BUMPER:
A TOOL FOR ANALYZING SPACECRAFT MICROMETEOROID AND ORBITAL DEBRIS RISK

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ABSTRACT

"*Bumper*" is a computer program for analyzing spacecraft micrometeoroid and orbital debris (MMOD) risk. Bumper was developed in the late-1980s and has been continuously maintained and used since. The user base has grown from a few government entities now include numerous commercial entities as well. The National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) Hypervelocity Impact Technology (HVIT) group is responsible for all aspects of the Bumper software. Bumper has been used to characterize MMOD risk on many spacecraft. All of the International Space Station (ISS) modules, visiting vehicles and numerous external components and systems have been analyzed. Bumper was used to analyze the Space Shuttle, Orion, and many space probes, telescopes and satellites. Bumper is also being used to analyze future spacecraft such as the Deep Space Gateway (DSG) and Mars Sample Return (MSR) missions. The Bumper Configuration Control Board (CCB) ensures that all changes to the code are approved, reviewed, and documented. The current Bumper version – "Bumper 3" – is a Fortran executable that utilizes a 64-bit architecture. Bumper has numerous features that make it a powerful tool for analyzing spacecraft MMOD risk. Bumper uses the latest orbital debris and meteoroid environment models. Bumper also has a large library of ballistic limit "damage" equations available that can be used for a wide variety of MMOD shielding configurations. Bumper can also handle large spacecraft finite element models (FEMs) and conducts checks of the model. This paper introduces Bumper and the MMOD risk analysis process using a simplified cube-shaped spacecraft model.

1 INTRODUCTION

"Bumper" is a spacecraft risk reduction tool. More specifically, "Bumper" is a computer program used to analyze spacecraft micrometeoroid and orbital debris (MMOD) impact risk or penetration risk [1]. This risk information can then be used to identify high-risk areas and develop risk mitigation strategies such as enhanced shielding, spacecraft reorientation, and visual inspection. Similarly, the same risk results can help identify low-risk areas that may be opportunities for mass reduction and cost savings. Bumper also includes tools to help reduce testing costs. Bumper is an extremely valuable risk reduction and cost savings tool in the spacecraft risk management tool set [2].

2 BUMPER

In the context of MMOD shielding, a "bumper" is the name of the outermost layer of most types of multi-layered MMOD shielding. It is usually a thin metal or fabric layer positioned at a short distance from a protected surface (e.g., pressure module, fuel tank, battery). The bumper works by turning the high velocity of the impacting particle against it by instigating shockwaves within the particle that break it up before it has a chance to damage the underlying protected surface. The bumper was invented by Dr. Fred Whipple in 1947 as part of his Whipple "meteoroid bumper" shield [3]. A bumper is the key component in many types of MMOD shields and is the namesake of the Bumper risk analysis program. The Bumper risk analysis program was created in the late-1980s. The National Aeronautics and Space Administration (NASA) Hypervelocity Impact Technology (HVIT) group has been responsible for the Bumper software for most of the time since. HVIT's Bumper Software Configuration Control Board (CCB) oversees all changes and distributions of Bumper. Bumper has also been provided to the ISS International Partners (IPs) as well as many commercial aerospace companies.

3 CAPABILITIES

The Bumper program can provide spacecraft MMOD risk for a wide variety of space environments including near-Earth and within the orbit of Mars. Bumper has many analysis options including those for: type of threat (meteoroids, orbital debris), type of analysis (impact, penetration), type of result (probability of event, or number of events), MMOD environment model (numerous meteoroid and orbital debris models since 1991 are available), spacecraft finite element model type (universal file format), spacecraft orientation (roll, pitch, and yaw), altitude, inclination, exposure time period, and other analysis-specific options. Bumper also has several additional options to support data visualization.

4 SPACECRAFT

NASA HVIT has used Bumper to analyze a variety of spacecraft [4]. The International Space Station (ISS) and the Space Shuttle programs were the main users of Bumper in the 1990s and early 2000s [5, 6, 7]. For ISS, all of the modules, visiting vehicles, and many of the external exposed hardware components have been analyzed in detail using Bumper. ISS hardware has been designed and even modified on orbit based on results from Bumper. Bumper supported almost every Space Shuttle mission since the early-1990s to analyze the risk of “critical penetration,” “radiator leak,” and “window replacement” risks. These results were presented to NASA Management as part of each shuttle mission flight readiness review. More recently, Bumper has been used on new crewed vehicles such as Orion, Boeing Starliner, and SpaceX Crew Dragon. Cargo vehicles such as Northrop Grumman Cygnus, SpaceX Cargo Dragon, Automated Transfer Vehicle, and H-II Transfer Vehicle have been developed in part using Bumper. Bumper has also been used on numerous satellites and space probes including Hubble Space Telescope, James Webb Space Telescope, Fermi Gamma-ray Space Telescope, Stardust, New Horizons, Parker Solar Probe Plus, Joint Polar Satellite System, Landsat, and the Alpha Magnetic Spectrometer (AMS-02). Bumper is also being used on future spacecraft such as Lunar Gateway, Mars Sample Return Earth-Entry Vehicle, and advanced spacesuits.

