

Meteoroids and Orbital Debris: Effects on Spacecraft

C.A. Belk

Universities Space Research Association • Huntsville, Alabama

J.H. Robinson and M.B. Alexander

Marshall Space Flight Center • MSFC, Alabama

W.J. Cooke

Computer Sciences Corporation • Huntsville, Alabama

S.D. Pavelitz

Sverdrup Technology, Inc. • Huntsville, Alabama

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PREFACE

The effects of the natural space environment on spacecraft design, development, and operation are the topic of a series of NASA Reference Publications* currently being developed by the Electromagnetics and Aerospace Environments Branch, Systems Analysis and Integration Laboratory, Marshall Space Flight Center. The objective of this series is to increase the understanding of natural space environments (neutral thermosphere, thermal, plasma, meteoroids and orbital debris, solar, ionizing radiation, geomagnetic and gravitational fields) and their effects on spacecraft, thereby enabling program management to more effectively minimize program risks and costs, optimize design quality, and achieve mission objectives.

This primer, seventh in the series, focuses on the source, size, and lifetime of orbital debris, discusses understanding the meteoroid and orbital debris environments in order to design spacecraft to survive debris impacts, and promotes awareness of debris mitigation policy.

See NASA RP 1350 for an overview of eight natural space environments (including meteoroids and orbital debris) and their effects on spacecraft.

*NASA Reference Publications Natural Space Environment Series, available from the Marshall Space Flight Center Electromagnetics and Aerospace Environments Branch, include the following:

“The Natural Space Environment: Effects on Spacecraft,” James, B.F., Norton, O.A., Jr., and Alexander, M.B., November 1994, NASA RP 1350.

“Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging,” Herr, J.L. and McCollum, M.B., November 1994, NASA RP 1354.

“Electronic Systems Failures and Anomalies Attributed to Electromagnetic Interference,” Leach, R.D. and Alexander, M.B., July 1995, NASA RP 1374.

“Failures and Anomalies Attributed to Spacecraft Charging,” Leach, R.D. and Alexander, M.B., August 1995, NASA RP 1375.

“Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment,” Bedingfield, K.L., Leach, R.D., and Alexander, M.B., August 1996, NASA RP 1390.

“Spacecraft Environments Interactions: Solar Activity and Effects on Spacecraft,” Vaughan, W.W., Niehuss, K.O., and Alexander, M.B., November 1996, NASA RP 1396.

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ABBREVIATIONS AND ACRONYMS

ASAT	antisatellite
CDR	Critical Design Review
cm	centimeter
GEO	geosynchronous-Earth orbit
HEO	high-Earth orbit
HST	Hubble Space Telescope
kg	kilogram
km	kilometer
km/s	kilometers per second
LDEF	Long Duration Exposure Facility
LEO	low-Earth orbit
m	meter
mm	millimeter
M/OD	meteoroids and orbital debris
M/OD TP	Meteoroid and Orbital Debris Technology Program
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PC	personal computer
PDR	Preliminary Design Review
SAIL	Systems Analysis and Integration Laboratory
SSN	Space Surveillance Network
U.S.	United States
WSTF	White Sands Test Facility
yr	year



REFERENCE PUBLICATION

METEOROIDS AND ORBITAL DEBRIS: EFFECTS ON SPACECRAFT

INTRODUCTION

In the natural space environment meteoroids, small bits of cometary ice or rock, travel through Earth's orbital space at an average speed of 20 km/s (44 000 mph). An average 40 000 metric tons of micrometeoroids, small dust particles, enter the Earth's atmosphere each year.¹ In geosynchronous orbits, altitudes around 35 000 km, meteoroids are more likely to be encountered than orbital debris and are the only penetration hazard in interplanetary space, where their velocities can reach 70 km/s. Measurements by Pegasus spacecraft in 1965 found that, in Earth orbits, the probability of collision with a meteoroid large enough (greater than 1 cm) to create significant damage is remote.¹

Orbital debris is not a naturally occurring phenomenon in the natural space environment. It is man-made space litter resulting from 40 years of space exploration. Released parts of spacecraft, unintentional explosions, and spent satellites have created this growing threat to space operations. Orbital debris includes rocket bodies, mission related debris, fragmentation debris, and nonfunctional spacecraft. This debris population distribution is customarily classified as large, medium, and small. The cumulative mass of these objects is approximately 2 000 000 kg with an average velocity of 10 km/s.² Figure 1 depicts the area and density of currently cataloged orbital debris.

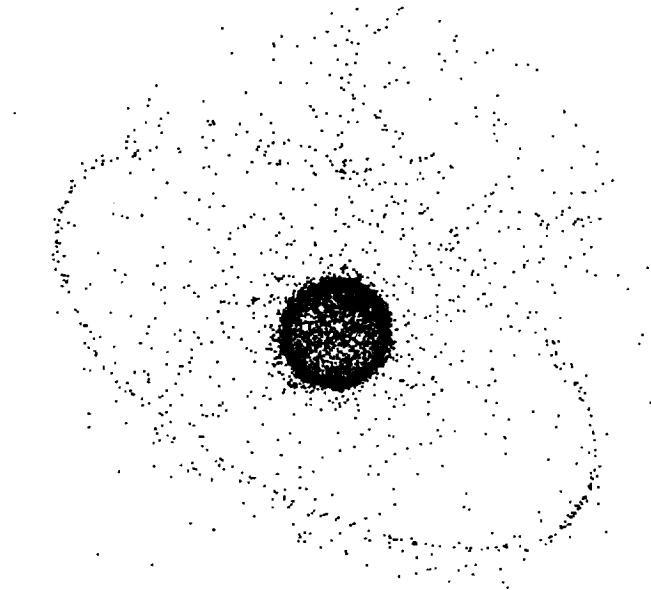


Figure 1. Depiction of cataloged orbital debris.

