# THE SPACE SHUTTLE PROGRAM PRE-FLIGHT METEOROID AND ORBITAL DEBRIS RISK/DAMAGE PREDICTIONS AND POST-FLIGHT DAMAGE ASSESSMENTS

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## ABSTRACT

Pre-flight meteoroid/orbital debris risk assessments are conducted prior to each Shuttle mission. The pre-flight risk assessments are used to determine the relative risk of each proposed mission. When the assessment indicates that the mission profile results in risks outside the accepted limits, changes to the mission profile are analyzed until such time as an acceptable risk is achieved. Pre-flight risk assessments are also used to test our knowledge of the orbital debris environment.

NASA's BUMPER code is utilized to compute the probability of damage from debris and meteoroid particle impacts based upon the Poisson statistical model for random events. To compute the probability of a penetration and/or failure of the Space Shuttle Orbiter requires inputting the geometry of critical systems; data on each subsystems ability to tolerate damage ( i.e. its "failure criteria"); the penetration resistance or ballistic limit equations for each system; and mission profile parameters such as flight altitude, attitude and the time spent in each altitude and attitude.

At the conclusion of each Shuttle mission the Orbiter is carefully inspected for meteoroid/orbital debris damage. Areas that are of particular importance are the Orbiter's radiator panels, the windows, and the reinforced carbon-carbon on the leading edge of the wings and on the nose cap. Contents of impact damage craters are analyzed using a scanning electron microscope to determine the nature and origin of the impactor.

Hypervelocity impact tests are often performed to simulate the observed damage and to estimate the size and velocity of the particle causing the damage. The number and type of impact craters provides valuable data that is used to monitor the orbital debris environment.

A review of the pre-flight predictions, and post flight assessments is presented for a series of Space Shuttle missions. In addition data is presented on meteoroid/orbital debris damage to the Hubble Space Telescope observed during the 1994 Hubble repair mission.


## 1. INTRODUCTION

Prior to every flight of the Space Shuttle, NASA performs a pre-flight meteoroid and orbital debris (M/OD) risk assessment. The purpose of the assessment is to ensure that each Shuttle mission is conducted in a manner that is consistent with NASA safety standards. It is NASA's objective to ensure that the M/OD is proportional to all the other risks associated with Shuttle missions and that the total risk is acceptable. Critical penetration odds for each Shuttle mission are generally maintained above 1 in 248 - a number which is equivalent or better than the estimated launch risk. Early mission termination risk due to radiator puncture is generally 1 in 60 or better. This risk is best managed by minimizing the time the Orbiter is flown in the payload bay forward attitude.

To perform this M/OD risk assessment, NASA/JSC has developed BUMPER, a M/OD threat assessment code. The overall concept of the BUMPER threat assessment is illustrated in Figure 1. To model the Orbiter the BUMPER code employs a finite element model of over 25,000 elements. The size of the elements vary with location on the Orbiter. The most critical areas are represented by the smallest elements. The BUMPER code also allows NASA to simulate the effects of shadowing of various parts of the Orbiter. Penetration equations are tailored to each element representing a portion of the Orbiter.