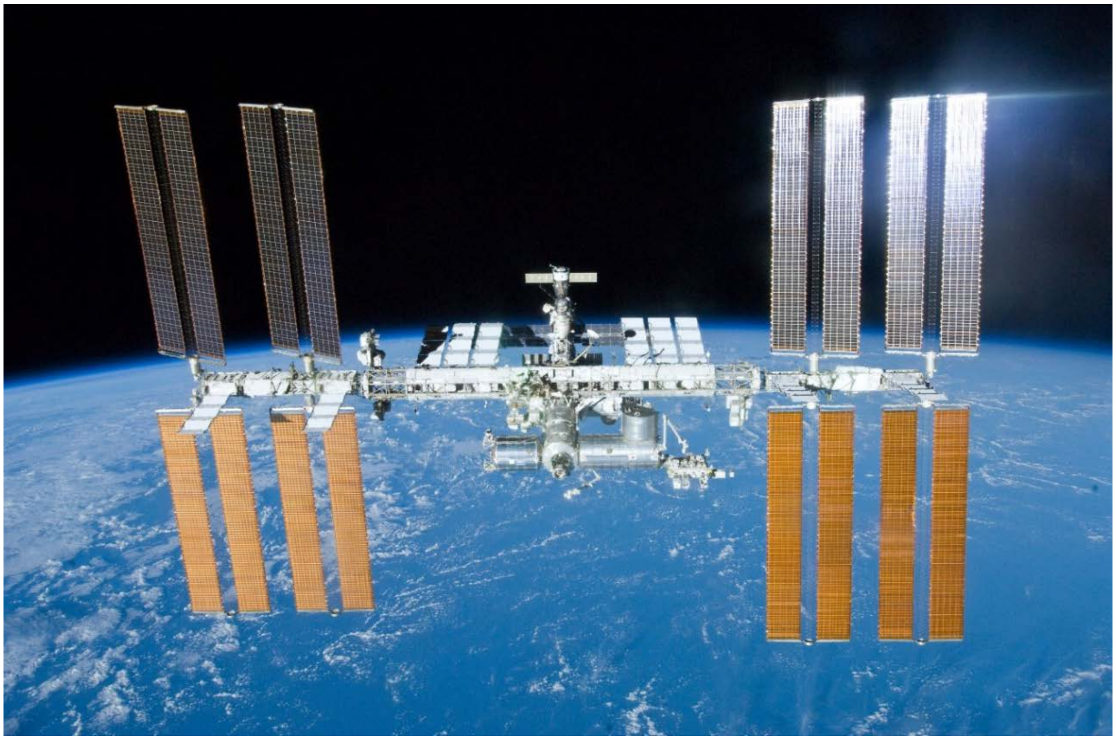

Fig. 1. International Space Station.

5 RISK ANALYSIS PROCESS

The Bumper MMOD risk analysis process is shown in Fig. 2. It is an iterative process that starts with (note purple-colored boxes) defining the spacecraft shape, meteoroid and orbital debris environment models, operating parameters (e.g., orbit, altitude, and inclination), failure criteria for each spacecraft surface, and hypervelocity impact test and analysis results. Bumper uses these inputs along with the MMOD environment models and ballistic damage equations to calculate probability of no failure. The resulting probability is then compared to a protection requirement to see if it meets the requirement or not. If not, then an initial iteration to verify inputs (failure criteria, ballistic limit equations, test data, and spacecraft shape) is performed. If changes were made during any part of the iteration, then Bumper is run again with the updated information and another comparison is made to the requirement. The process is iterated until no additional changes in the inputs occur. A typical Bumper risk analysis takes at least several of these iterations, often more. If the probability meets the protection requirement, then additional steps are taken (see cyan-colored boxes) to compare the probability result against actual observed impact damage. This is often done through post-flight visual impact inspections of returned spacecraft hardware [8].

