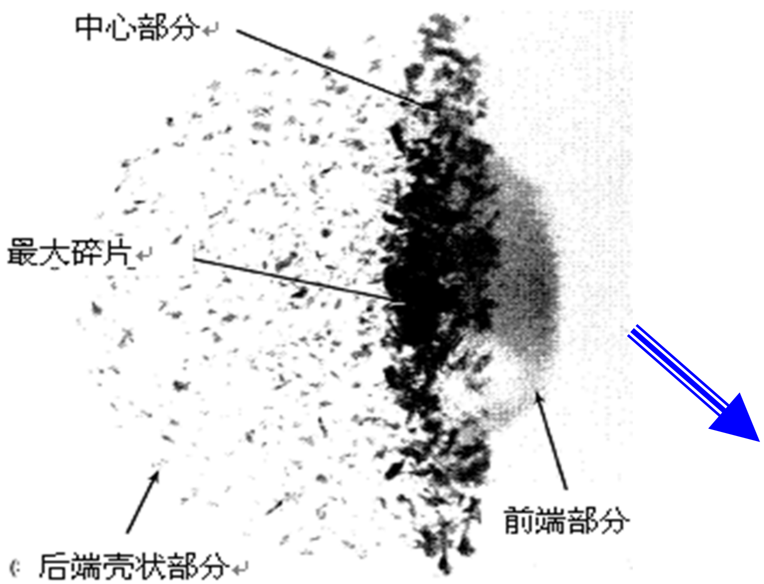


Swift model

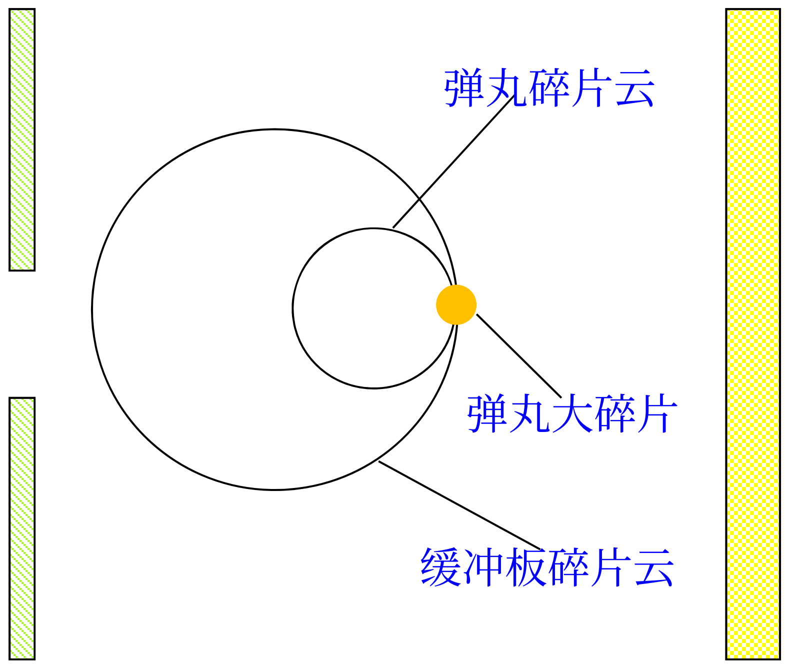


Schonberg model

Our work:

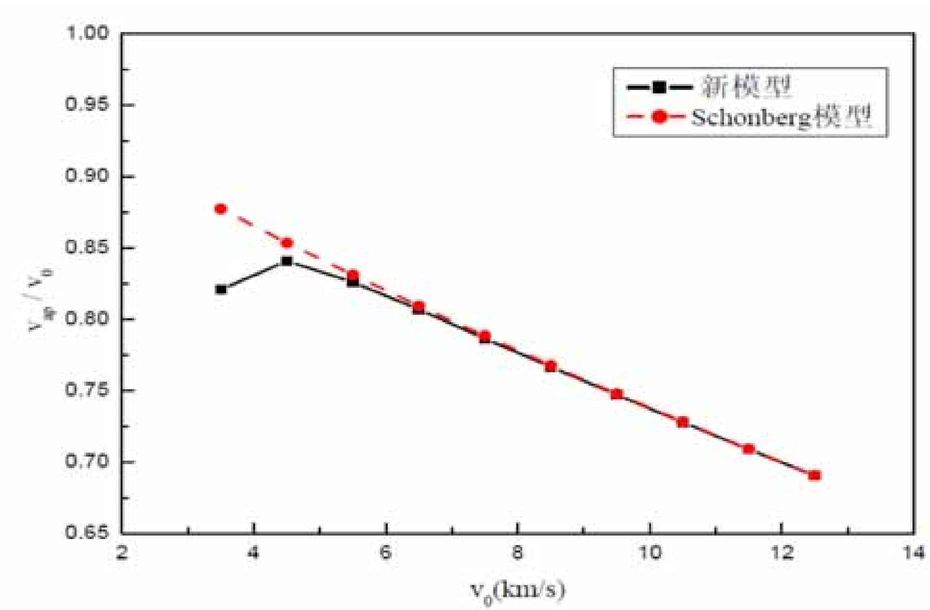


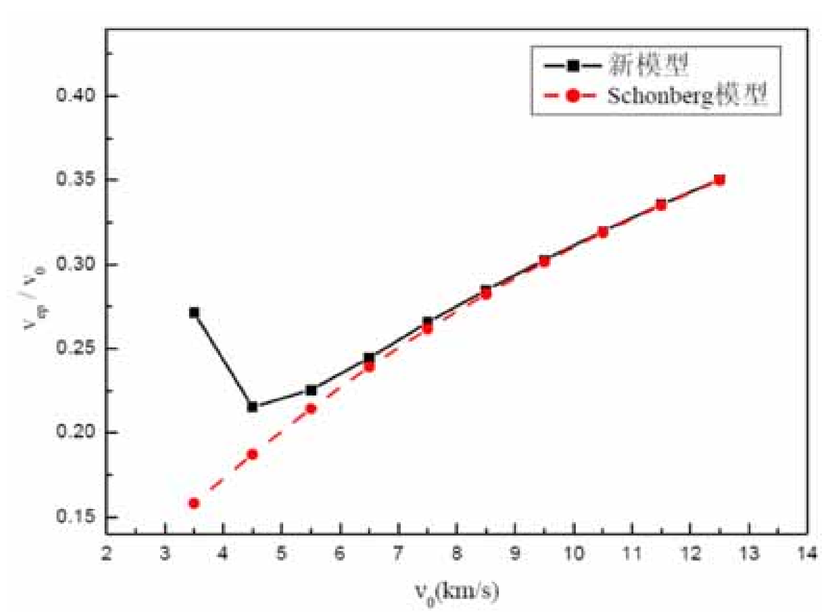
X-ray image of debris cloud



The new debris cloud model

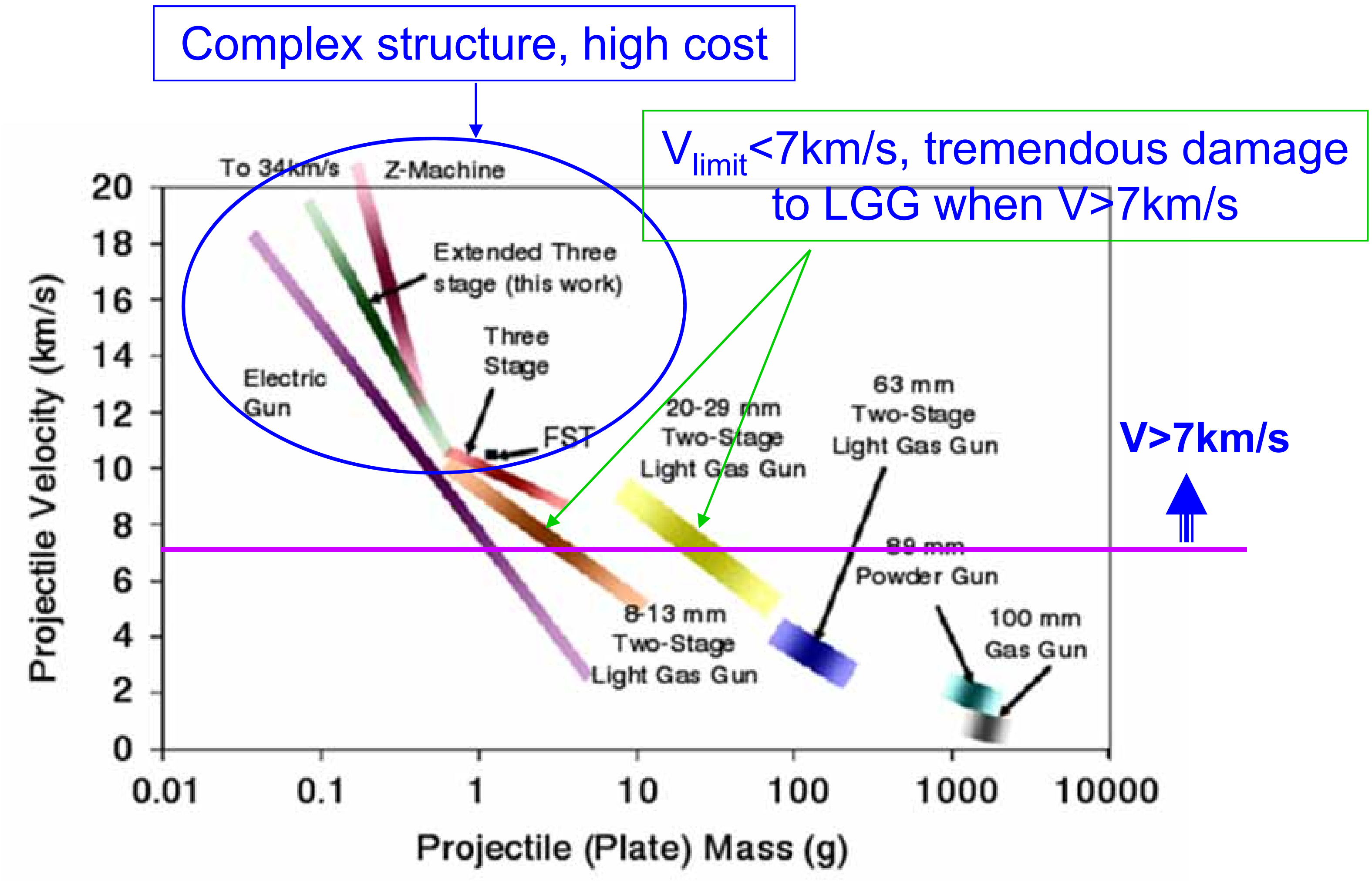
Verification:





The results of new model show that V_{ap}/V_0 and Vcp/V_0 are identical with Schonberg after 4.5km/s

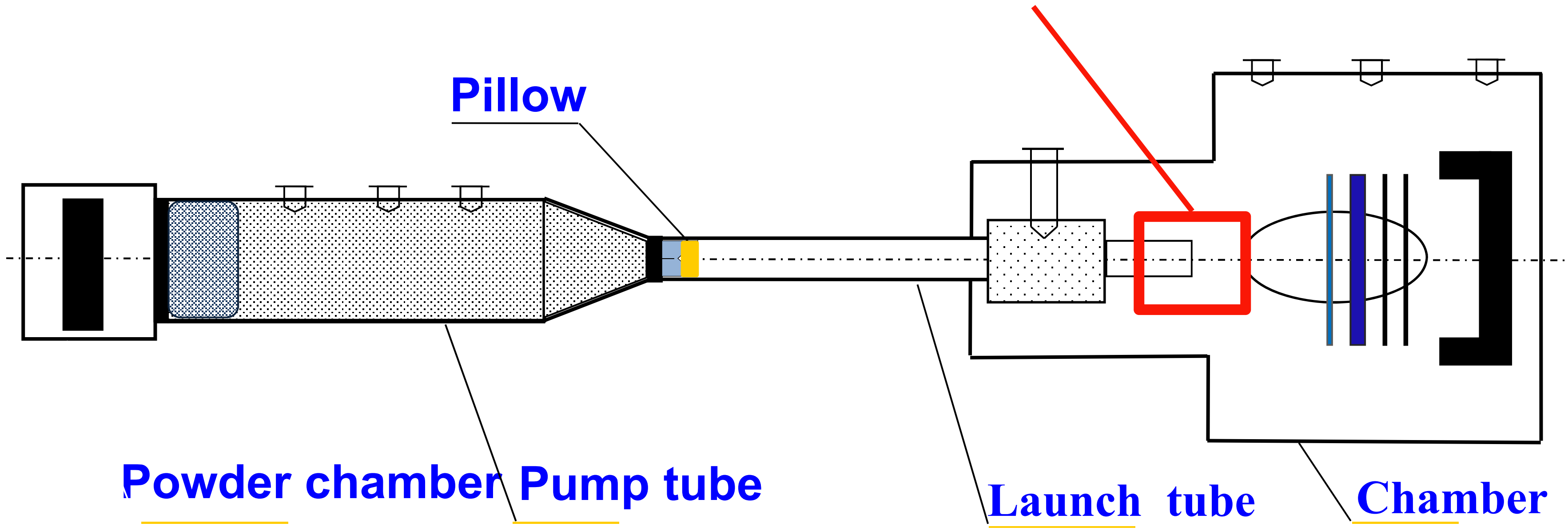
77. Hypervelocity launch technique (V>7km/s)