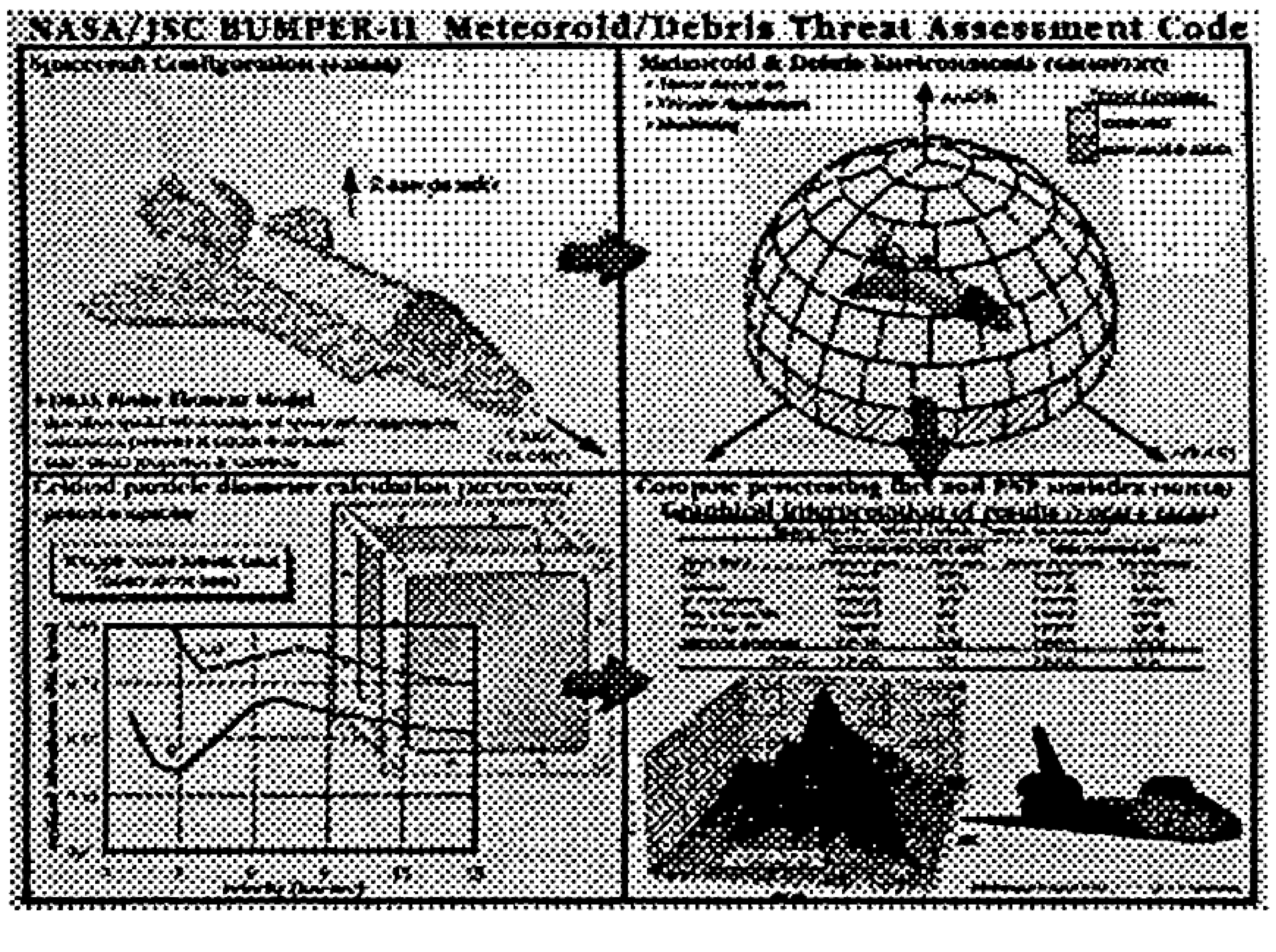


Figure 1. NASA/JSC BUMPER-II Meteoroid/Debris Threat Assessment Code

BUMPER uses the standard reliability equation for independent events - the Poisson Model - to compute the probability of no critical penetration or failure(PNCF).

PNCF(Total) = PNCF(1) x PNCF(2) x....x PNCF(i) x.....x PNCF(n)

The total system PNCF is computed from the product of each subsystem PNCF(i). Each PNCF(i) is determined from Poisson statistics using the flux of M/OD particles above the "ballistic limit" of the subsystem, F(i) - (#/sq.m.-yr); exposed area A - (sq. m.); and time t - (yr). Where

PNCF(i) = exp.{-F(i)*A*t}

This is the standard analytical tool used by NASA since pre-Apollo days. The Poisson Model is valid when there is a large number of independent events and each event has a small probability of occurring. M/OD meet the criteria for independence and are analyzed with BUMPER using the NASA M/OD environment model. Cases involving a recent breakup or meteor storm are analyzed separately using specialized break-up models.

## 2. INPUTS TO THE BUMPER CODE

To compute the probability of impact using the Poisson Model requires an accurate M/OD environment model, the configuration of the Orbiter, and a mission profile. To compute the probability of penetration and/or failure requires: a. knowledge of the geometry of all critical subsystems; b. data on each system's ability to tolerate damage (i.e. failure criteria); and c. penetration resistance or ballistic limit equations for each system.