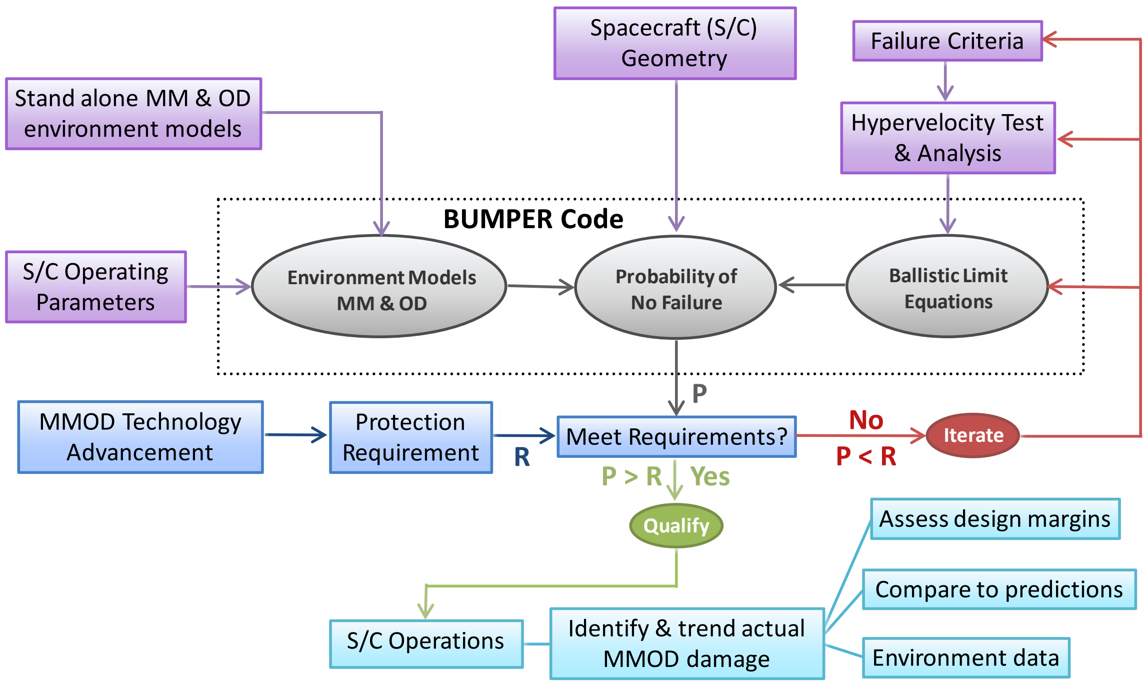

Fig. 2. Bumper Risk Analysis Process.

6 RUNNING BUMPER

Bumper has three main modules: (1) Geometry, (2) Response, and (3) Shield. They are generally run in that order, but the sequence depends on the type of analysis. Bumper can provide results for two types of analysis: (1) Impact, or (2) Penetration. "Impact" risk pertains to the chance of a MMOD particle contacting the outermost surface of a spacecraft. It does not consider anything that could happen after impact such as cratering or module penetration. "Penetration" risk does include the chance of some level of damage after impact. The level of damage depends on the impact resistance of that region of the spacecraft. The impact resistance is defined using mathematical descriptions of the damage known as ballistic limit equations (BLEs). The BLE and failure criteria information is specified in the Response module (2) and consists of informing Bumper which BLE to use for each region and supplying the shield-specific inputs required for that BLE. The inputs are usually related to physical aspects of the hardware such as thicknesses, types of materials, gap distances, and areal densities. Most of the BLEs are also a function of impact velocity, impact angle, particle density, wall density, yield strengths, etc., but Bumper calculates or gets these inputs from other sources. So, for an impact risk analysis - which does not require BLEs - typically just Geometry (1), then Shield (3) are run since the damage equations are not needed. For a penetration risk analysis, Geometry (1), Response (2), and then Shield (3) are run, although Response can be run at any time before Shield including before Geometry. Geometry (1) must always be run before Shield (3).

7 FAILURE CRITERIA

How much damage can a spacecraft surface withstand before it fails? What exactly is a fail? Is failure a crater in a window pane or a crack all the way through? If it is a crater, how wide or deep of a crater? If it is all the way through, is there another layer beneath it? Can that next layer withstand damage? How much damage? Can the crater be anywhere on a window? Is the crater diameter or depth a function of location on the window pane? If in defining failure criteria for say a heat shield, can the heat shield withstand a through-hole or just a surface crater? Maybe the shield is an inflatable module that can handle some damage but not a complete perforation. How deep – specifically to which exact layer – can the penetration go before the shield fails? Is hypervelocity impact test data needed? Is additional related testing such as fracture tests or reentry simulation tests needed? These questions are meant to illustrate the level of specificity necessary to adequately define the failure criteria for an analysis. Answers to these questions often are not immediately available and require additional research, analysis, and sometimes testing before defining the failure criteria. Additionally, sets of failure criteria are often grouped under a common outcome such as Loss-of-Crew (LoC), Loss-of-Mission (LoM), Evacuation, or Penetration.

8 ANALYSIS EXAMPLE

The following risk analysis example illustrates how to analyze a simple cube-shaped spacecraft measuring 1 meter on a side in an ISS altitude of 400 kilometers and orbit inclination of 51.6 degrees. Exposure period is January 1, 2020 through December 31, 2020 (i.e., exactly 1 year). The 1991 meteoroid and orbital debris models defined in NASA Space Station Program (SSP) document SSP-30425, Rev. B were used in the analysis. While the 1991 MMOD environment models are not the latest, they are sufficient for this example. Results are presented in tabular format in addition to some of the optional graphical outputs (i.e., color-contour, vbeta, rplot).