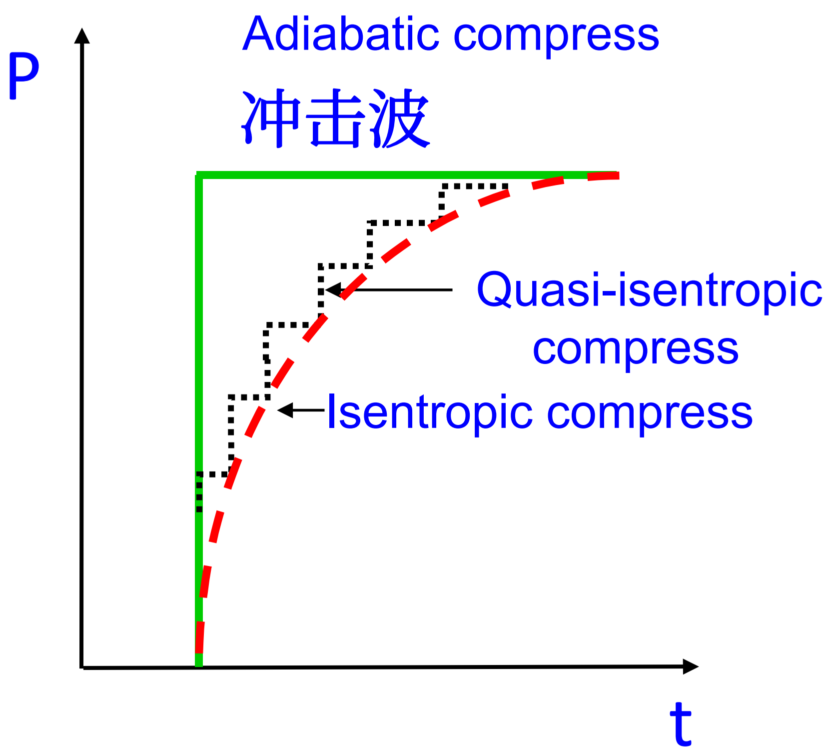
Mass versus velocity of several launch instruments

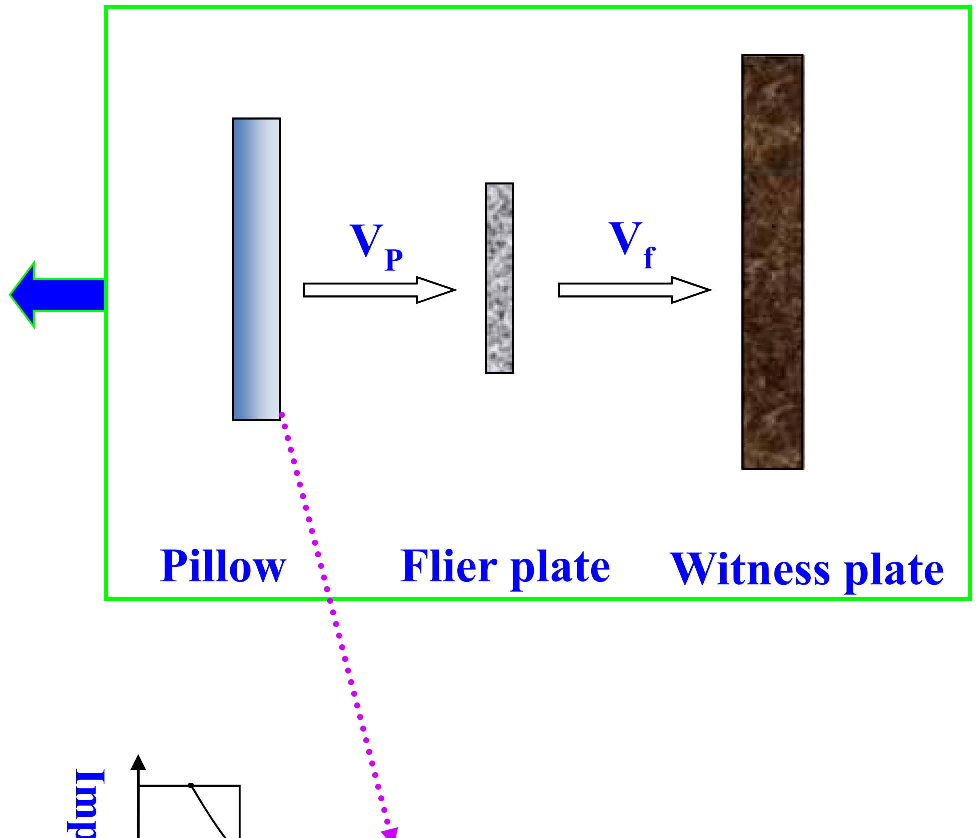
Configuration of pillow:

Add an extra device on LGG, in which pillow will impact flier-plate. The flier-plate can reach ~16km/s.

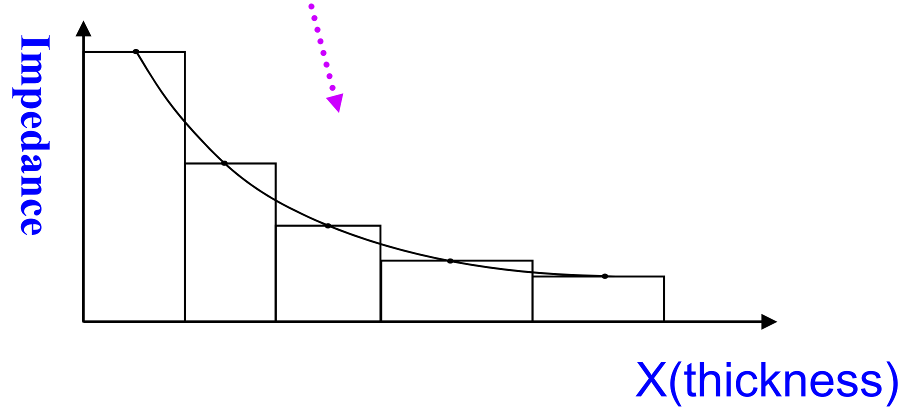


Quasi-isentropic compress:

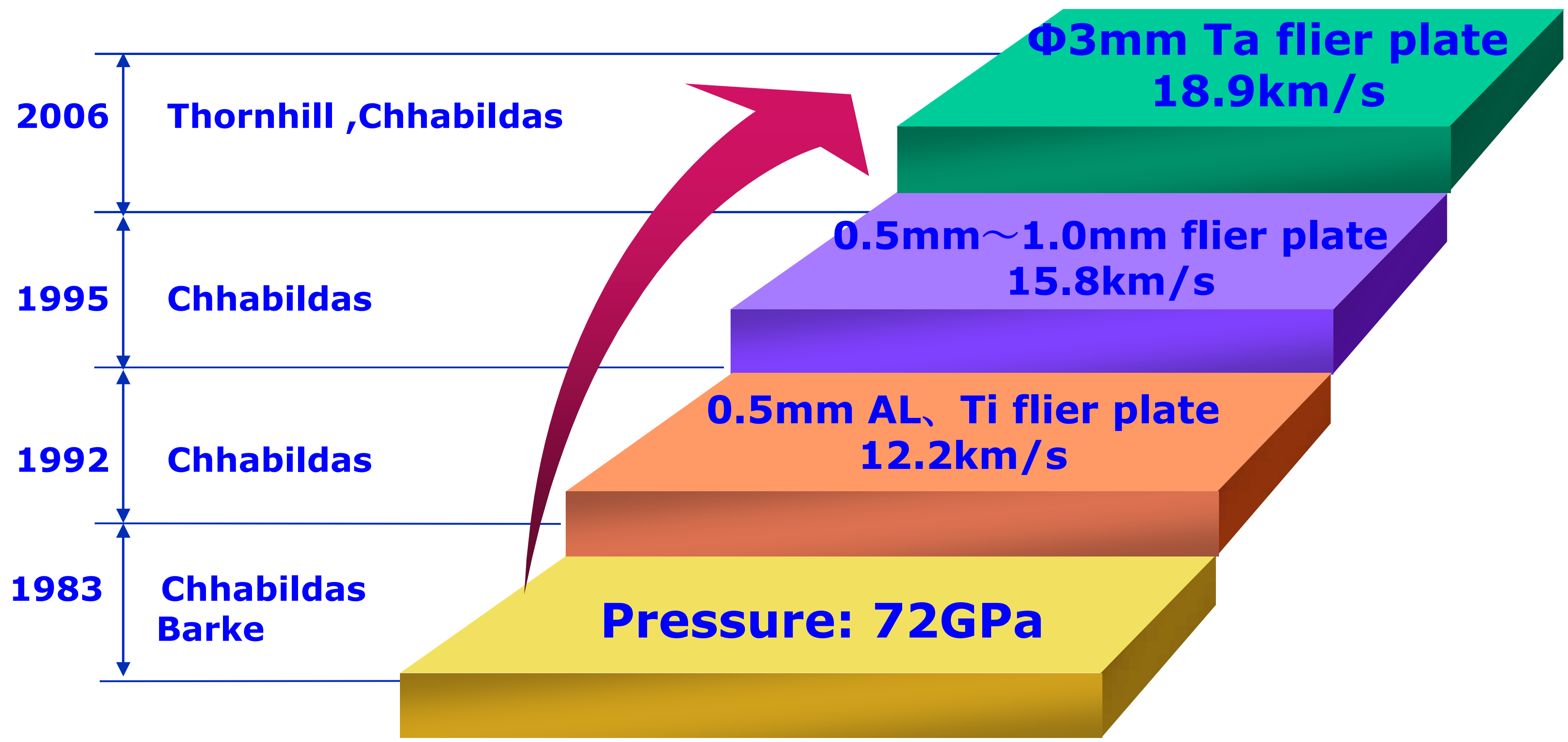




$$Z(x) = Z_0 + A(x/d)^P$$



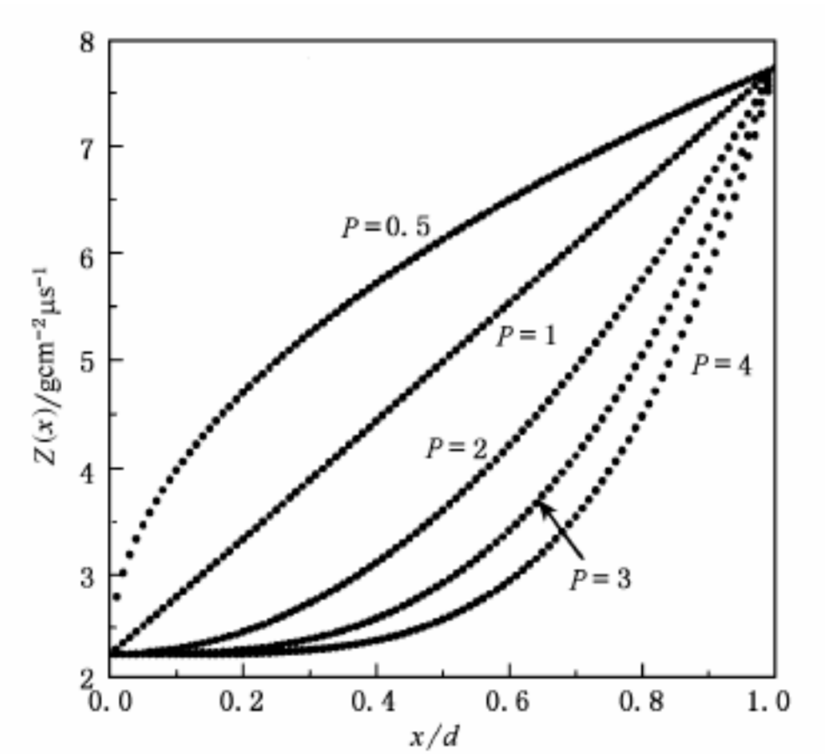
Pillow technique progress

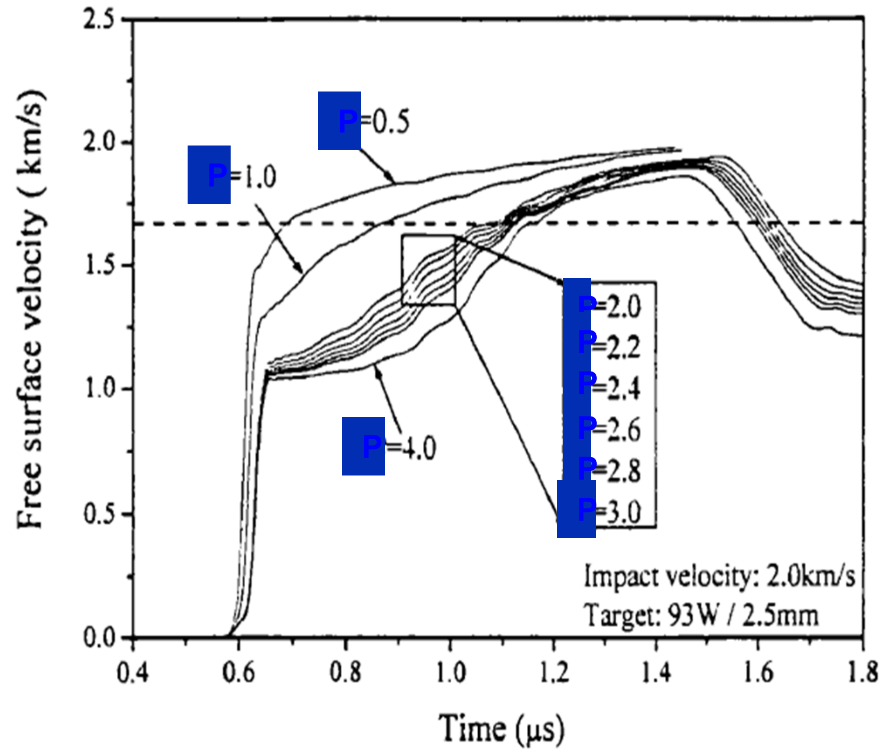


Design of Pillow:

$$Z(x) = Z_0 + A(x/d)^P$$

P=2: Best



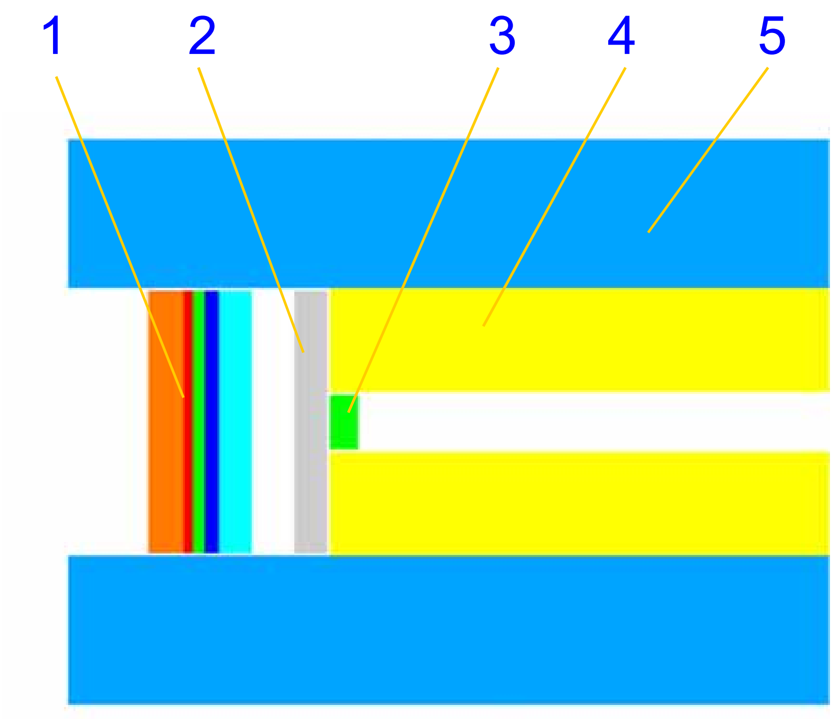


Different P and their impact pressure

Our work:

Material	Thick (mm)	Density (g/cm^3)	C_0 (km/s)	Impedance ($\times 10^9 g/m^2 s$)
93W	1.3	17.64	4.005	70.648
OFC	0.4	8.93	3.96	35.363
TC_4	0.4	4.45	4.695	20.893
Al	0.6	2.70	5.328	14.386
MB_2	1.2	1.77	4.500	7.965

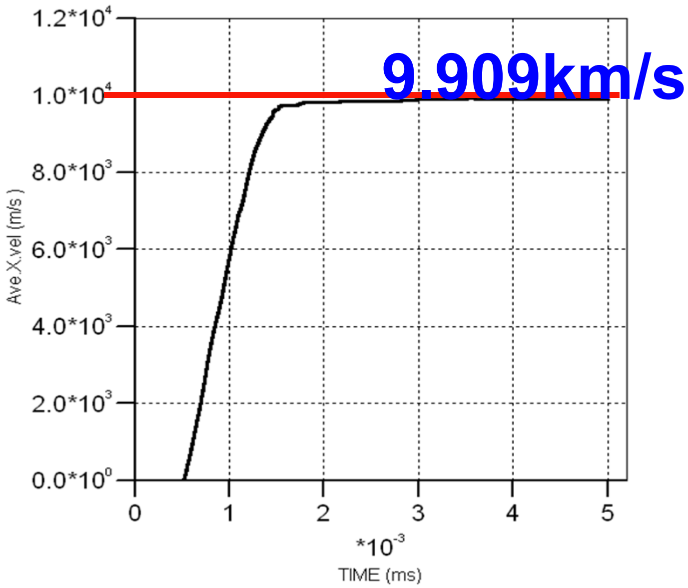
Simulation model:



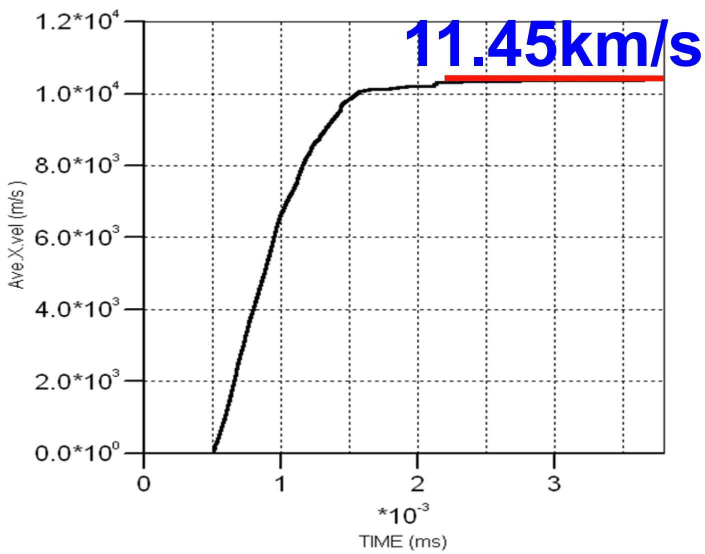
1—Pillow
2—bumper
3—Flier plate
4—inner tube
5—Launch tube

Bumper material effect:

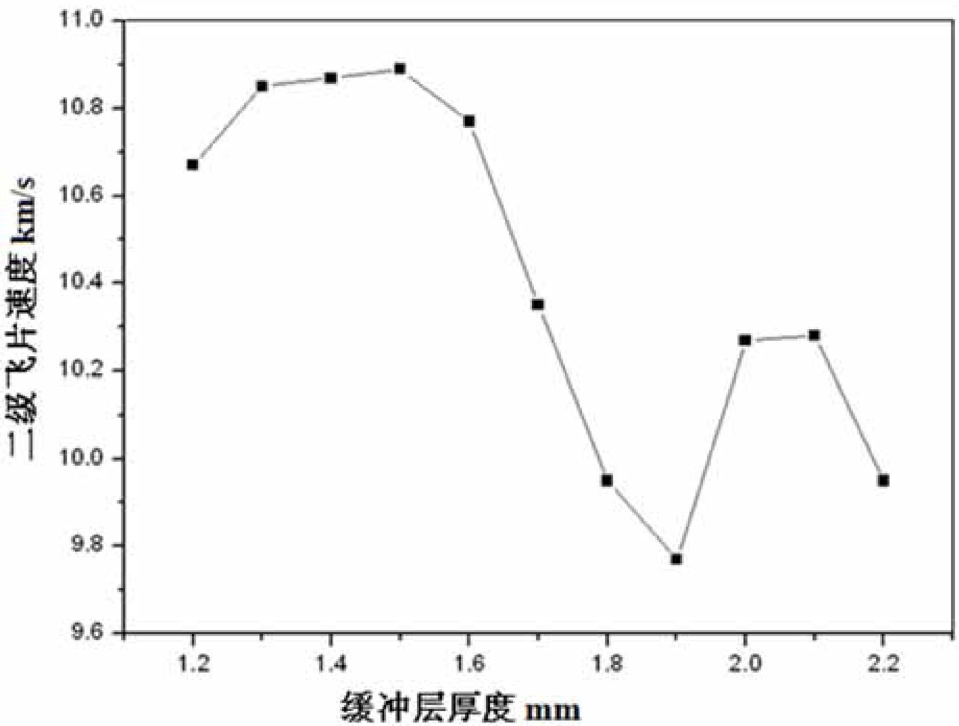
Lexan



TPX



Cushion thickness effect:



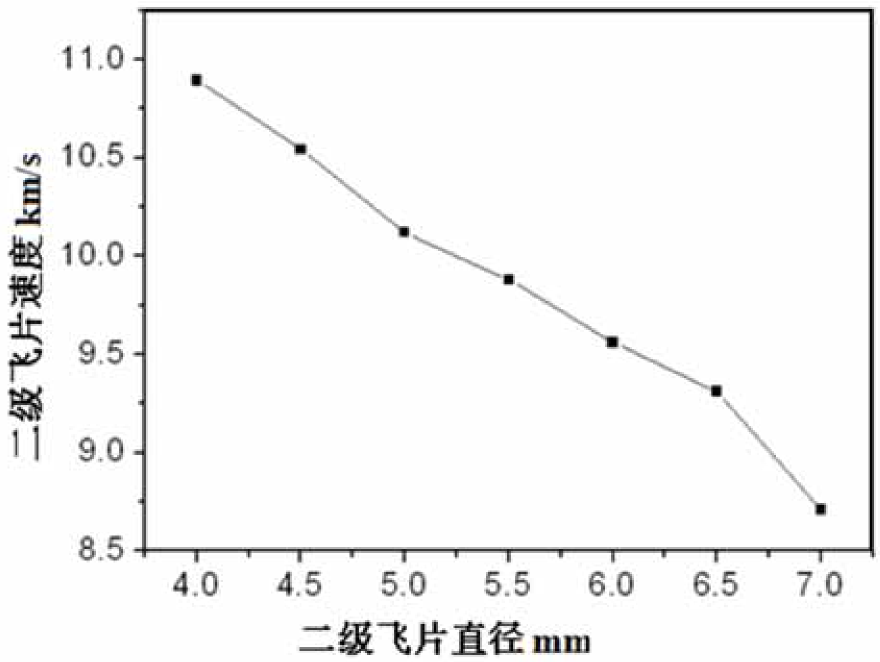
Velocity of flier plate versus bumper thickness

Vp=5km/s:

◆t_{bumper}≤1.1mm or t_{bumper}≥2.3mm, flier plate breaks up.

◆1.8mm≤ t_{TPX}≤2.2mm, flier plate bends.

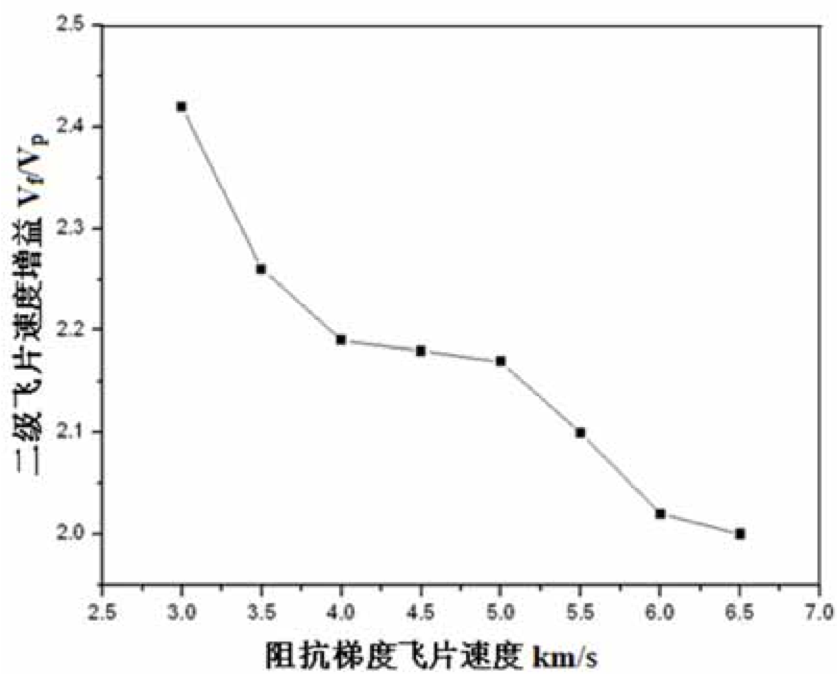
Influence of flier plate diameter to its velocity:



Vp=5km/s:

- **$D_f \leq 4$mm, flier plate breaks up;**
- **Velocity decreases when the diameter of flier plate increases.**

Velocity of Pillow and V_f/V_p:



- ◆V_f/V_p decreases as a function of velocity of Pillow ;
- ◆The quasi-isentropic compress effect decrease as the pillow velocity increases.

Conclution：

1 TPX is a better bumper material compared to lexan. (best thickness:1.5mm)

2 Ti flier palte：Φ4mm×1mm

3 Maximum velocity: 13.01km/s

8. Shape effects of projectile during HVI

Debris shape:

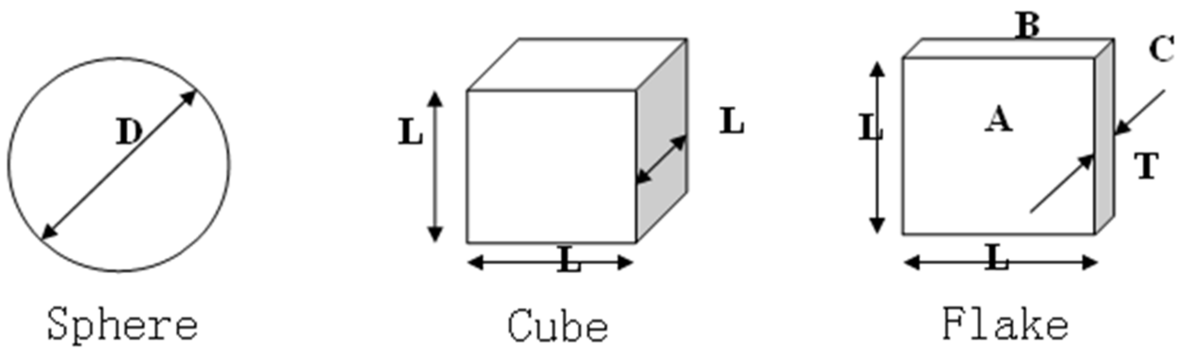
Table: Distribution of fragment shapes from satellite orbital characterization impact test (SOCIT) experiment.

Shape	1	2	3	4	5	6	7	8	9	10
Number of fragments	36	60	15	1	628	96	12	2	1112	2799
Among the 112 largest fragments	9	33	10	0	0	0	2	2	56	0
Among the rest of smaller fragments	27	27	5	1	628	96	10	0	1056	2799
Shapes:1=Flat plate; 2=Curled plate; 3=Box; 4=Sphere; 5=Flake; 6=Rod; 7=Cylinder; 8=Box and plate; 9=Other;10=Nugget (cube).										