## 3. OUTPUTS OF THE BUMPER CODE

BUMPER generates the probability of M/OD impacts for given size particles and the probability of M/OD impact damage. Impact damage includes a prediction of the number of window replacements; penetration of the reinforced carbon carbon (RCC) on the leading edge of the Orbiter wings and on the nose cap; and the probability of penetrating one of the Orbiter's radiator tubes. BUMPER also predicts a probability of "critical" damage from an M/OD impact. BUMPER predicts these probabilities as a function of their location on the Orbiter and splits these probabilities between meteoroids and orbital debris.

Calculating the critical penetration of the Orbiter is, in many ways, similar to calculating the survivability of combat damaged aircraft. The later case involves the identification of critical components. It also involves computing the probability of loss due to combat damage based upon the critical components projected area, a projectiles ability to penetrate the aircraft's skin, and the degree of damage to each critical component. The primary difference is that much data exists on returning aircraft that have sustained significant combat damage.

It was recognized by the Shuttle Program that the original catastrophic failure criteria set by the Shuttle Program was unrealistically severe. The original criteria allowed no penetrations in the bottom side of the leading edge RCC on the Orbiter's wings nor did it allow penetrations of the wings or wing elevons. Relaxation of these severe criteria was recently implemented.

Today, 2.5 cm. diameter holes are allowed to occur in the upper portion and most of the lower portion of the leading edge RCC. Penetrations are now allowed in many areas of the wing, as long as these penetrations are not near major support structure. It should be noted that although significant damage to the Orbiter is allowed from a catastrophic viewpoint (i.e. it will not result in loss of the vehicle), damage of this type is still of concern to NASA, because it could require significant downtime to repair.

## 4. ANALYSIS OF BUMPER CODE PREDICTIONS

Table 1 shows the minimum size particle that can damage or penetrate various systems on the Orbiter. Table 2 shows a comparison of the critical areas on the Orbiter.

Table 1. Damage Thresholds of the Orbiter

- To Penetrate EMU: 0.4 mm
- To Penetrate Orbiter's Radiator Tubes: 0.5 mm
- To Penetrate Orbiter's Reinforced Carbon Carbon Panels on Leading Edge of Wings: 1.0 mm
- To Penetrate Orbiter's Thermal Protection System Tiles: 3 - 5 mm
- To Penetrate into Orbiter Crew Cabin: 5.0 mm
- To Cause Payload Bay Damage: 0.1 - 1.0 cm
  - Contains Exposed Pressurized Tanks Covered with MLI
  - Spacelab/Spacehab Modules do not have Bumper Shields
- To Require Replacement of Window: 0.04 mm

Table 2. Comparison of Critical Areas

- Total Window Area = 3.7 sq. m.
- Critical Radiator Area = 12.9 sq. m.
  - Out of a Total of 129 sq. m.
- Projected Area of Reinforced Carbon Carbon (Wing) = 10.8 - 17 sq. m.
- Projected Area of Reinforced Carbon Carbon (Nose) = 2.2 sq. m.

Total Wetted Area of Orbiter is 1199 sq. m.

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## 5. RESULTS OF BUMPER ANALYSES

Table 3 lists the BUMPER prediction for Orbiter window replacements and compares these predictions to actual window replacements for Shuttle missions STS-72 through STS-80. In almost all cases actual window replacement rates exceeded the BUMPER prediction. BUMPER analyses of STS missions prior to STS-80 used the 1991 model of the M/OD environment. This 1991 environment model under predicted the small (0.1 - 0.01 cm) size particles at Shuttle altitudes. Thus BUMPER under predicted the window replacement rate.

Table 3. Recent Shuttle Window Damage

| | BUMPER Prediction | Windows Replaced | Window Pits |
|---|---|---|---|
| STS - 73 | 1.21 | 2 | 8 |
| STS - 74 | 0.73 | 0 | 2 |
| STS - 72 | 0.3 | 0 | 0 |
| STS - 75 | 0.5 | 1 | 7 |
| STS -76 | 0.7 | 1 | 20 |
| STS - 77 | 0.46 | 2 | 13 |
| STS - 78 | 0.3 | 1 | 2 |
| STS - 79* | 0.75 | 4 | 12 |
| STS - 80* | 0.42 | 2 | 31 |

* Orbiter flew through HAPS fragmentation cloud

Post flight damage analysis of Orbiter windows was one of the main data sources that led to the development of the 1996 M/OD environment.