8.1 Spacecraft Model:

Bumper uses the spacecraft shape and size to accurately calculate how many MMOD particles reach each of the spacecraft's surfaces. Bumper recognizes that some spacecraft surfaces face away and some towards the direction that the MMOD particle is approaching. Bumper also accounts for situations where one hardware structure blocks, or "shadows" another. It also uses this spacecraft shape to determine the angle of impact since many of the BLEs use impact angle. The spacecraft shape and size is specified by generating a Finite Element Model (FEM) containing three-dimensional coordinates of a sufficient number of surface points called nodes. These nodes are then collected into sets of three or four nodes called elements. A FEM is usually produced using one of the available computer-aided design (CAD) software applications. Creating the spacecraft FEM is usually the first step in the analysis process and is often the most time consuming step. The FEM should be based on the most current, accurate, CAD model of the spacecraft. This CAD model typically comes from the spacecraft manufacturer. In cases where a CAD model is not available, representative models and FEMs of the spacecraft and hardware can be produced but is usually more time consuming and potentially less accurate.

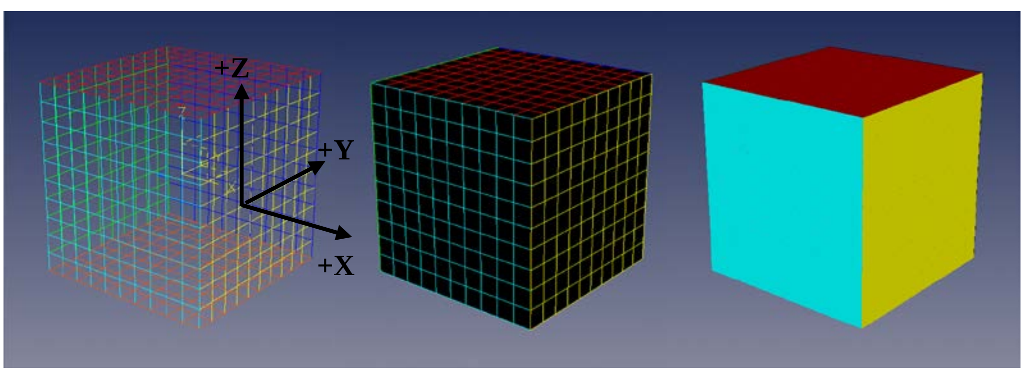

Fig. 3. Spacecraft "Cube" Finite Element Model (wireframe, solid with mesh, solid views).

Three images of our cube spacecraft model are shown in Fig. *3*. The leftmost is a wireframe, or "see-through" representation. The one in the middle has the backside "hidden surfaces" removed, but the edges of the elements visible. The rightmost one is an opaque "solid" view without the wireframe visible. In the left and middle images, the squares are Elements and the corners of the Elements are Nodes. For the cube FEM, each side is 10 elements wide by 10 elements high, so 10 x 10 = 100 elements on each side and 600 elements total. Bumper uses only quadrilateral and triangular thin-shell elements having four nodes and three nodes each, respectively. The colors of these elements and nodes are arbitrary and are only used by the analyst to simplify visual identification of a given surface or other attribute. Bumper does not recognize FEM element colors in the analysis.

8.2 Geometry:

Geometry is the foundation of the analysis so it is typically run first, but only after the FEM is produced. Geometry inputs include: spacecraft FEM name, analysis type (meteoroids or debris), environment model (meteoroids or debris), and user-defined names of two output files. One of these two output files is a binary (i.e., not visually readable) format and the other is a readable text file. The binary is used by Bumper in the Shield module and the text file is a log of user Geometry inputs. Note that Geometry is usually run at least twice – once for meteoroids and once for orbital debris. Additional pairs of runs are also needed for changes in spacecraft attitude, altitude, inclination, year of flight, failure criteria. For cislunar and other non-Earth orbit missions, only meteoroid Geometry runs are needed due to the lack of orbital debris in that region of space. The Geometry text file logs for our example Geometry runs are shown in Fig. 4. Note that several options for MMOD environment models are available.

```
BUMPER3-SAT-3.19.0305.0   ** G E O M E T R Y **        03-NOV-2019 14:56:47.298
LAST COMMIT DATE: 2019/03/05 14:17:13 STATE OF CURRENT EXE: Modified

NAME OF THIS FILE: example_d.gsum

ANALYSIS TYPE ?
   1 - MAN-MADE DEBRIS
   2 - METEOROIDS
CHOICE ? (1 OR 2) =>  1

ENVIRONMENT DEFINITION ?
   1 - SSP30425
   2 - ORDEM2000
   3 - ORDEM 3.0 <CR>
CHOICE ? (1, 2, OR 3 [3] =>   1

SUPERTAB UNIVERSAL FILENAME ? [ model.unv ] => cube.unv

GEOMETRY BINARY OUTPUT FILENAME ? [ geometry.gem ] => example_d.gem

ROTATE THE MODEL (Y/N) ? [ NO ] => N

NUMBER OF THREATS =>    45

   ********** MAN-MADE DEBRIS THREAT CASES COMPLETED  45 **********
```

```
BUMPER3-SAT-3.19.0305.0   ** G E O M E T R Y **        03-NOV-2019 14:57:22.379
LAST COMMIT DATE: 2019/03/05 14:17:13 STATE OF CURRENT EXE: Modified

NAME OF THIS FILE: example_m.gsum

ANALYSIS TYPE ?
   1 - MAN-MADE DEBRIS
   2 - METEOROIDS
CHOICE ? (1 OR 2) =>  2

ENVIRONMENT DEFINITION ?
   1 - SSP30425
   2 - MEMCxPv2
   3 - MEMR2 <CR>
CHOICE ? (1, 2, OR 3) [ 3 ] =>  1

SUPERTAB UNIVERSAL FILENAME ? [ model.unv ] => cube.unv

GEOMETRY BINARY OUTPUT FILENAME ? [ geometry.gem ] => example_m.gem

ROTATE THE MODEL (Y/N) ? [ NO ] => N

NUMBER OF THREATS =>   149

SPACECRAFT ALTITUDE (KM) ? [ 400.0 ] =>     400.00

   ********** METEOROID THREAT CASES COMPLETED 149 **********
```