Significance of the meteoroid and orbital debris (M/OD) threat is evident in numerous spacecraft anomalies. Unexplained destructions of spacecraft are believed caused by impacts with large debris. A French military research satellite, Cerise, was struck July 24, 1996, by an Ariane booster fragment about the size of a suitcase. The Cerise began tumbling after the 6-m boom which stabilizes the satellite was cut in half.³ This incident was the first witnessed impact of two tracked space objects.

The Long Duration Exposure Facility (LDEF) was deployed April 7, 1984. Its mission was to test the stability and interaction of thermal coatings in the low-Earth orbit (LEO) space environment. LDEF, in orbit for 69 months, experienced approximately 140 significant impact craters/m² per year. Data from LDEF coupled with hypervelocity impact tests with the Light Gas Gun have provided a wealth of information on the effects of orbital debris impacts on aerospace materials.⁴

Examples of spacecraft anomalies caused by the M/OD environment include:

- A cracked Space Shuttle window from impact with a paint chip (fig. 2)
- Penetration of high gain antenna dish aboard the Hubble Space Telescope (HST)
- Marred surfaces on the Solar Maximum Mission spacecraft.



Figure 2. Shuttle window pit caused by impact with a paint chip.

Because space exploration is vital to national, civil, and commercial interests, it is necessary to understand the current orbital debris environment, have design guidelines that protect spacecraft from orbital debris particle impacts, and take measures to guard against orbital debris proliferation.

SOURCE AND SIZE OF ORBITAL DEBRIS

Since the advent of space exploration, a growing population of orbital debris has accumulated in orbits around the Earth. These objects include rocket bodies, nonfunctional spacecraft, fragmented material from both intentional and unintentional explosions, rocket fuel ejecta, and various other mission related items. Unless this accumulation is addressed, continued operations in these orbits could severely augment the orbital debris population. To minimize the potential hazard of these objects, it is necessary to understand the current orbital debris environment.

Each object is classified according to one of the following five debris types:

- (1) **Fragmentation material** consists of pieces of destroyed vehicles (antisatellite (ASAT) tests, upper stage explosions) and fragments dislodged from satellites (paint flakes, pieces of thermal blankets, etc.). This is the single largest component of the tracked debris population, about 40 percent of the total.
- (2) **Nonfunctional spacecraft** are intact structures that have completed their mission or have had shortened mission life due to a nondestructive malfunction, approximately 25.3 percent of the debris population.
- (3) **Rocket bodies** are spent upper stages, about 19.4 percent of the tracked debris population.
- (4) **Mission-related items** include explosive bolts, vehicle shrouds, etc., released during staging and spacecraft separation, approximately 13.3 percent. This category also includes two families of solid rocket motor debris, those with diameters less than 25 microns and those around 1 cm, and a population of small particles near 900 km believed to be sodium potassium (NaK) droplets.
- (5) **Debris from unknown sources** account for the remaining 2.0 percent.

Although orbital debris has various sources, sizes, and compositions, it is customarily classified by the following particle sizes:

Large—Objects with diameter greater than 10 cm are classified as large debris. Many can be cataloged and monitored by ground-based sensors but not all large objects are visible from the ground. Optical telescopes rely on albedo (light reflection) to detect objects and, typically, fragments reflect only 10 percent of the sunlight they receive.¹ There are also limitations in low inclination orbits, due to lack of sensors directed to those areas, and in highly elliptical orbits where debris spends much of its time at very high altitudes. Probability is low of encounters with large debris. However, such an impact would cause catastrophic breakup of a spacecraft.

Medium—Objects with diameter of 1 mm to 10 cm are classified as medium debris. Its population, estimated to be in the tens of millions, is based on measurements with Haystack radar which can detect objects as small as 1 cm. A collision with debris of medium size could cause significant damage to a spacecraft and possible mission failure.

Small—Objects with diameter less than 1 mm are classified as small debris. Because the population of small debris is so great, data are best acquired by in-situ sampling, examining damage to spacecraft returned from space. Examination of damage to spacecraft, such as LDEF, HST, and Space Shuttle, shows the effects of collisions with small debris are component damage, craters, spallations, and degradation of spacecraft surfaces. Because of their small diameter and long length, tethers may be frayed or completely severed by impacts with small debris.

Debris flux is the amount of debris passing through a given area at a given time. The flux experienced by a spacecraft is directly proportional to the probability of impact.¹ Figure 3 depicts the variation in the debris flux as a function of time at the *International Space Station's* altitude and inclination, as calculated by the National Aeronautics and Space Administration (NASA) debris model, ORDEM96.