Sphere: 0.02% Flake: 13.19% Other: 23.43% Cube: 58.79%

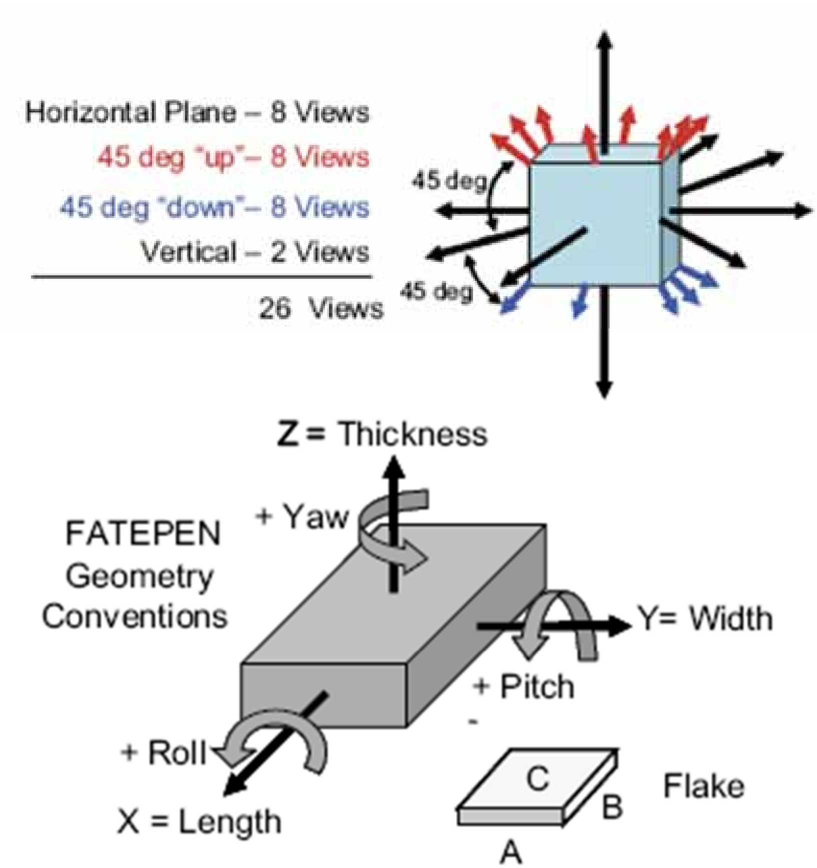
The chosen shape:

sphere (standard shape), cube, and flake



Characteristic length (based onRadar Cross Section):

Shape	Calculation function for L_C
Sphere	$L_C = D$
Cube	$Lc = \frac{L}{3}(\sqrt{3} + \frac{2\sqrt{6}}{3} + \sqrt{2})$
Flake	$Lc = \frac{1}{3}(\sqrt{2L^2 + T^2} + \frac{2L\sqrt{L^2 + T^2}}{\sqrt{2L^2 + T^2}} + \frac{2LT}{\sqrt{L^2 + T^2}})$



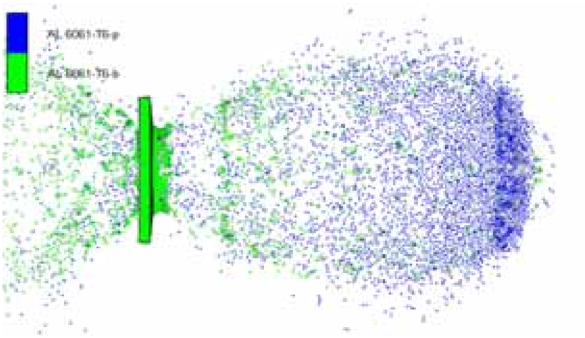
Normal Target Impacts

Cube Case	X	Y	Z	Freq.
Face On	0	0	0	6/26
Edge On	0	45	0	12/26
Point On	0	45	45	8/26

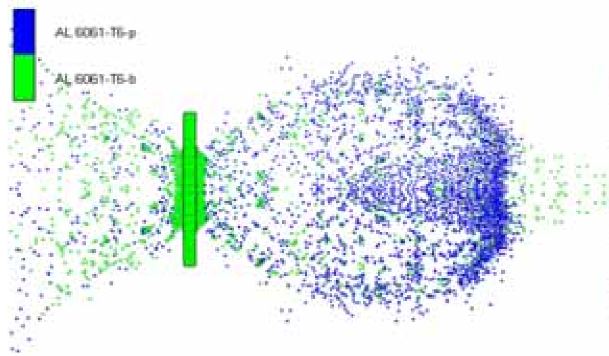
Flake Case	X	Y	Z	Freq.
Face (C)	0	90	0	2/26
Edge (A or B)	0	0	0	4/26
Point (A-B)	0	0	45	4/26
Edge A-C	0	45	0	8/26
Point A-B-C	0	45	45	8/26

Orientations considered using the 26-view methodology

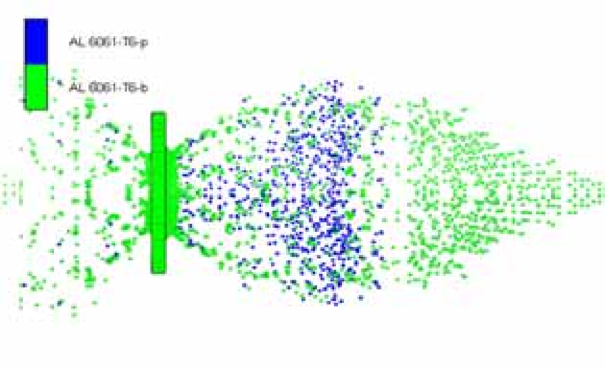
Image of debris cloud



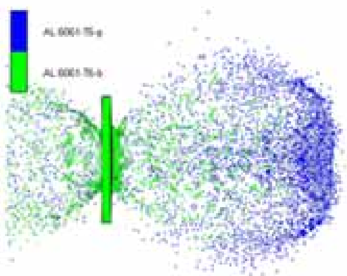
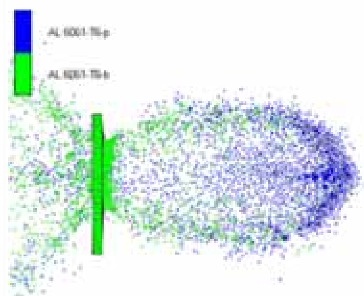
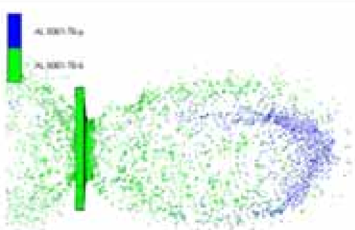
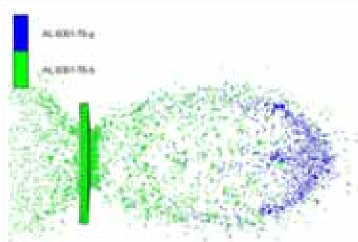
Sphere



Cube (face)



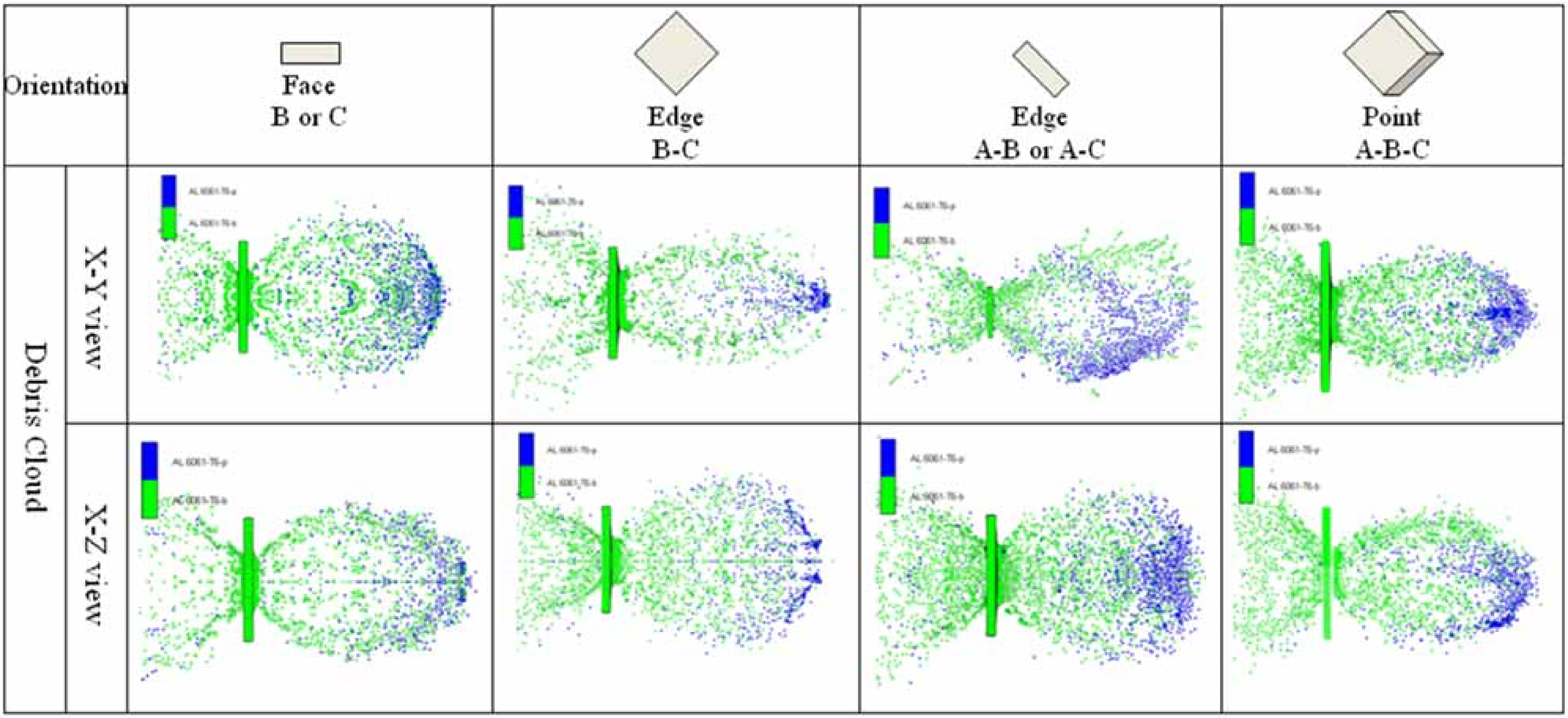
Flake (face)

Orientation	Debris cloud	
	X-Y view	X-Z view
 Edge		
 Point		

Orientation effect of Cube projectile during hypervelocity impact.

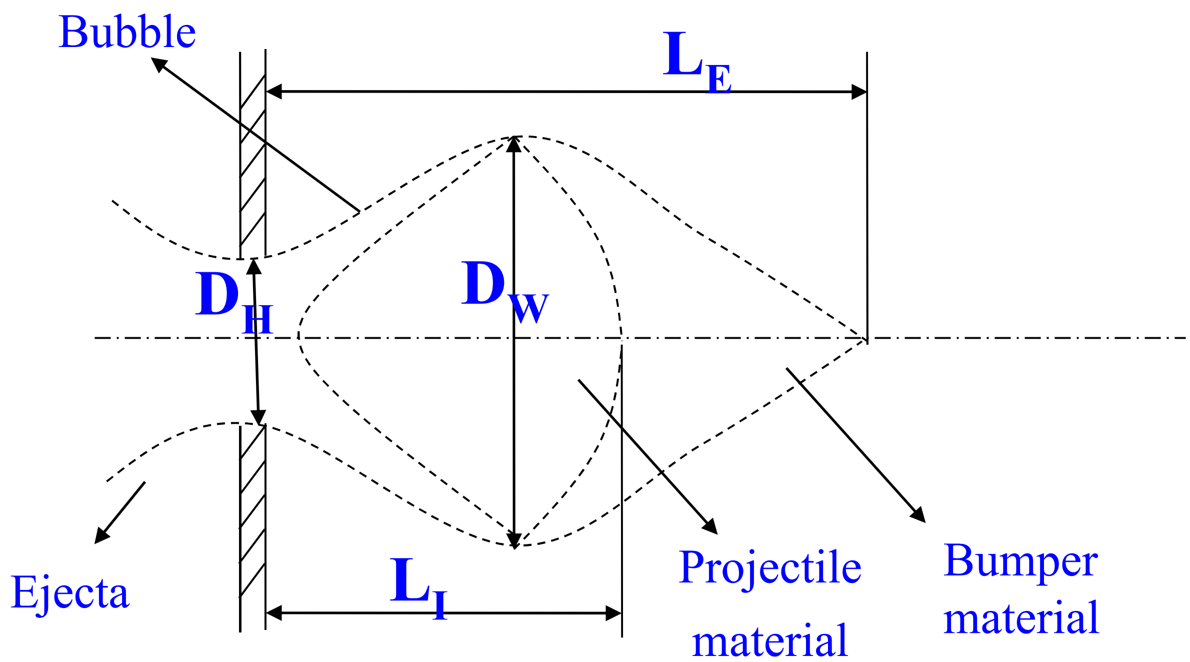
Debris cloud takes on different shapes.

Orientation effect of Flake projectile during hypervelocity impact.



Debris cloud takes on different shapes

Characteristic parameters of debris cloud:



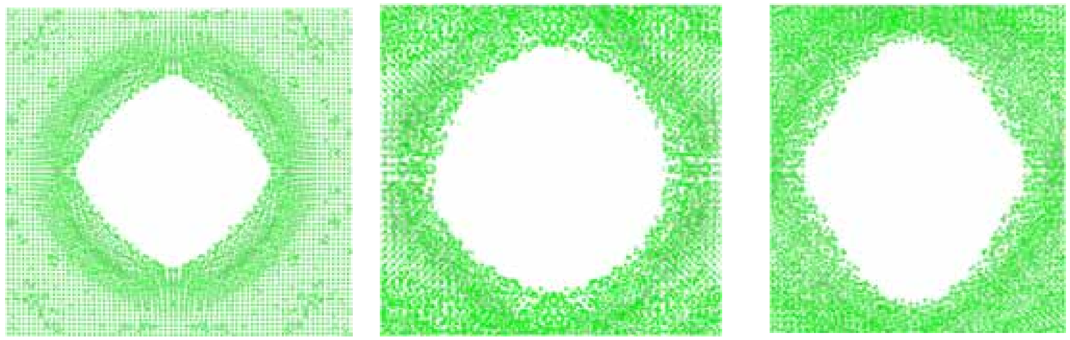
D_W: radical wideness;

L_E: expanding length;

L_I: interface of projectile and bumper fragment.