Fig. 4. Geometry module log files for orbital debris (left) and meteoroids (right).

8.3 Response:

Response can be run at any time before Shield. Like Geometry, Response is typically run once for meteoroids and once again for orbital debris. Changes in spacecraft attitude or altitude do not require additional Response runs. However, if there are multiple sets of failure criteria (e.g., PNP, LoC, LoM, etc.), then additional pairs of meteoroid and debris response files are run for each of those cases as well. Response inputs include analysis type (meteoroids or debris), environment model, environment-specific inputs, and user-defined names of two output files. One of these two output files is a binary and the other is a text file. The binary is used by Bumper in the Shield module and the text file is a log of user Response inputs. The binary can be converted to a readable format (described in Section 0) and tabulated or graphed as shown in Fig. 5. These are graphs of the BLEs called Ballistic Limit Curves (BLCs). Bumper currently has over a hundred BLEs, but not all are available in all versions of Bumper due to distribution limitations. In our cube example, each side of the cube requires a BLE defined in the Response step. For this analysis, we will just assign a basic 1mm thick aluminum single-layer shield BLE with threshold perforation failure criteria to each of the six cube surfaces. The readable text log files are shown in Fig. 6.

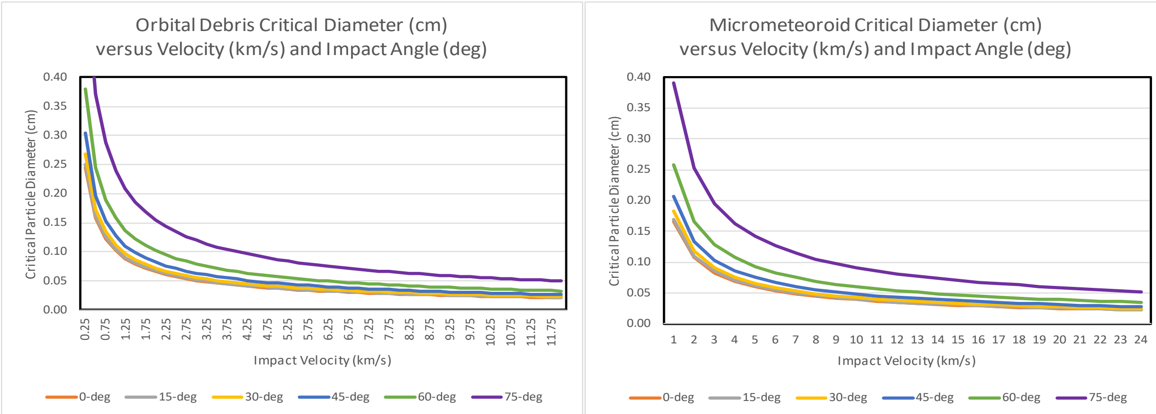

Fig. 5. Ballistic Limit Curves (BLCs) of damage equations (BLEs) used in this analysis for orbital debris (left) and meteoroids (right).

```
BUMPER3-SAT-3.19.0305.0    ** R E S P O N S E **   03-NOV-2019 14:20:17.666
LAST COMMIT DATE: 2019/03/05 14:17:13 STATE OF CURRENT EXE: Modified

RESPONSE MODULE SUMMARY FILE

NAME OF THIS FILE:                              example_d.rsum

NAME OF THE RESPONSE BINARY OUTPUT FILE:        example_d.rsp
MAN-MADE DEBRIS ANALYSIS
SSP 30425 DEBRIS ENVIRONMENT
MAN-MADE DEBRIS CONSTANT DENSITY OPTION (2.80 g/cm^3)


 PROPERTY ID NUMBER =      1
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      2
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      3
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      4
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      5
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      6
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI
```

```
BUMPER3-SAT-3.19.0305.0    ** R E S P O N S E **   03-NOV-2019 14:42:30.092
LAST COMMIT DATE: 2019/03/05 14:17:13 STATE OF CURRENT EXE: Modified

RESPONSE MODULE SUMMARY FILE

NAME OF THIS FILE:                              example_m.rsum

NAME OF THE RESPONSE BINARY OUTPUT FILE:        example_m.rsp
METEOROID ANALYSIS
SSP 30425 METEOROID ENVIRONMENT
METEOROID CONSTANT DENSITY OPTION (1.00 g/cm^3)


 PROPERTY ID NUMBER =      1
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      2
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      3
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      4
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      5
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI


 PROPERTY ID NUMBER =      6
   BLE name => courpal
        PERFORATION FAILURE CRITERIA
        REAR WALL MATERIAL =>                          6061-T6
        REAR WALL THICKNESS (CM) =>                    0.1
        MLIposition =>                                 NO_MLI
```

Fig. 6. Response module text log files for orbital debris (left) and meteoroids (right).

8.4 Shield:

Shield is always run last and is the step that generates the actual MMOD risk results. The results are written out in readable text files, which are then usually imported into Excel for analysis. Shield is run once for meteoroids and once for orbital debris for each failure criteria. Shield inputs include: result type (probability or number of events, impact or penetration), Geometry binary filename (generated in earlier Geometry step), Response binary filename (also generated earlier in the Response step), environment-specific inputs, exposure time period, altitude, inclination, and FEM element number ranges that we want to know the MMOD risk. We could simply ask Bumper for MMOD risk for each individual or all of the cube's 600 elements, but we can ask Bumper to produce results at a meaningful level of detail, such as one result for each of the six sides of the cube. Bumper will combine results from contiguous set of element numbers to yield the same result as if we combined the results from each element. For our simple cube, the element identification (EID) numbers ranges are: front face 1000-1099, port face 1100-1199, aft face 1200-1299, starboard face 1300-1399, zenith face 1400-1499, and nadir face 1500-1599. These orientation references "faces" refer to the un-rotated cube.

8.5 Results:

Results from the Shield output text files are shown in Fig. 7, and were analyzed in Excel as shown in the Table 1, below.

```
 BUMPER3-SAT-3.19.0305.0    *** S H I E L D ***    03-NOV-2019 15:25:28.459
LAST COMMIT DATE: 2019/03/05 14:17:13 STATE OF CURRENT EXE: Modified

RSP FILE CREATED USING BUMPER =>      SAT-3.19.0305.0
GEM FILE CREATED USING BUMPER =>      SAT-3.19.0305.0

SHIELD MODULE SUMMARY FILE

M A N - M A D E   D E B R I S    A N A L Y S I S

Summary file : example_d.sum
I-Deas file  : cube.unv
Geometry file: example_d.gem
Response file: example_d.rsp
Contour file : example_d.uni

ROTATION AXES AND ANGLES (DEGREES)
 No Rotations

SSP 30425 DEBRIS ENVIRONMENT
NUMBER OF THREATS                  =                         45
SPACECRAFT ORBIT INCLINATION (DEG) =                    51.6000
SPACECRAFT ALTITUDE (KM)           =                     400.00

BEGINNING EXPOSURE DATE            =                  2020.0000
SPACECRAFT EXPOSURE TIME (YEARS)   =             0.1000000E+01
SOLAR RADIO FLUX LEVEL (10**4 JY)  =                    70.0000

RANGE  STARTING EID  ENDING EID  PENETRATIONS      AREA (M^2)
    1         1000        1099    4.52929E-01       1.0000000
    2         1100        1199    1.05100E-01       1.0000000
    3         1200        1299    0.00000E+00       1.0000000
    4         1300        1399    1.05100E-01       1.0000000
    5         1400        1499    0.00000E+00       1.0000000
    6         1500        1599    0.00000E+00       1.0000000

TOTAL NUMBER OF PENETRATIONS =  6.63128E-01
```

```
 BUMPER3-SAT-3.19.0305.0    *** S H I E L D ***    03-NOV-2019 15:27:02.273
LAST COMMIT DATE: 2019/03/05 14:17:13 STATE OF CURRENT EXE: Modified

RSP FILE CREATED USING BUMPER =>      SAT-3.19.0305.0
GEM FILE CREATED USING BUMPER =>      SAT-3.19.0305.0

SHIELD MODULE SUMMARY FILE

M I C R O - M E T E O R O I D    A N A L Y S I S

Summary file : example_m.sum
I-Deas file  : cube.unv
Geometry file: example_m.gem
Response file: example_m.rsp
Contour file : example_m.uni

ROTATION AXES AND ANGLES (DEGREES)
 No Rotations

SSP 30425 METEOROID ENVIRONMENT
NUMBER OF THREATS                  =                        149
SPACECRAFT EXPOSURE TIME (YEARS)   =              0.1000000E+01
SPACECRAFT ALTITUDE (KM)           =                     400.00
METEOROID VELOCITIES IN SSP 30425 REV. A

RANGE  STARTING EID  ENDING EID  PENETRATIONS      AREA (M^2)
    1         1000        1099    4.67960E-01       1.0000000
    2         1100        1199    1.05912E-01       1.0000000
    3         1200        1299    1.60957E-02       1.0000000
    4         1300        1399    1.05912E-01       1.0000000
    5         1400        1499    1.38128E-01       1.0000000
    6         1500        1599    9.82598E-04       1.0000000

TOTAL NUMBER OF PENETRATIONS =  8.34991E-01
```