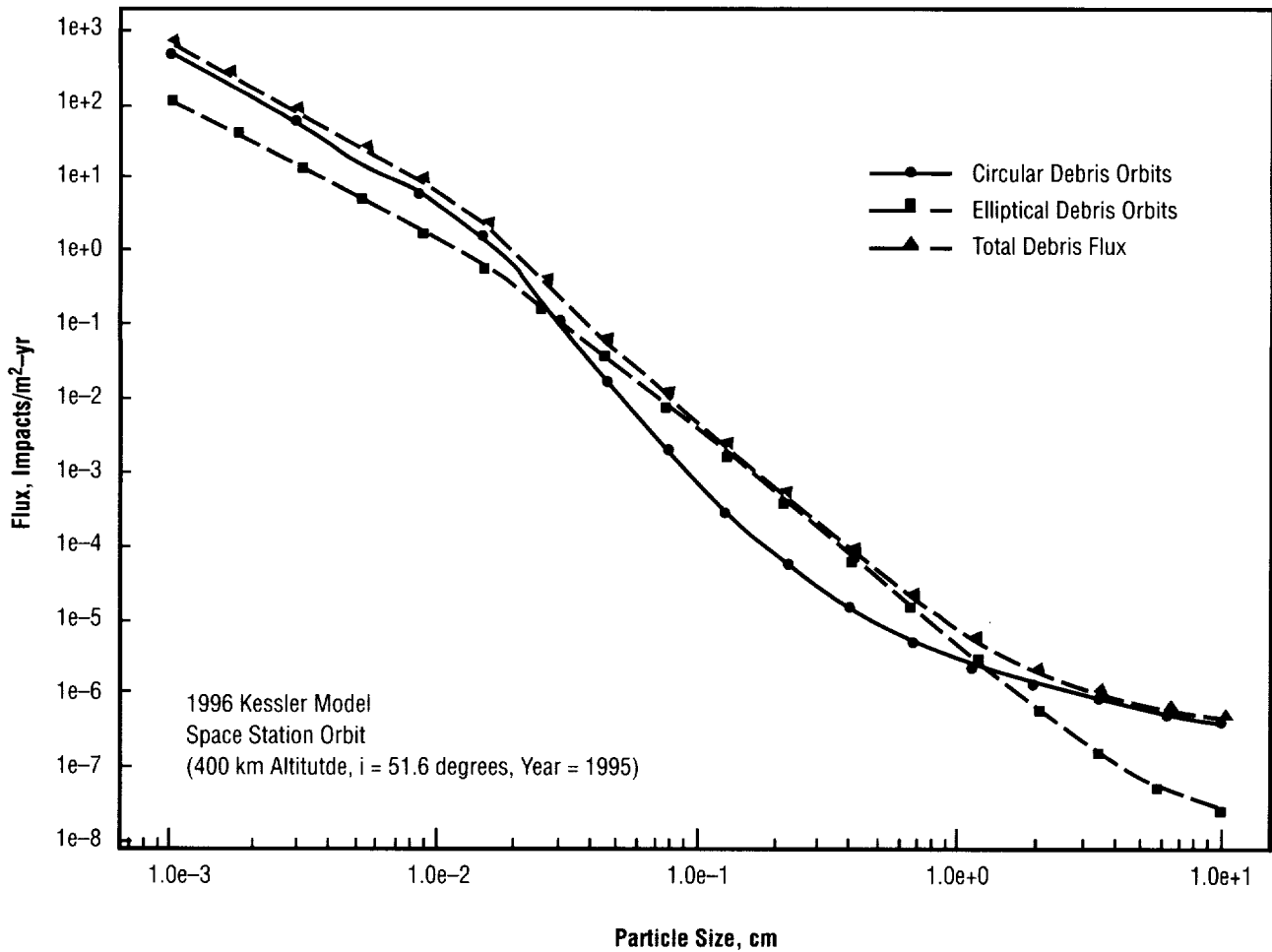


Figure 3. Orbital debris flux calculated by ORDEM96.

All objects tracked by the U.S. Space Command, whether functional spacecraft or orbital debris, have orbital elements and other properties stored in what is called the catalog. Currently, about 8000 objects in the catalog have their orbital parameters updated on a regular basis. The catalog is reasonably complete for 10 cm or larger objects. Smaller ones are not easily tracked (if at all) by the Space Surveillance Network (SSN) and, thus, are not well represented in the catalog.

Orbital debris is monitored in several ways. Larger objects are detected by land-based radars and optical telescopes which have limited visibility due to the light and radar reflectivity on debris material. The diameter of an object must be 1 m in geosynchronous orbits (GEO) to be visible.¹ In LEO, Haystack radar can detect objects with a diameter as small as 5 mm. The population of small debris, expected to be in the trillions, is via examinations of damage on returned spacecraft such as LDEF. An in-orbit photograph of LDEF, taken from the Space Shuttle during retrieval, is shown in figure 4. LDEF data show evidence of “debris swarms,” increases of 3 to 5 magnitudes in flux of small orbital debris lasting for a few minutes.¹ Density of the population of these “debris swarms” causes extensive corrosion to spacecraft surfaces.



Figure 4. In-orbit photograph of LDEF.

ORBITAL DEBRIS LIFETIME

As debris moves along its trajectory at approximately 10 km/s, ions in the atmosphere impinge on its surfaces and gradually deteriorate the material. This atmospheric drag (retarding force) determines the decay rate of orbital debris. Because atmospheric density decreases as altitude increases, debris in low altitude orbits decays more quickly. Objects in altitudes around 400 km or less decay in a few months. Density decreases rapidly in altitudes above 600 km and decay time increases to tens, hundreds, or thousands of years.² Objects in GEO, where atmospheric drag is low and has little effect on materials, can have an orbital lifetime of a million years. At the current rate of growth, debris generation can easily exceed decay rates and make higher orbits unusable in as few as 20 years.

Several factors affect the amount of atmospheric drag an object is exposed to. These factors include altitude, area-to-mass ratio, eccentricity of orbit, and perturbation forces. The most significant of these is altitude. The atmosphere in LEO is several orders of magnitude more dense than the atmosphere in high-Earth orbit (HEO). Density is not constant, especially at altitudes below 1000 km that are greatly affected by the 11-year solar cycle. Density affects decay rate by the number of particles impinging the surface. Surface area determines deterioration time. The more area exposed to the environment the more ionized particles of the atmosphere impact it. This means the greater the area-to-mass ratio the shorter the orbital lifetime. For example, a square sheet of aluminum foil decays more quickly than a small aluminum sphere of the same mass.