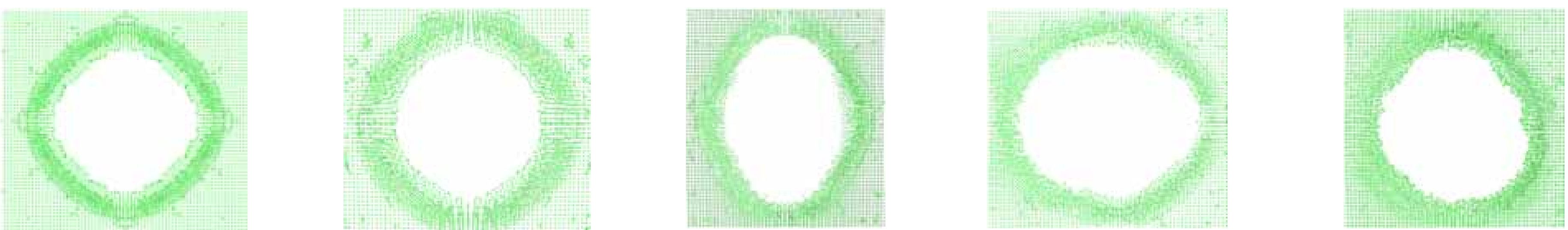
Penetration in bumper:

V=5km/s;
Cube projectile



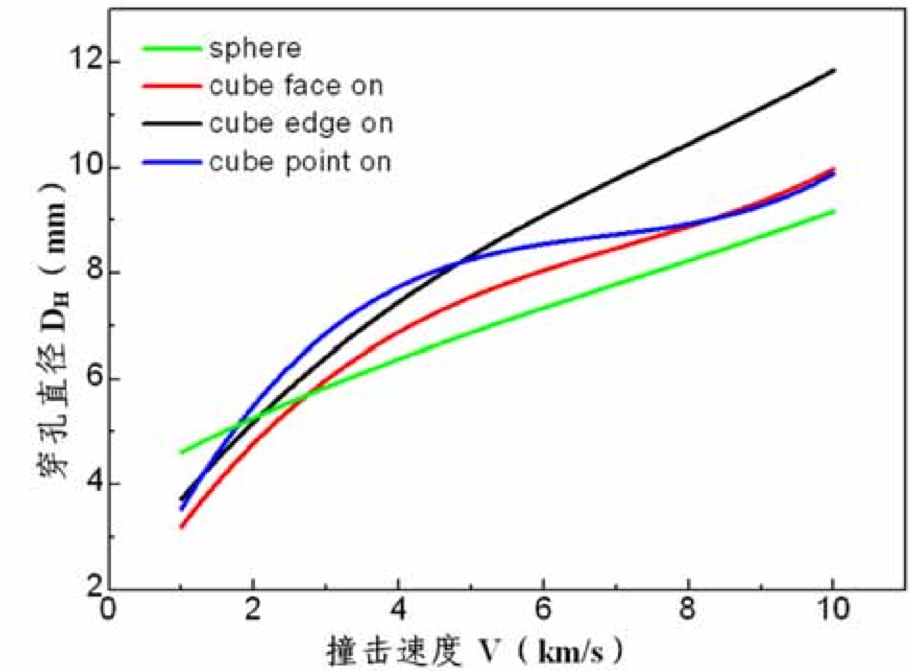
Face edge point

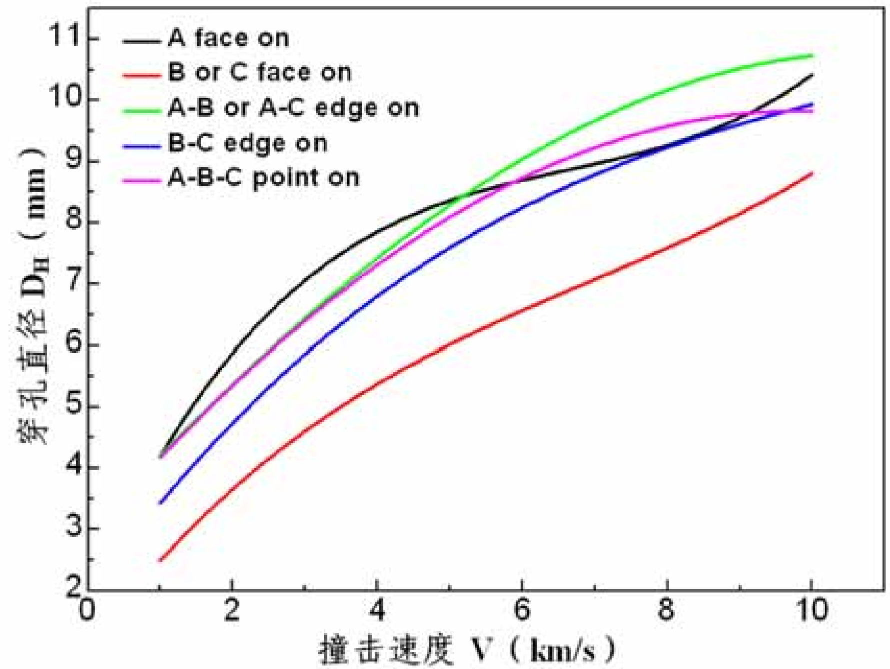
V=5km/s;
Flake projectile



Face (A) Face (B or C) Edge(B-C) Edge(A-B or A-C) Point (A-B-C)

Diameter of penetration in bumper:



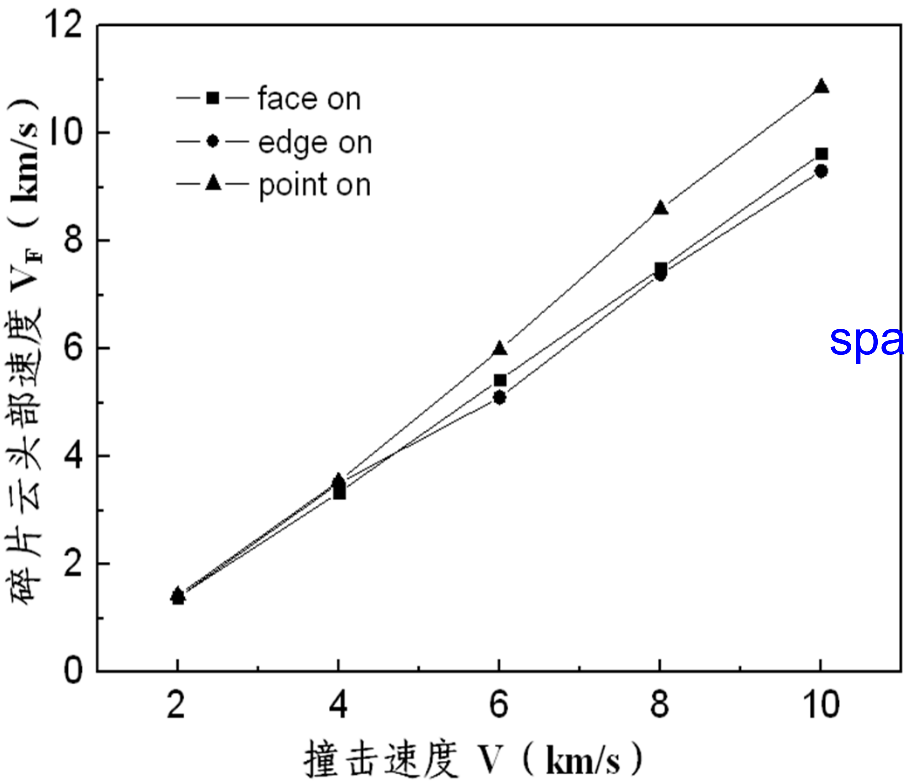


Sphere and Cube

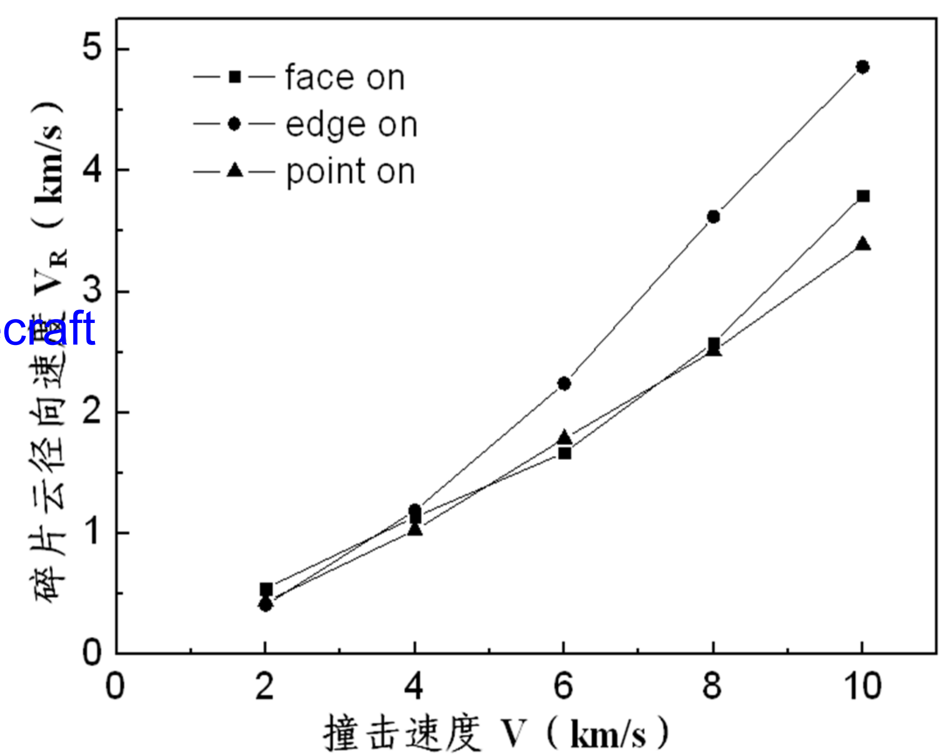
Flake

Front-end velocity and expanding velocity when impacted by cube projectile:

spacecraft



Front-end velocity



Expanding velocity

Characteristic parameters of maximum fragment in debris cloud:

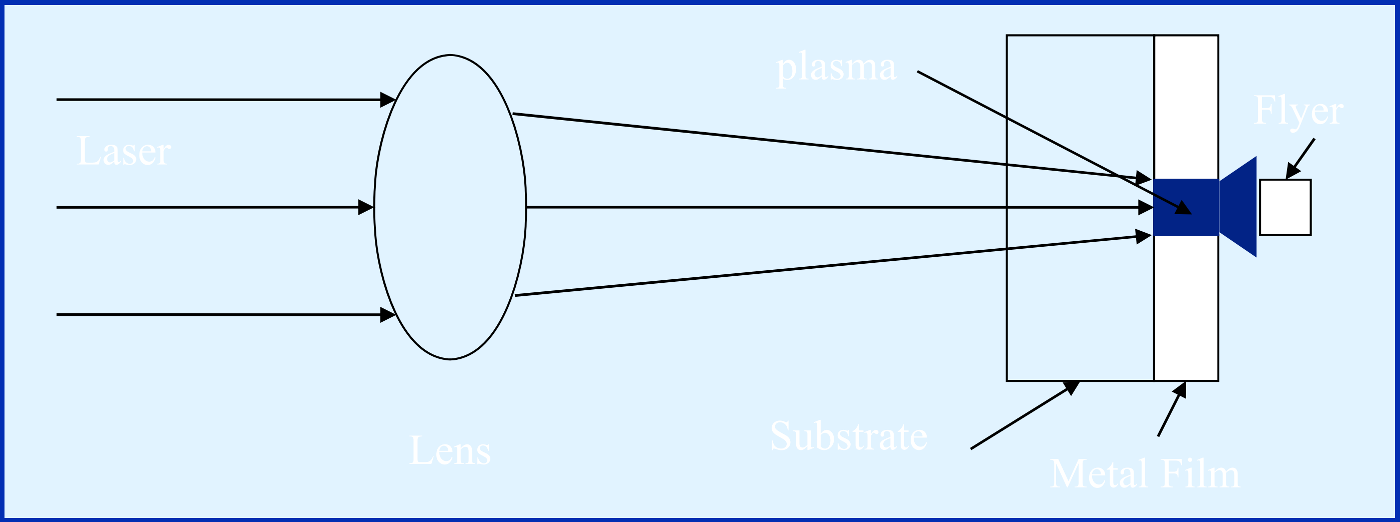
Shape		coordinate (mm)	Kinetic energy (mJ)	Momentum in x-axis ($mg \cdot m \cdot s^{-1}$)	Momentum in y-axis ($mg \cdot m \cdot s^{-1}$)	Momentum in y-axis ($mg \cdot m \cdot s^{-1}$)
Sphere		(3.13,1.85,5.66)	79	445	179	594
Cube	face	(8.54,9.62,1.66)	199	263	243	44
	edge	(2.91,4.84,0.50)	21	110	148	69
	point	(2.88,-2.33,-5.75)	45	222	-132	-270
Flake	Face (A)	(5.42,0.625,8.8)	25	69	2	96
	Face B or C	(35.9,-0.19,-2.47)	13400	6720	-26	-421
	Edge (B-C)	(38.9,0.57,-2.96)	38600	18300	-12	-1410
	Edge A-B A-C	(3.66,1.7,-6.54)	95	380	95	-370
	point A-B-C	(31.3,4.76,7.27)	36500	19700	2690	4660

Conclusion:

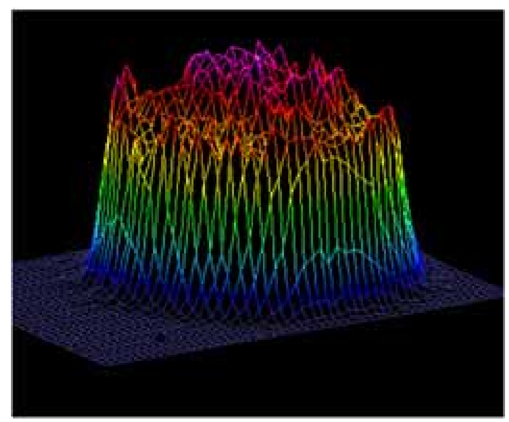
1. Space debris has many kinds of shapes, little of which are sphere. While cube and flake are the most common shape ;
2. The penetration and debris cloud of cube and flake are totally different from that of sphere;
3. Cube and flake are more harmful than sphere to spacecraft.