BUMPER was not used for pre-flight M/OD analysis during most early Shuttle missions. BUMPER predictions for window replacements for selected Shuttle missions through STS-73 were 30% below actual window replacements. BUMPER predicted 15 window replacements on these selected missions versus and actual replacement of 21 windows. A total of 63 windows have been replaced due to M/OD window pits through the STS-80 mission.

## 6. BUMPER ANALYSIS ON HUBBLE SPACE TELESCOPE

The Hubble Space Telescope (HST) was put into orbit in April 1990. NASA conducted the first Hubble Space Telescope Repair Mission in December 1993. During that repair mission NASA conducted a photographic survey of parts of the HST using the Orbiter's closed circuit television cameras. The purpose of the survey was look for signs of M/OD damage. The survey showed a major M/OD impact site located in one of the one meter diameter graphite epoxy TDRSS high antennas. Analysis of the photographs indicate a hole of approximately 1.0 cm x 1.9 cm.

Hypervelocity impact tests on the graphite epoxy honeycomb structure of the high gain antenna indicate that the damage was caused by a 0.5 to 1 cm. class impactor. An impactor this size is almost certainly orbital debris as opposed to a micrometeoroid.

There is no way to ascertain when, during the 43 months that the HST was in orbit, this 1 cm. object penetrated the high gain antenna. The most conservative assumption would be that the damage occurred just prior to the HST servicing mission. Using this assumption, BUMPER analysis, of the 172 square meter wetted area of the HST, indicates a 1/200 probability of no penetration by an object this diameter in the 43 months the HST was in orbit.

## 7. SIGNIFICANCE OF STS 73/72/75/79 IMPACTS

Rigorous post flight M/OD damage assessments began on all Orbiters following the STS-71 mission. Because large areas of the Orbiter are subject to damage from debris during launch and landing, the M/OD damage assessments are limited to selected areas such as the Orbiter windows, the payload bay doors, the RCC surfaces on the wings and nose cap, and a limited number of other surfaces.

A large impact crater was detected on each of the STS-73, 72, 75, and 79 Orbiters during these post flight damage assessments. In each case the impactor was a one millimeter class orbital debris object. Post flight analysis indicated that the impactor during the STS-73 mission was a piece of electronics, the impactor during the STS-72 mission was aluminum, the impactor during the STS-75 mission was aluminum, and the impactor during the STS-79 mission was aluminum.

BUMPER analysis indicated that the probability of a impact for a particle greater than 1 mm on the payload bay doors during the STS-73 mission was 1 in 700. Similarly the probability of a single 1 mm impact on the observed surfaces of all Shuttle missions through STS-73 was only 1 in 11.

## 8. IMPROVING THE VULNERABILITY OF THE SHUTTLE TO M/OD DAMAGE

Preflight BUMPER analyses often result in the necessity to replan Shuttle missions when these analyses indicate that the risk of M/OD damage exceeds acceptable limits. The areas of greatest concern on the Orbiter most often include the RCC on the leading edge of the wings, the freon tubes associated with the payload bay door radiators, and pressure bottles located on the extended duration pallet in the Orbiter's payload bay.

Two activities are underway to examine and improve the vulnerability of the Orbiters to M/OD damage. An internal study headed by Dr. William Schneider is looking at improving the protection on the pressure bottles and freon tubes. This study is also aimed at a better understanding of the acceptable level of damage the Orbiter can tolerate from M/OD impacts during a mission.

The "Schneider Committee" is studying safety improvements which include the addition of Nextel shielding around exposed high pressure bottles in the payload bay and the addition of aluminum shielding over the vulnerable portion of the freon tubes in the Orbiter's radiators.

A second study has been commissioned by NASA. This study will be conducted by a committee of the Nation Research Council and will review the Shuttle Program's approach to M/OD risk assessments.

## 9. SUMMARY AND CONCLUSIONS

BUMPER has proven to be a valuable tool for assessing the M/OD risk to the Shuttle. In all cases where adequate data exists, actual M/OD damage has exceeded the BUMPER predictions. The preflight BUMPER assessment process has reduced M/OD damage and enhanced safety during Shuttle missions.

## 10. REFERENCES

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