Eccentricity of orbit affects orbital life. An object in an elliptical orbit with the same average altitude as a circular orbit, decays more quickly because perigee, point of orbit closest to the Earth, of the ellipse brings the object closer to the Earth and rapidly deteriorates it. However, if the circular orbit has a lower average altitude, the object decays more quickly.

In LEO, Earth gravitation is sufficient to gradually affect an object's trajectory by pulling it closer to the Earth. This perturbation force does not affect objects in higher orbits where the solar and lunar gravitational fields are more significant. The 11-year solar cycle also influences orbital life in LEO. During the 11-year cycle, the Sun has periods of low solar activity (solar minimum) and high solar activity (solar maximum). During the years of increased activity, the atmosphere is heated and atmospheric density increased to produce a faster decay rate. LEO is continuously replenished as objects from higher altitudes draw closer to the Earth. Only during times of solar maximum does this population of debris decrease. The next solar maximum is expected around the year 2000.⁵

More information about the solar cycle is found in NASA Reference Publication 1396 "Spacecraft Environments Interactions: Solar Activity and Effects on Spacecraft." Solar and lunar gravitational forces affect higher, very elliptical orbits such as the Geostationary Transfer Orbit used to transfer hardware from LEO to GEO. Depending on alignment of the object with the Sun and the Moon, these forces reduce orbital life to a few months. No significant forces in GEO expedite the decay process.

EFFECTS OF ORBITAL DEBRIS ON SPACE OPERATIONS

Large, medium, and small debris is found in all orbital altitudes. Where debris concentrations are more dense, hot spots exist. Debris dense areas include low-Earth, semisynchronous, and geosynchronous orbits. These frequently-used areas offer benefits to spacecraft designers such as providing high-resolution images or retaining constant longitude over the Earth.

The probability of collision with debris depends on orbital altitude, inclination, spacecraft size, and length of time in orbit. Hypervelocity impact testing is a procedure performed on critical spacecraft components to determine effects of impact and survivability of the spacecraft. Because of the many variables these tests are case specific and do not offer standards to judge all materials. To date very little data exist for composite material structures.

Altitude is the most important factor to consider in collision avoidance. Low-Earth orbits are most heavily populated with debris. Altitudes from 900 to 1000 km have an average population of 100 cataloged objects in a 10-km altitude band.² These altitudes have the highest probability of collision—second highest are from 1400 to 1500 km. Although these altitudes offer lower launch costs and other benefits to designers, spacecraft in LEO are 100 times more likely to experience collisions than in semisynchronous and geosynchronous orbits.¹

Inclination refers to the orbital plane of a spacecraft with respect to the Earth's equator. High inclination orbits are close to the Earth's poles and frequently used for remote sensing. The orbital debris population is dense in these areas. Although all spacecraft encounter the path of this orbiting debris, those in high inclination orbits are subjected to the harsher environment for longer periods at increased likelihood of collision.

Spacecraft size and length of time in orbit are also important collision factors. A large spacecraft with much area exposed to the environment is more likely to encounter significant debris. The longer it remains in orbit increases the possibility of impact. Figure 5 shows impact damage to a silver Teflon™ blanket on LDEF after 69 months in orbit.

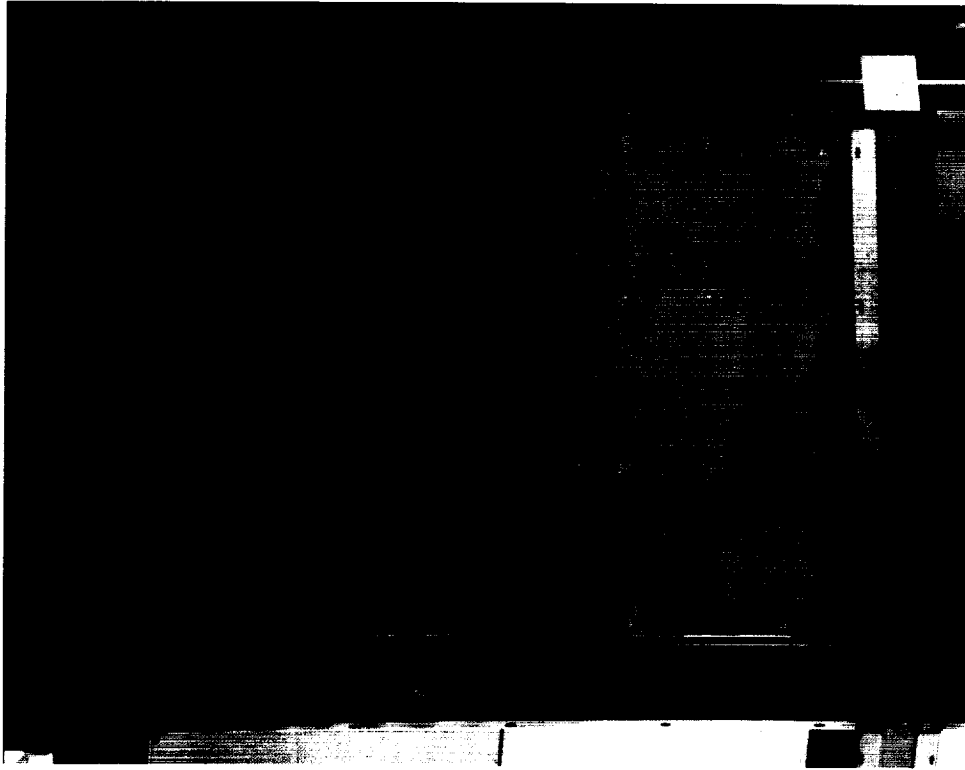


Figure 5. Orbital debris impact damage to silver Teflon™ blanket on LDEF.