9. LDF (Laser-Driven Flyer) system in CAST

- Schematic diagram of LDFT in CAST
  - To simulate micro space debris (diameter<1mm)



- Laser parameters
  - Nd:YAG laser
  - Wavelength:1064nm
  - Pulse duration (FWHM)
    10ns
  - Energy range: 0.1～2J
  - Spot diameter>700μm。
  - Frequency: 1Hz
  - Beam shaping： ” top-hat”
  - Lens：f=200mm， 400mm
- Vacuum chamber
  - 10^{-3}Pa



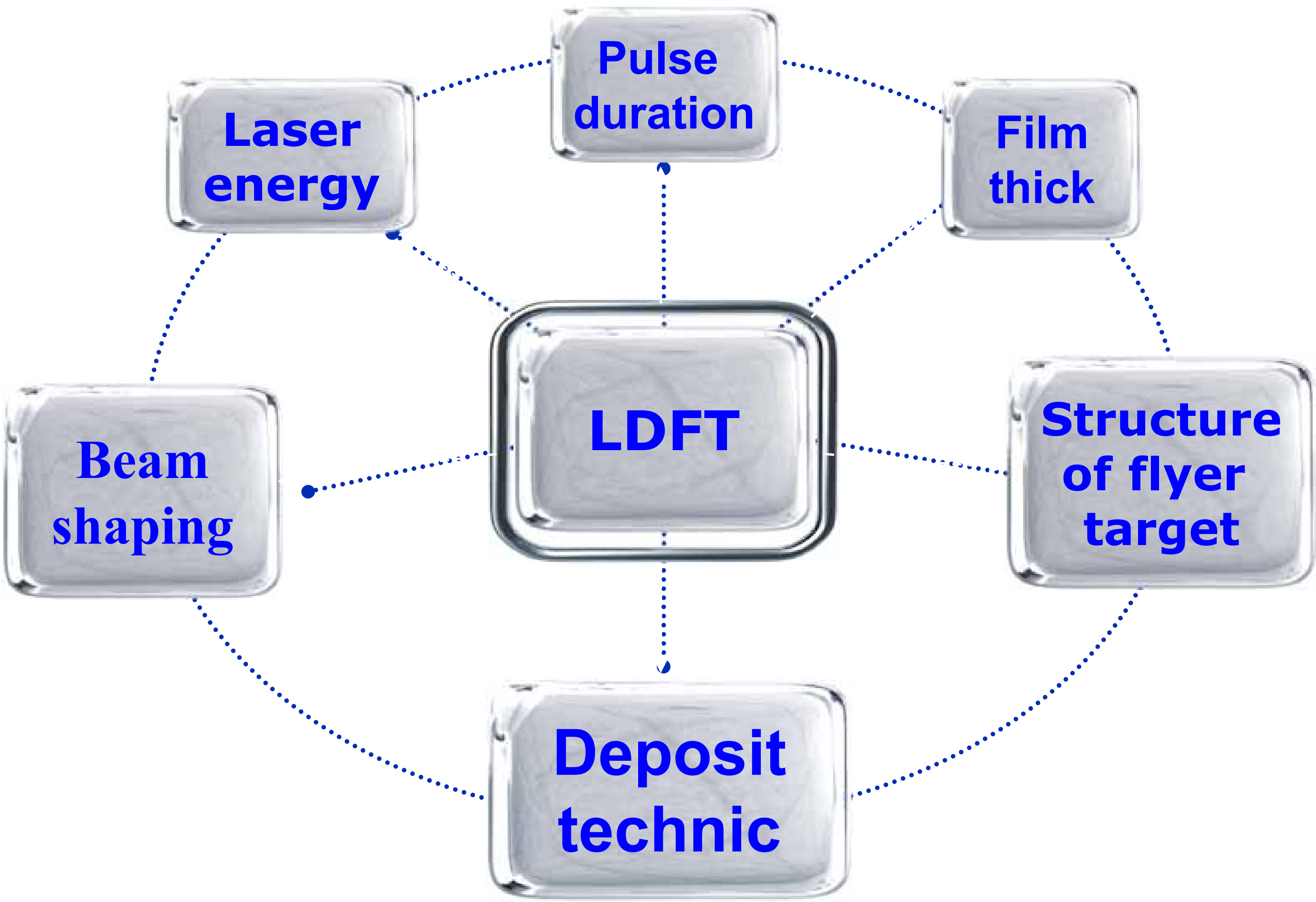
- Flyer target
  - Substrate materials：K9 glass and fused silica
  - Single layer：AL， Ti and Ta
  - Multi-layer：Cr/AL， Cr/AL/SiO_2
  - Thick of metal film：3～10μm；AL foil: 13 μm and 26 μm
  - Deposit method：magnetron sputtering， electron beam evaporation， ion beam sputtering， field-assisted diffusion， and Al foil.

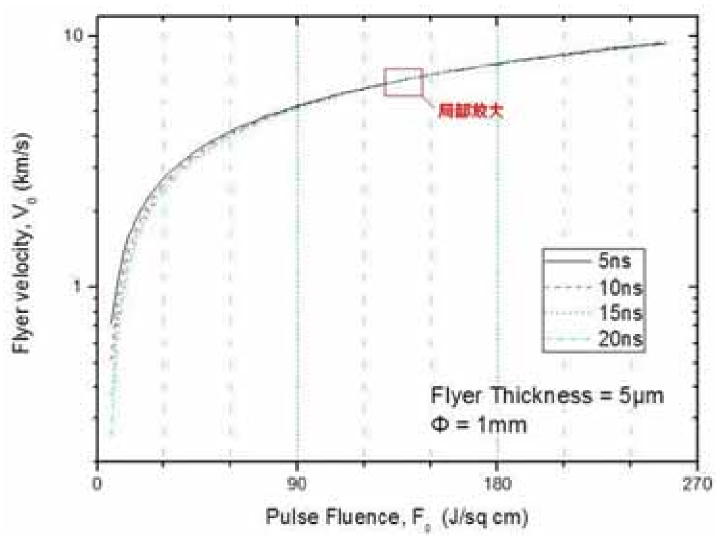
Appearance after launching on a Al flyer target deposited by ion beam sputtering

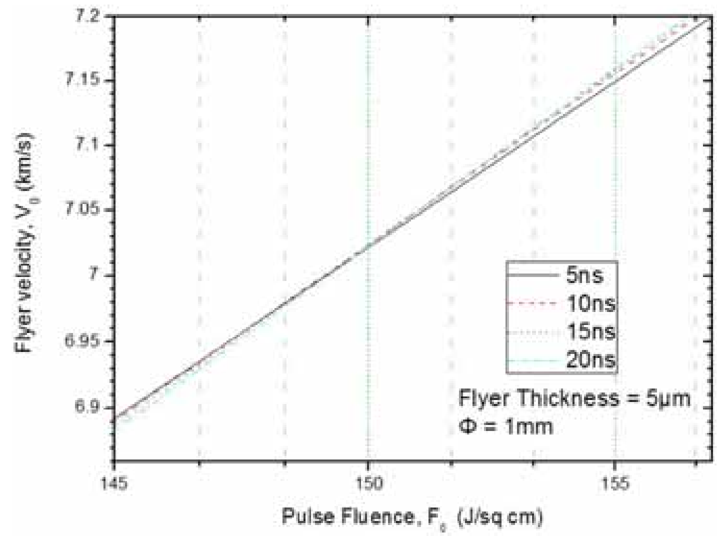
- Velocity measurement system
  - PVDF piezoelectricity sensor
  - Non-touched laser profile velocity measurement system
    - Measurement error: <10% (if v<5km/s, the error is no more than 4 %, and v~10km/s error ~9%)
    - Real time measurement in HVI experiments
- Oscillograph
  - Time resolution: 2.5GHz
- Microscope
  - × 50

10. Research on LDFT

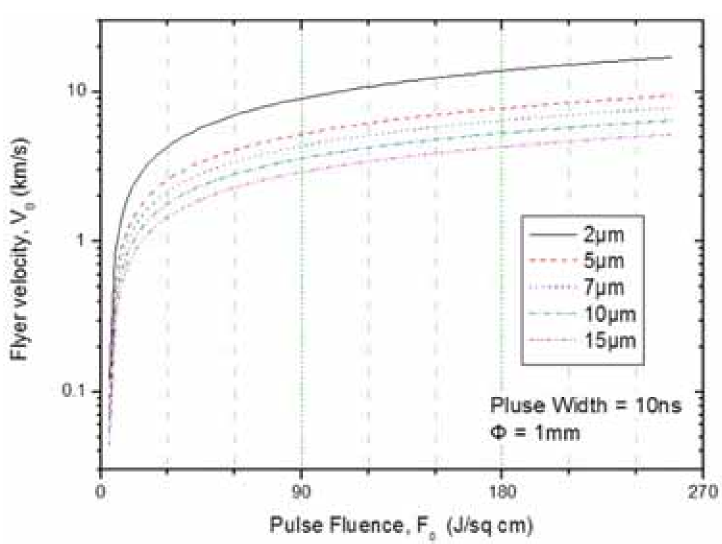
- Analysis of factors in determining flyer velocity

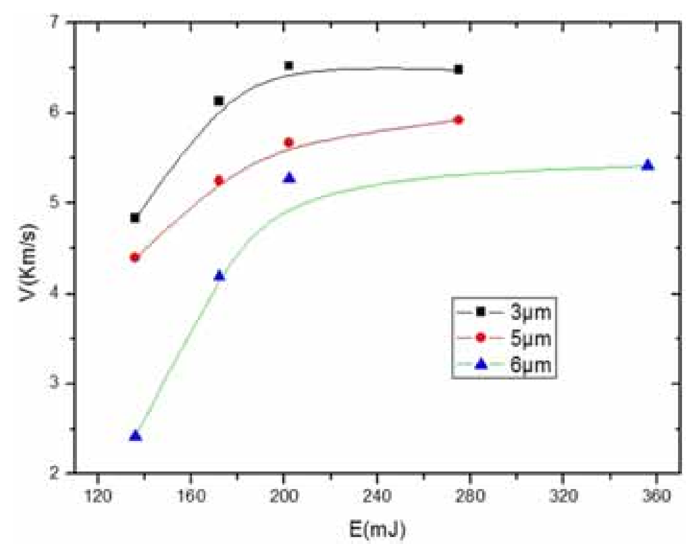






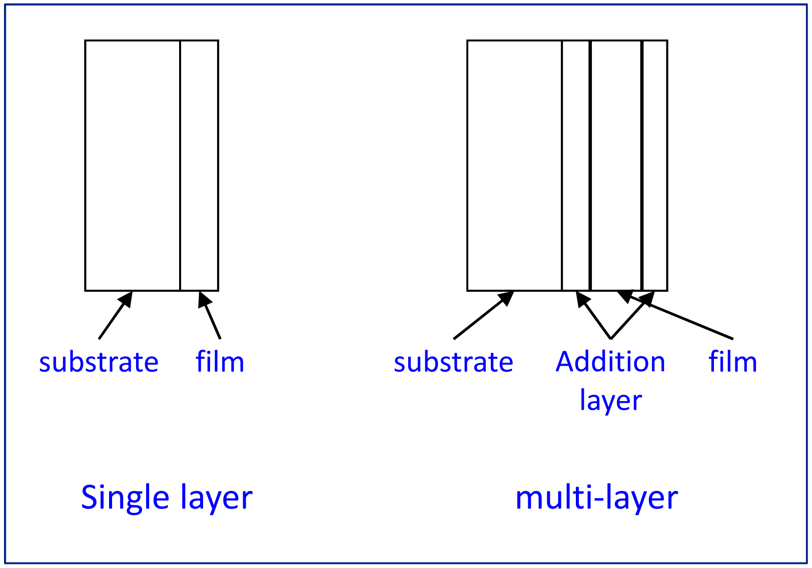
Flyer velocity is not sensitive to pulse duration



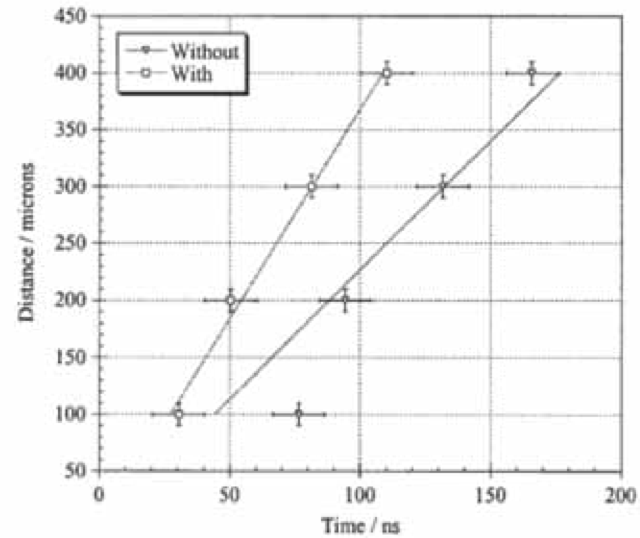


Higher flyer velocity is easy to achieve using thin film

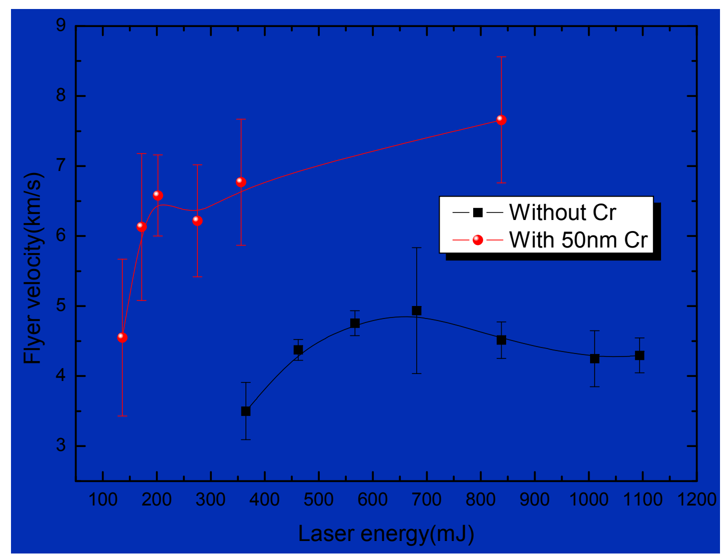
- Influence of film structure



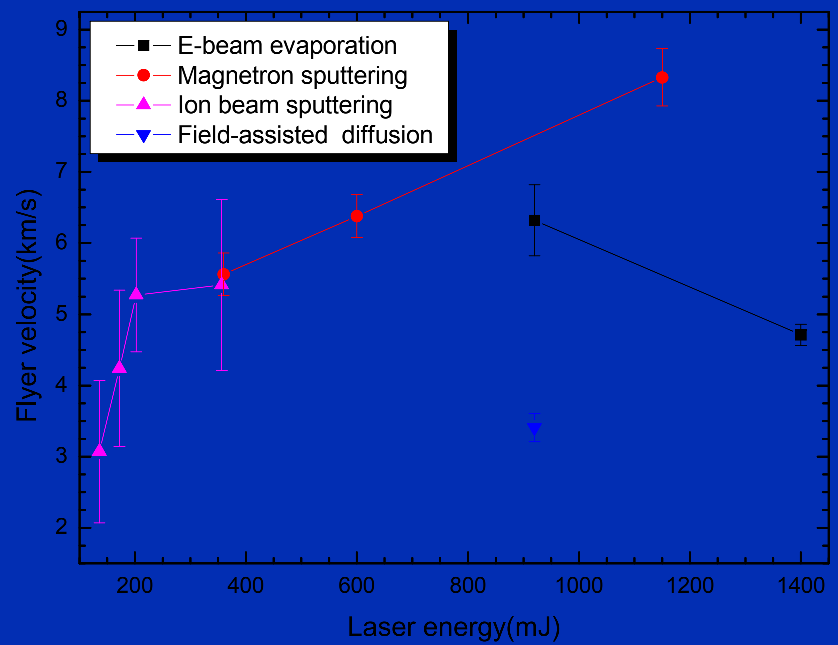
- Glass/Cr/Al—(Glass:50nm:3μm)