Fig. 7. Bumper MMOD Risk Results with debris (left) and meteoroids (right).

Table 1. Example Analysis Results for Cube Spacecraft.

Example Analysis Results: Cube																		
			Number of Penetrations (Np) (from Bumper text file)			Probability of No Penetration (PNP) ($PNP = e^{-Np}$)			Penetration Risk (Risk = 1-PNP)			Odds (Odds = 1/Risk)						
Region	From EID	To EID	Debris	Meteoroids	Combined	Debris	Meteoroids	Combined	Debris	Meteoroids	Combined	Debris	Meteoroids	Combined	% of Total Risk	FEM Surface Area (m^2)	% of Total Area	% of total risk / % of total area
front	1000	1099	4.53E-01	4.68E-01	9.21E-01	0.6358	0.6263	0.3982	3.64E-01	3.74E-01	6.02E-01	1 in 2.7	1 in 2.7	1 in 1.7	61%	1.0	16.7%	3.7
port	1100	1199	1.05E-01	1.06E-01	2.11E-01	0.9002	0.8995	0.8098	9.98E-02	1.00E-01	1.90E-01	1 in 10.0	1 in 10.0	1 in 5.3	14%	1.0	16.7%	0.8
aft	1200	1299	0.00E+00	1.61E-02	1.61E-02	1.0000	0.9840	0.9840	0.00E+00	1.60E-02	1.60E-02	-	1 in 62.6	1 in 62.6	1%	1.0	16.7%	0.1
starboard	1300	1399	1.05E-01	1.06E-01	2.11E-01	0.9002	0.8995	0.8098	9.98E-02	1.00E-01	1.90E-01	1 in 10.0	1 in 10.0	1 in 5.3	14%	1.0	16.7%	0.8
zenith	1400	1499	0.00E+00	1.38E-01	1.38E-01	1.0000	0.8710	0.8710	0.00E+00	1.29E-01	1.29E-01	-	1 in 7.8	1 in 7.8	9%	1.0	16.7%	0.6
nadir	1500	1599	0.00E+00	9.83E-04	9.83E-04	1.0000	0.9990	0.9990	0.00E+00	9.82E-04	9.82E-04	-	1 in 1,018	1 in 1,018	0%	1.0	16.7%	0.0
		totals:	**6.63E-01**	**8.35E-01**	**1.50E+00**	**0.5152**	**0.4339**	**0.2236**	**4.85E-01**	**5.66E-01**	**7.76E-01**	**1 in 2.1**	**1 in 1.8**	**1 in 1.3**	**100%**	**6.0**	**100%**	**1.0**
		% of total:	**44%**	**56%**	**100%**													

The results show that our cube spacecraft should expect to see about 1.5 penetrations in 2020 with 61% of the penetrations on the forward-facing surface (i.e., in the direction of motion) while the nadir (Earth-facing) surface has no orbital debris penetrations and negligible meteoroids. About half (56%) of the penetrations are from meteoroids and 44% from orbital debris. The rightmost column compares the "percentage of total numbers of penetrations" to "percentage of total area". This is a simple method used to determine which shield regions are carrying more risk than other regions. The front is carrying 3.7 times as much risk as it should be (i.e., ideally all areas could carry the same average amount of risk ≈1.0 for each surface). Conversely, the nadir-facing area is carrying almost no risk. An initial optimization iteration could look at improving the shielding on the front of the spacecraft by possibly reducing the mass of the nadir-facing and aft-facing surfaces.

9 OPTIONAL TOOLS

Bumper has three optional outputs to support analysis: (1) Response File Plot “RPLOT”, (2) Velocity-versus-Impact (Beta) Angle “VBETA”, and (3) Color Risk Contour “Contour”.

9.1 RPLOT:

RPLOT generates an output text file containing critical particle diameters versus impact velocity and impact angle for each shield type. The text file is typically imported into Excel and displayed as a table as shown in Table 2 or displayed as a BLC graph as was shown in Fig. 5. RPLOT is often run within the Response module but is provided as a Bumper Main Menu option as well for convenience. The critical particle diameter tables are one of the most used features in Bumper. These tables of critical particle diameters can be used to guide decisions regarding shield performance and shield testing.

Table 2. Response RPLOT BLC Critical Particle Diameters for debris (left) and meteoroids (right).