DESIGNING FOR THE ORBITAL DEBRIS ENVIRONMENT

Inevitably, spacecraft encounter orbital debris during their functional lifetime. However, there are passive and active ways to protect them from damage. Passive protection includes shielding or augmenting components to withstand impact. Whipple bumpers protect against impacts at typical LEO velocities. These bumpers are designed to breakup debris on impact and distribute the particle energy and momentum over a large area. Due to the reduction in particle size and velocity, the resulting debris cloud does not penetrate the monolithic pressure wall behind them. Active protection uses sensors and warning systems to detect an impending debris impact early enough to allow spacecraft time to change position or close shutters to protect sensitive components. This is an extremely demanding and not widely used procedure.¹

Hypervelocity impacts of orbital debris cause several levels of damage to spacecraft structures because the majority of particles are small (less than 1 mm). Most debris encounters are expected to result in insignificant damage such as micron-size craters in surfaces. Collision with large objects (greater than 10 cm) could result in total breakup of a spacecraft, but these objects are infrequent and probability of impact is low. The challenge to spacecraft designers is medium debris. Although less numerous than small debris, medium debris is more dangerous and could cause significant damage to spacecraft and possible failure of mission. Partial structure penetration by medium size particles has many possible effects on a spacecraft. The smaller cratering can degrade surface coatings, thermal materials, and windows or mirror surfaces and affect thermal and optical properties required for spacecraft mission success.

Particle cratering that extends through approximately 70 percent of an aluminum structural wall can create spallation from the material on the back of that wall. Spallation is a phenomenon in which a stress wave moves through a surface, causing a thin sheet of material to separate from the back of the surface. Figure 6 shows front and rear views of spallation damage to a surface on LDEF. This particle could continue into the spacecraft to cause more severe damage, or penetrate through other structures to degrade structural strength properties. For a high-pressure, liquid-filled tank, the possibility exists that a nonperforating impact could catastrophically rupture the tank due to the hydraulic ram created within the tank by the impact shock wave.

Total penetration of a wall can cause damage more severe than partial penetration. When a structural wall is penetrated by hypervelocity particles, a debris cloud is created and spreads broken wall and particle materials radially in the shape of a cone (fig. 7). This spreading mass of energy could severely damage electrical circuits, thermal insulation, or other delicate components. In a liveable environment such as a space station, the expanding debris cloud of particles is accompanied by a pressure pulse and an extremely bright flash of light. Secondary results could be fire and explosions of internal components. Perforation of fuel tanks, batteries, and other pressure vessels could lead to more explosions, depending on the fluid or gas inside the vessels and the amount of pressure. A very large perforation in a structural wall could weaken the wall itself. Because of high reentry loads, this is

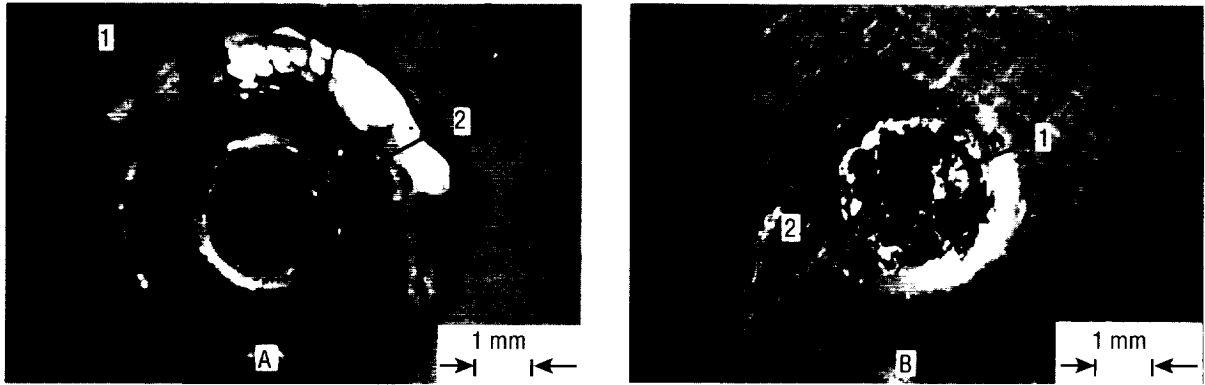


Figure 6. Front (left) and rear (right) views of spallation damage to LDEF surface.

especially important to vehicles required to reenter the Earth's atmosphere. Finally, perforations could simply cause a single component to fail. Depending on the component, this failure could be functional, critical, or catastrophic. For example, perforation of a small, low-pressure air tank stored outside the manned modules of a space station would probably be labeled a "functional" failure. However, if it is the only air tank left or the pressure is high enough to cause sufficient thrust to disorient the station, this failure might be labeled "critical." If the disorientation is too severe to allow an attitude recovery, it would be labeled "catastrophic."