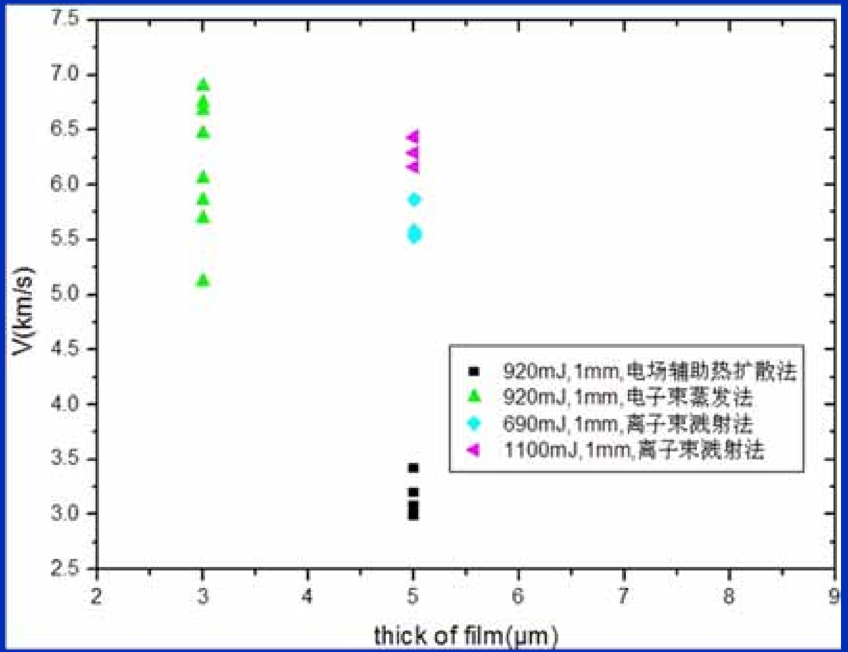


M.W. Greenaway--ablation layer

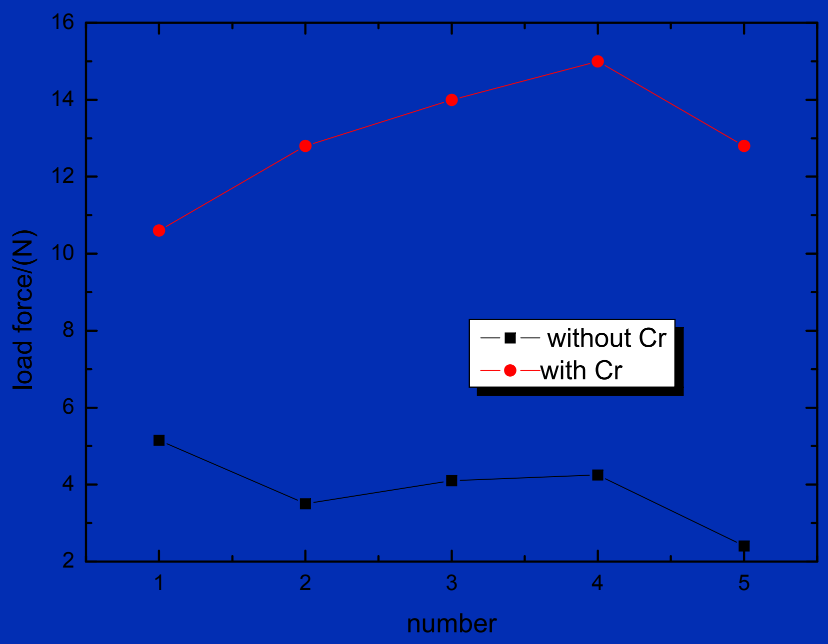


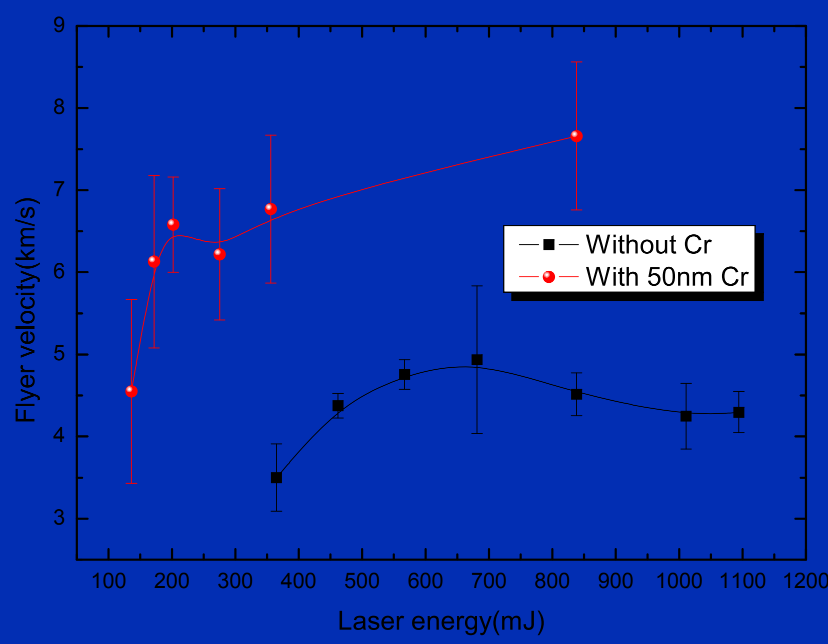
• Deposit techniques





- Binding intensity
  - The velocity of flyer is increased significantly with the inclusion of Cr layer which can improve the binding intensity between the substrate and the metal film.

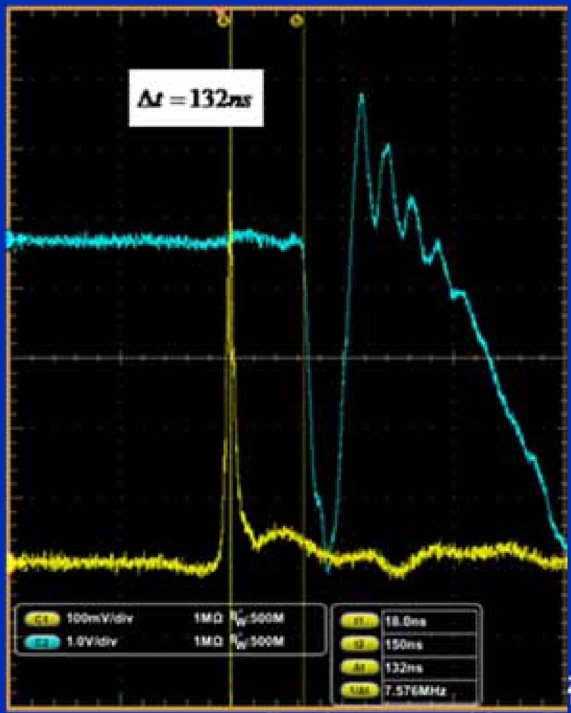




- Flyer velocity exceeding 10km/s
  - K9/Cr/Al—(K9/50nm/5μm) flyer target prepared using ion beam sputtering
  - A flyer plate with diameter about 1mm and 5 μm thick was accelerated to 10.4km/s at 853mJ laser energy.

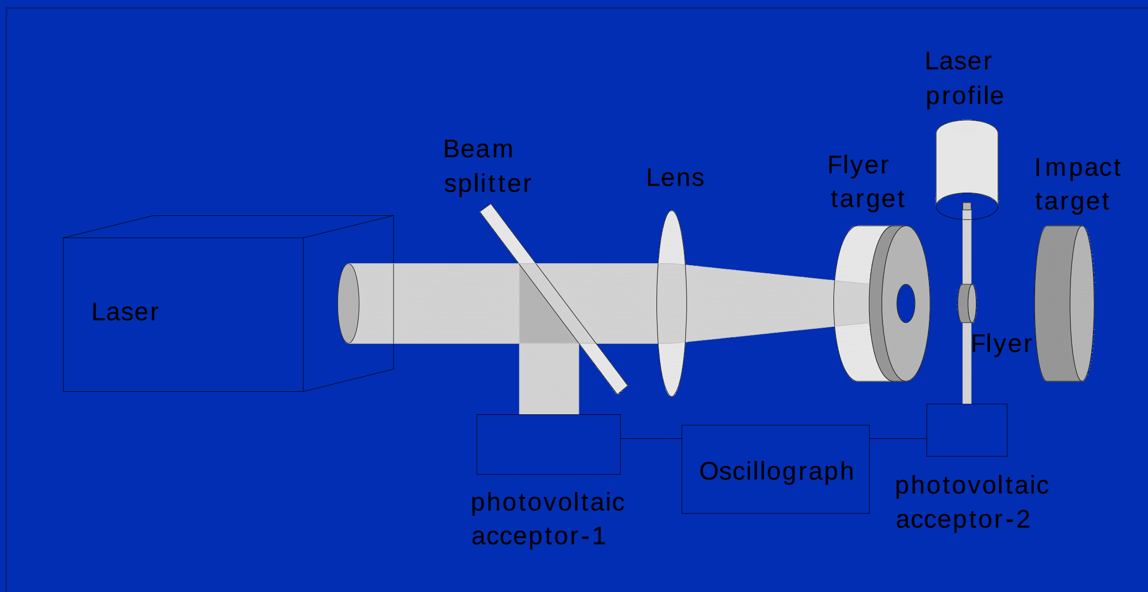
Fused silica/Cr/Al/SiO2—(glass/50nm/3 μm/100nm) flyer target prepared using E-beam evaporation.

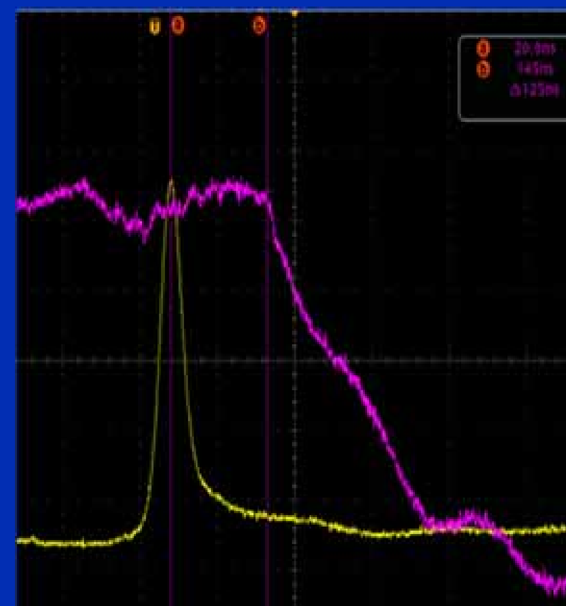
Flyer velocity ranges from 9 km/s to 11 km/s with the laser energy no more than 1J.



Velocity Measurement method:

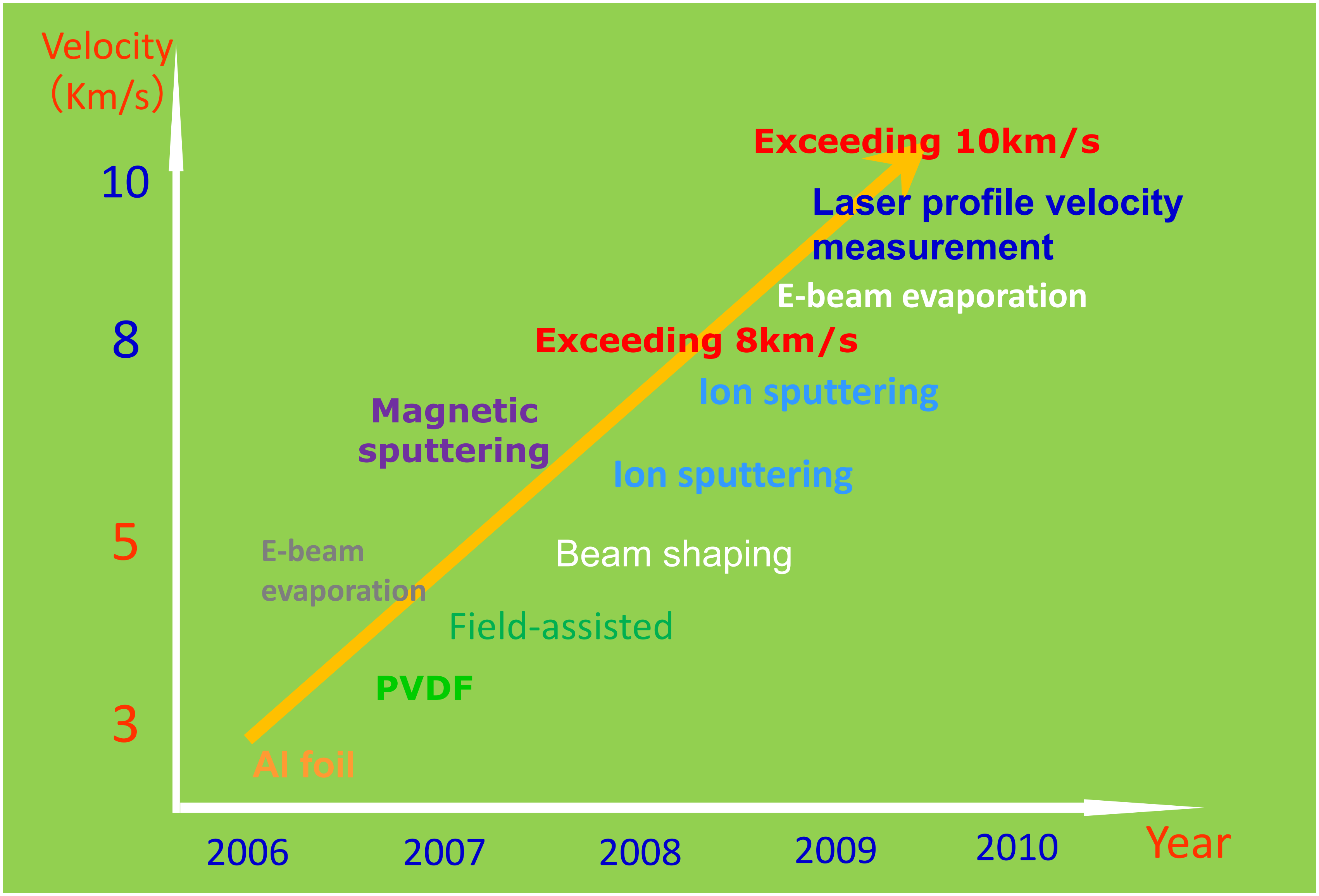
- Schematic diagram of Non-touched laser profile velocity measurement method for LDFT system





$$\sigma_v = \sqrt{\left(\frac{\partial v}{\partial d}\right)^2 \sigma_d^2 + \left(\frac{\partial v}{\partial t}\right)^2 \sigma_T^2} = \sqrt{\left(\frac{1}{\Delta t}\right)^2 \sigma_d^2 + \left(-\frac{d}{\Delta t^2}\right)^2 \sigma_T^2}$$