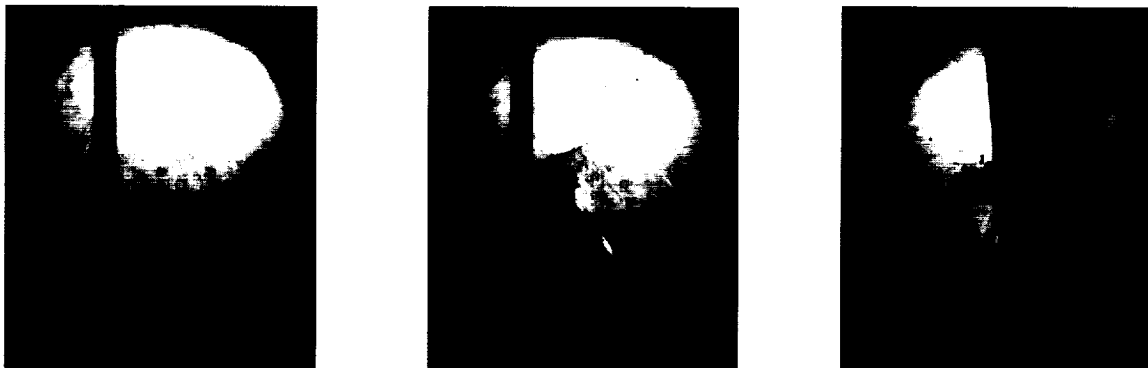


Figure 7. Series of photographs as 1-cm projectile impacts a target and produces a debris cloud.

Many components of a spacecraft are considered critical to the mission, until an M/OD damage analysis and hypervelocity impact test show otherwise. The exception to this may be if the components are redundant and failure of one cannot cause failure to any other. One must be very careful in evaluating redundancy. Electrical components are sometimes said to be redundant when there is a primary and secondary component. However, if they are in the same container the debris cloud created when the box is penetrated could severely damage both. In this case the components are not redundant.

Many penetration predictor equations have been developed over the last 40 years. Many equations are empirical, based on a significant number of tests, and applicable only to those materials tested. The great majority of published equations are for metallic materials. Prediction equations for composite

material structures are needed and development tests are planned. Equations are published for single- and multi-plate penetration for metals and multilayer penetration for ceramic cloth. For the Space Station Program published papers contain the penetration predictor equations for a combination of two aluminum plates with ceramic and high strength cloth fabrics suspended between the two spaced plates. Equations developed for the Space Shuttle Program predict penetration of thermal blankets and tiles. Reusable launch vehicle researchers are deriving predictor equations for advanced thermal blankets and tiles, including metallic thermal protection systems bonded to composite or aluminum lithium substructures. The variety of equations needed is as endless as the variety of structures and materials used to build spacecraft.

Figure 8 shows three predictor curves, one for a single aluminum plate, one for a two-plate Whipple shield, and the third for a space station type Whipple shield with Nextel and Kevlar fabrics between the plates.⁷ The combinations of particle size and velocity beneath each curve are those particles the configuration is expected to stop or those particles that will not totally perforate the last wall of the configuration. The curve separating the perforating and nonperforating areas of the graph is known as the ballistic limit curve. The particle size and velocity combinations above the curves are those expected to totally perforate the configuration. These curves along with the spacecraft orbit, altitude, orientation, and mission duration are used to assess the probability of mission failure from meteoroid and orbital debris impacts. Notice the improvement in stopping power from the more advanced shield systems.

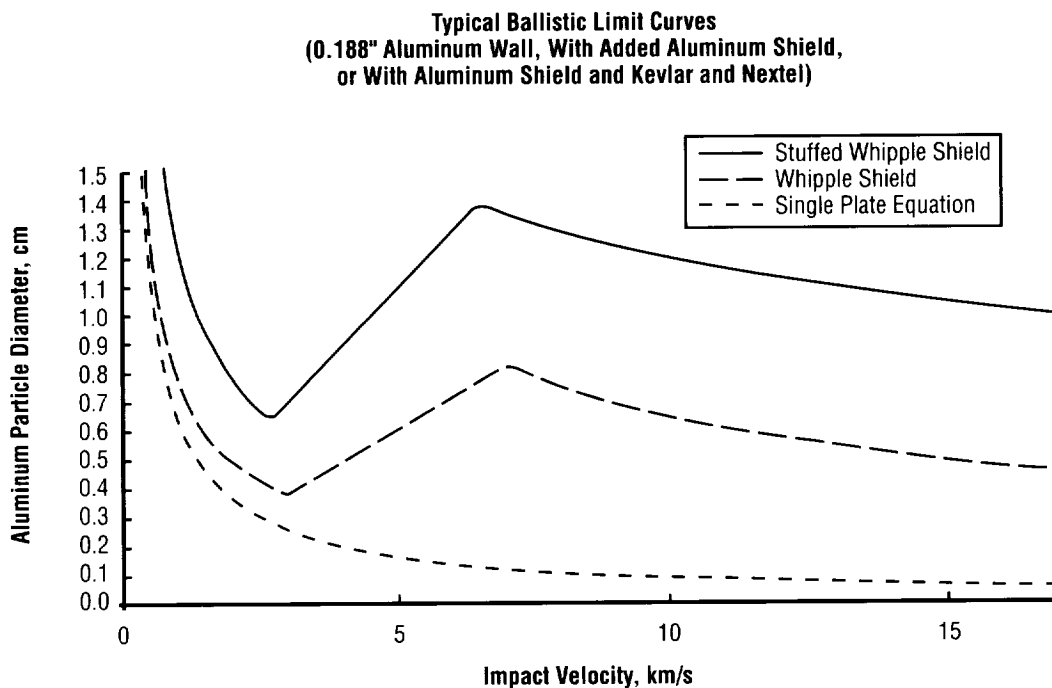


Figure 8. Typical ballistic limit curves.

Hypervelocity impact tests are used in the development, characterization, and qualification of hypervelocity shields for space vehicles and structures. Tests characterize performance models for various materials and structural configurations. The NASA White Sands Test Facility (WSTF) Hypervelocity Test Facility includes two-stage Light Gas Guns that use highly compressed hydrogen to launch projectiles near orbital debris velocities. Typical impact test requirements are (1) impactor sizes ranging from 0.4 mm to 19 mm, (2) velocities up to 7.5 km/s, (3) targets that can produce toxic, reactive, or explosive results, and (4) large test volume up to 700 successful tests per year. Figure 9 shows the WSTF Hypervelocity Test Facility.

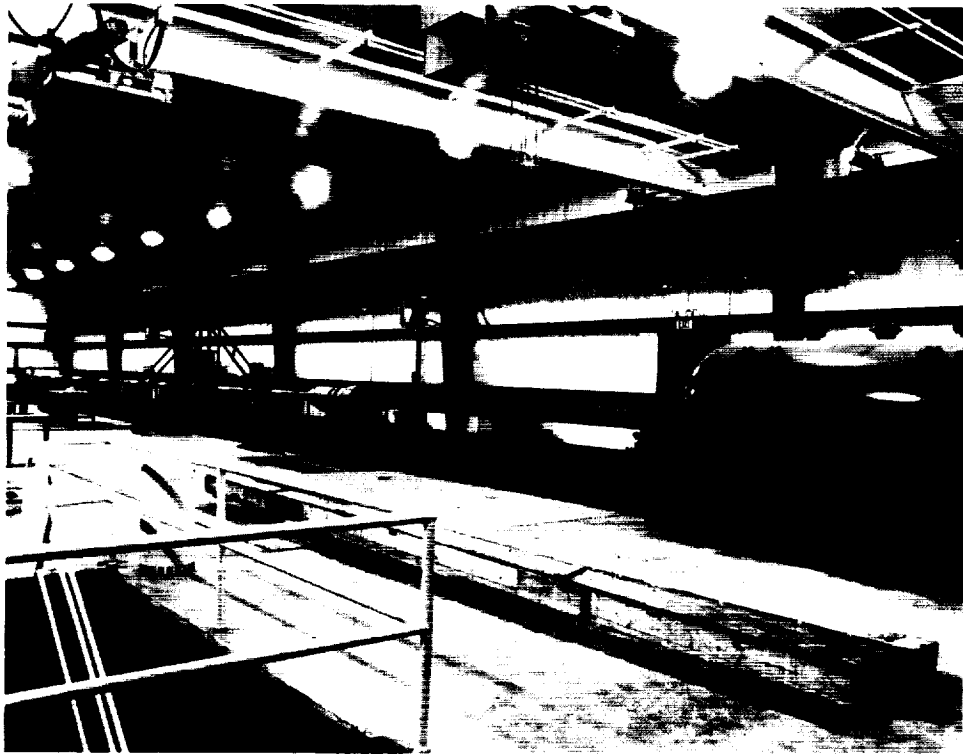


Figure 9. Hypervelocity Test Facility at White Sands Test Facility.

ORBITAL DEBRIS MITIGATION

To reduce the orbital debris threat to future space operations, NASA has established policy to guide programs in minimizing additions to the M/OD environment by reducing the number of objects released in space and lowering the possibility of accidental breakup. NASA Management Instruction 1700.8 defines the “Policy for Limiting Orbital Debris Generation” and calls for a formal assessment of programs relative to orbital debris generation potential. This policy requires programs to consider the debris generation potential during normal and malfunction conditions as well as their susceptibility to on-orbit impacts with existing debris. Final approval rests with the NASA Headquarters Program Associate Administrator.⁶

“Guidelines and Assessment Procedures for Limiting Orbital Debris,” NASA Safety Standard 1740.14, provides details on how to perform the assessment required by NASA policy. Assessments are to be performed at least twice during a program cycle: prior to the Preliminary Design Review (PDR) and prior to the Critical Design Review (CDR).

In the assessment, guidelines concerning debris generation potential are provided in the following events:

Normal Operations—Programs must limit the number and size of orbital debris with diameter greater than 1 mm and the orbital lifetime of objects passing through GEO including staging components, launching mechanisms, vehicle shrouds, and others. This is achieved by releasing objects at low altitudes where they will not remain in orbit or attaching objects such as lens caps with lanyards to the craft until reentry.⁸

Explosions and Intentional Breakups—Programs must reduce the risk of accidental explosion during mission operations and after the mission is complete. Intentional explosions must be planned so resulting debris has a short orbital lifetime. It is necessary also to assess risks to other programs due to debris clouds and to limit objects larger than 1 mm. Expelling remaining propellants and pressurants lowers the probability of accidental explosion. Intentional explosions in low altitudes have acceptable decay times.⁸

On-Orbit Collisions—Programs must assess the probability of collision with large debris or other space systems and design the spacecraft to withstand expected orbital debris impacts. Providing proper shielding to systems and components guards against fragmentation and mission failure.⁸

Post-Mission Disposal—After its functional lifetime the spacecraft must be removed from orbit to not hinder future operations. Removal is achieved by retrieving the craft within 10 years, designing it to decay within 25 years, or transferring it to a disposal orbit.⁸

Survival of Reentering Systems—The number and size of systems reentering the Earth's atmosphere must be limited in order to reduce the risk of human casualties caused by falling debris. The total debris casualty area may not exceed eight square meters. This reduces the probability of human injury to 0.0001 per reentry event.⁸

NASA METEOROID AND ORBITAL DEBRIS TECHNOLOGY PROGRAM

NASA has addressed the threat of meteoroids and orbital debris to orbiting spacecraft by establishing a Meteoroid and Orbital Debris Technology Program (M/OD TP), managed by the Systems Analysis and Integration Laboratory (SAIL) at the Marshall Space Flight Center (MSFC) and chaired by Mr. Pedro Rodriguez. The Program Working Group with members from across the Agency offers expertise and experience in many M/OD disciplines. These combined resources enhance accessibility to new technologies for all spacecraft development organizations.