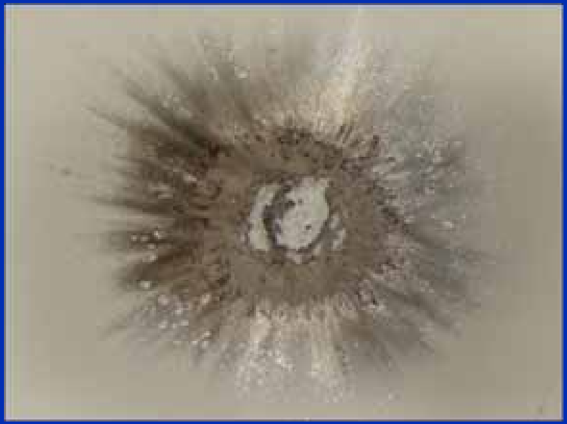
- Error analysis: error can be controlled by changing the value of d

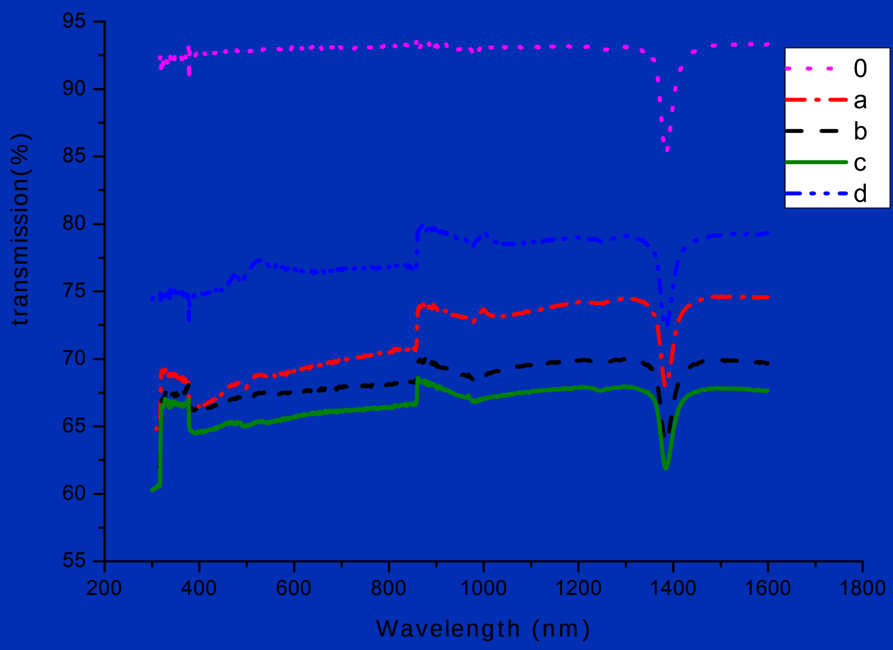


Velocity
(Km/s)
10
8
5
3
Exceeding 10km/s
Laser profile velocity
measurement
E-beam evaporation
Exceeding 8km/s
Ion sputtering
Magnetic
sputtering
Ion sputtering
E-beam
evaporation
Beam shaping
Field-assisted
PVDF
Al foil
2006
2007
2008
2009
2010
Year

11. HVI experiments

- Fused silica





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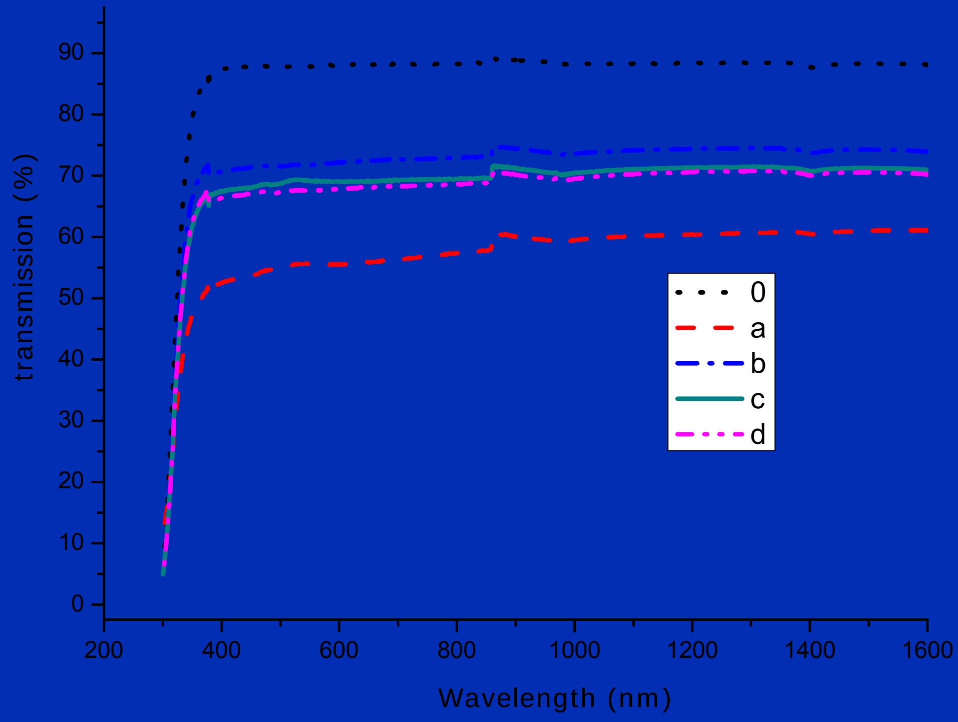
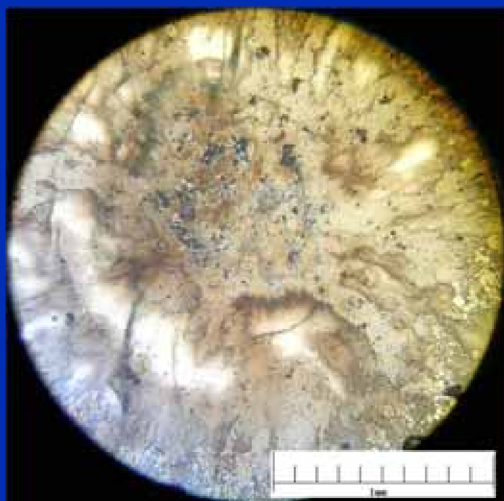
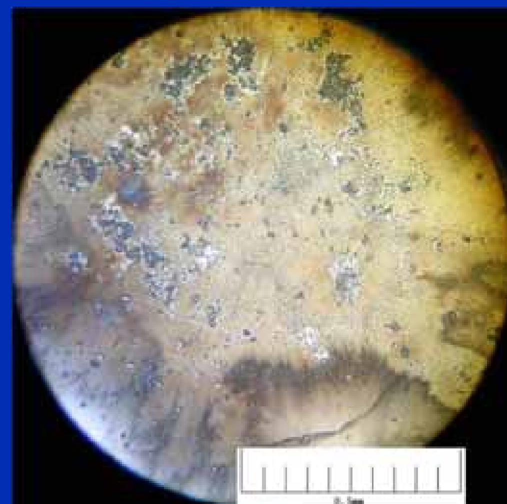
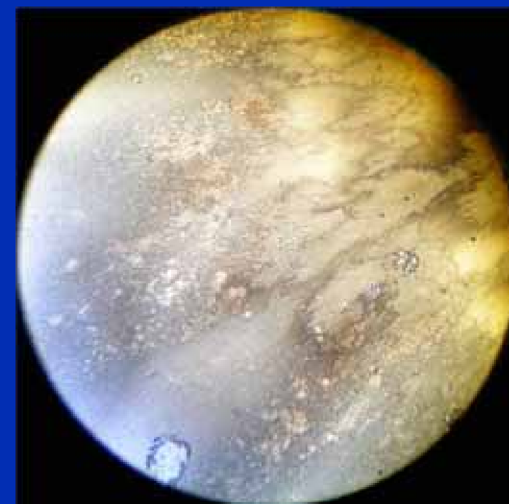
- K9 glass

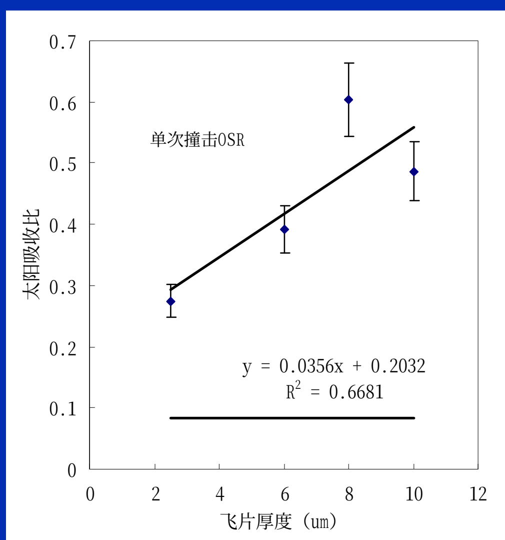

transmission (%)
Wavelength (nm)
0
a
b
c
d
0
10
20
30
40
50
60
70
80
90
200
400
600
800
1000
1200
1400
1600

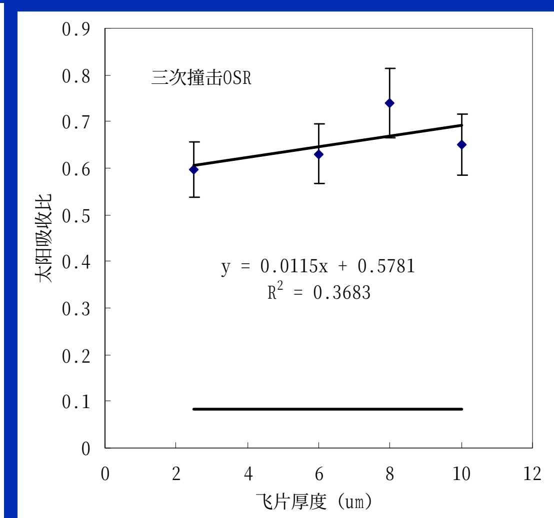
- # Optic Solar Reflector

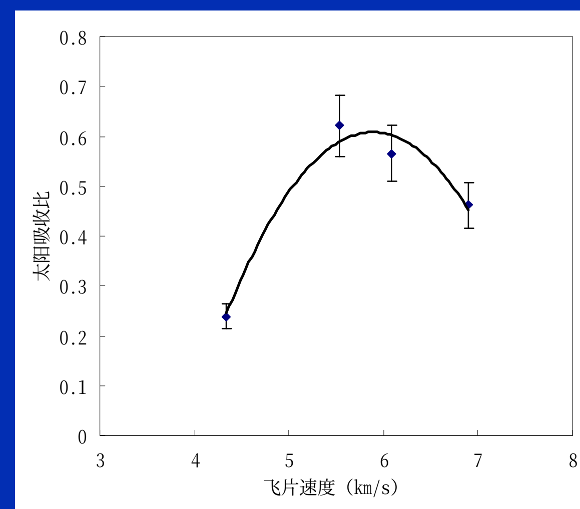








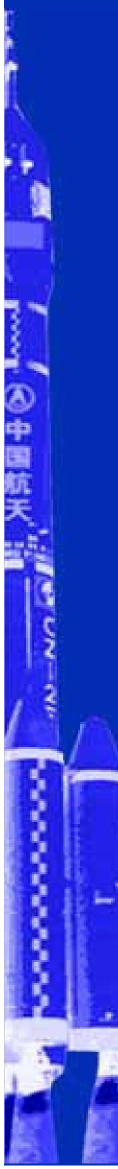




§ 5

Orbital Debris Mitigation in CAST

Orbital Debris Mitigation Standards in CAST & China



1. QJ3221-2005 Orbital Debris Mitigation Requirements (promulgated)
2. KJSP-T-1-01 rules of Spacecraft passivation desgin (under promulgated)
3. KJSP-T-1-02 R)equirements of GEO Spacecraft treatment and implement after task (under promulgated)
4. KJSP-T-1-03 Requirements of LEO Spacecraft treatment and implement after task (under promulgated)
5. KJSP-T-1-04 Control Requirements and desgin rules for operational Debris of Spacecraft (under promulgated)
6. KJSP-T-1-05 residual propellant measuring and estimating of Spacecraft (under promulgated)
7. KJSP-T-1-06 procedure Requirements and risk assessment of reentry of Spacecraft (under promulgated)
8. KJSP-M-1-01 Management Requirements for Orbital Debris Mitigation of Spacecraft (under promulgated)

Thank you!

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