The M/OD threat usually is addressed in preliminary design but often technical staffs do not have the benefit of results of relevant orbital debris studies. M/OD TP will coordinate resources, independent reviews, and assessments necessary for cost-effective spacecraft development for future missions.

Technologies developed under M/OD TP are divided into two categories:

Basic or Broad Based Technologies are tools, standards, and methodologies that will provide general engineering and scientific information to cover a broad spectrum of spacecraft. Key programs include creating a database on design performance, providing assessment models and guidelines, improving test capabilities, and offering independent review services.⁹

Depth Technologies will develop the capabilities needed to complete specific spacecraft development once an M/OD problem is identified. This includes providing performance models and supporting tests, developing design and analysis tools, and breaking new ground in M/OD technologies.⁹

The importance of this Program is recognized as the orbital debris population continues to grow because of increased frequency of space missions and collisions between existing debris result in a greater density of small and medium debris. Another benefit of the M/OD TP is the increased knowledge of the micrometeoroid environment. As deep space exploration advances, spacecraft enter environments with micrometeoroids traveling up to 250 km/s. Understanding the effects of impacts with these tiny particles is a crucial factor in design specifications.

Examples of current technology tasks of the M/OD TP include:

- On-Line Database for Orbital Impacts on Spacecraft
- PC Based M/OD Design Tool for Simple Spacecraft Geometries
- Meteoroid Impact Effects Model
- Review and Assessment Services
- Total System Risk Analysis Tool.

CONCLUSION

Meteoroids and orbital debris pose a serious threat to space operations. This primer addresses the need to maintain observations of current populations as well as develop new ways to better monitor smaller debris, design spacecraft to survive typical debris impacts, and follow NASA guidelines to curb debris proliferation.

Although orbital debris has various sources, compositions, and sizes, it is customarily classified by particle size. Large debris causes fatal damage to spacecraft in a collision, has a small population, and most objects are trackable. Medium debris is the most elusive because particles are too small to be adequately tracked by sensors. Medium debris offers the greatest challenge to designers since impacts have caused significant damage to spacecraft and threatened entire missions. Small debris is encountered but normal coating and shielding protect most sensitive areas from significant damage. Small debris, however, is a serious threat to tethers which are extremely long in length and small in diameter.

Designing spacecraft to withstand collisions without mission interruption is possible with passive protection systems such as Whipple bumpers, monolithic shields, and upgraded coatings. Developing systems to warn crews to actually move a spacecraft out of the path of oncoming debris is also possible.

Designing spacecraft not to breakup in expected collisions prevents debris proliferation. NASA has developed debris mitigation measures that require program management to assess and minimize the amount of debris released in orbit. Additional information on debris mitigation is in NASA Management Instruction 1700.8 and NASA Safety Standard 1740.14. In 1996 NASA established an M/OD Technology Program to provide necessary technologies to aid in the development of cost-effective and high-survivability spacecraft when exposed to the M/OD environment. For more information about the NASA Meteoroid and Orbital Debris Technology Program, contact Pedro Rodriguez (ED 51), George C. Marshall Space Flight Center at 205-544-7006.

If you have questions or comments concerning this primer, contact the MSFC Systems Analysis and Integration Laboratory, Electromagnetics and Areospace Environments Branch, Steven D. Pearson at 205-544-2350.

REFERENCES

1. National Research Council: "Orbital Debris A Technical Assessment." National Academy Press, Washington, DC, 1995.
2. The National Science and Technology Council Committee on Transportation Research and Development: "Interagency Report on Orbital Debris." Washington, DC, 1995.
3. David, Leonard: "Space Debris Damages French Military Satellite." *Space News*, August 26–September 1, 1996.
4. Zwiener, James M.: "Micrometeoroids/Space Debris Effects on Materials." NASA Conference Publication 3257, 1994.
5. Vaughan, W.W., Niehuss, K.O., and Alexander, M.B.: "Spacecraft Environments Interactions: Solar Activity and Effects on Spacecraft." NASA Reference Publication 1396, November 1996.
6. NASA Management Instruction 1700.8: "Policy for Limiting Orbital Debris Generation." Date TBD.
7. Frost, V.C.: "Meteoroid Damage Assessment." NASA Special Publication 8042, May 1970.
8. Office of Safety and Missile Assurance: "Guidelines and Assessments Procedures for Limiting Orbital Debris." NASA Safety Standard 1740.14, 1995.
9. NASA Marshall Space Flight Center: "NASA Meteoroid and Orbital Debris Technology Program." 1996.

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13. ABSTRACT (Maximum 200 words) The natural space environment is characterized by many complex and subtle phenomena hostile to spacecraft. The effects of these phenomena impact spacecraft design, development, and operations. Space systems become increasingly susceptible to the space environment as use of composite materials and smaller, faster electronics increases. This trend makes an understanding of the natural space environment essential to accomplish overall mission objectives, especially in the current climate of better/cheaper/faster. Meteroids are naturally occurring phenomena in the natural space environment. Orbital debris is manmade space litter accumulated in Earth orbit from the exploration of space. Descriptions are presented of orbital debris source, distribution, size, lifetime, and mitigation measures. This primer is one in a series of NASA Reference Publications currently being developed by the Electromagnetics and Aerospace Environments Branch, Systems Analysis and Integration Laboratory, Marshall Space Flight Center, National Aeronautics and Space Administration.				
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