	Orbital Debris Critical Particle Diameters (cm)					
Velocity	Angle (degrees)					
(km/s)	0	15	30	45	60	75
1	0.1022	0.1044	0.1119	0.1272	0.1583	0.2399
2	0.0659	0.0674	0.0722	0.0821	0.1022	0.1549
3	0.0510	0.0522	0.0559	0.0635	0.0791	0.1199
4	0.0426	0.0435	0.0466	0.0530	0.0659	0.1000
5	0.0370	0.0378	0.0405	0.0460	0.0573	0.0868
6	0.0329	0.0337	0.0361	0.0410	0.0510	0.0774
7	0.0299	0.0306	0.0327	0.0372	0.0463	0.0702
8	0.0275	0.0281	0.0301	0.0342	0.0426	0.0645
9	0.0255	0.0261	0.0279	0.0317	0.0395	0.0599
10	0.0239	0.0244	0.0261	0.0297	0.0370	0.0560
11	0.0225	0.0230	0.0246	0.0280	0.0348	0.0528
12	0.0213	0.0217	0.0233	0.0265	0.0329	0.0499
13	0.0202	0.0207	0.0221	0.0252	0.0313	0.0475
14	0.0193	0.0197	0.0211	0.0240	0.0299	0.0453
15	0.0185	0.0189	0.0202	0.0230	0.0286	0.0434
16	0.0177	0.0181	0.0194	0.0221	0.0275	0.0416
17	0.0171	0.0174	0.0187	0.0212	0.0264	0.0401

	Micrometeoroid Critical Particle Diameters (cm)					
Velocity	Angle (degrees)					
(km/s)	0	15	30	45	60	75
1	0.1664	0.1701	0.1822	0.2071	0.2578	0.3907
2	0.1074	0.1098	0.1176	0.1337	0.1664	0.2522
3	0.0831	0.0850	0.0910	0.1035	0.1288	0.1952
4	0.0693	0.0709	0.0759	0.0863	0.1074	0.1628
5	0.0602	0.0615	0.0659	0.0749	0.0933	0.1414
6	0.0537	0.0548	0.0588	0.0668	0.0831	0.1260
7	0.0487	0.0498	0.0533	0.0606	0.0754	0.1143
8	0.0447	0.0457	0.0490	0.0557	0.0693	0.1051
9	0.0415	0.0425	0.0455	0.0517	0.0644	0.0975
10	0.0389	0.0397	0.0426	0.0484	0.0602	0.0913
11	0.0366	0.0374	0.0401	0.0455	0.0567	0.0859
12	0.0346	0.0354	0.0379	0.0431	0.0537	0.0813
13	0.0329	0.0337	0.0361	0.0410	0.0510	0.0773
14	0.0314	0.0321	0.0344	0.0391	0.0487	0.0738
15	0.0301	0.0308	0.0329	0.0374	0.0466	0.0706
16	0.0289	0.0295	0.0316	0.0359	0.0447	0.0678
17	0.0224	0.0229	0.0245	0.0278	0.0346	0.0525

9.2 VBETA:

VBETA runs within the Shield module and outputs a text file containing a table of number of impacts or penetrations versus impact velocity and impact angle for each EID range. For example, our cube analysis generated 12 VBETA files from the 6 EID ranges and two environment models (i.e., 6 x 2 = 12). A VBETA file is typically imported into Excel and displayed in tabular format as shown in Table 3 or graphical format as shown in Fig. 8. These are used to determine which velocities and approach angles are driving the risk for that surface. This information is very often used to select relevant test conditions for hypervelocity impact testing.

Table 3. VBETA Results for cube front surface (EID Range 1000, 1099) shown in tabular format.

	Cube Front Surface (EID Range 1000,1099) VBETA								
Velocity	Impact Angle Bins (degrees)								
(km/s)	0 to 10	10 to 20	20 to 30	30 to 40	40 to 50	50 to 60	60 to 70	70 to 80	80 to 90
0-1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.06E-10
1-2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.13E-07
2-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.75E-06	4.83E-06
3-4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.19E-05	1.12E-06
4-5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.65E-04	0.00E+00
5-6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.28E-04	8.72E-05	0.00E+00
6-7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.98E-03	0.00E+00	0.00E+00
7-8	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.72E-03	2.25E-03	0.00E+00	0.00E+00
8-9	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.43E-03	3.58E-04	0.00E+00	0.00E+00
9-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.62E-03	9.49E-03	0.00E+00	0.00E+00	0.00E+00
10-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.89E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11-12	0.00E+00	0.00E+00	0.00E+00	1.22E-02	2.36E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12-13	0.00E+00	0.00E+00	4.64E-17	7.54E-02	2.97E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13-14	0.00E+00	0.00E+00	1.03E-01	3.78E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14-15	0.00E+00	6.80E-02	7.81E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15-16	0.00E+00	7.79E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18-19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
19-20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

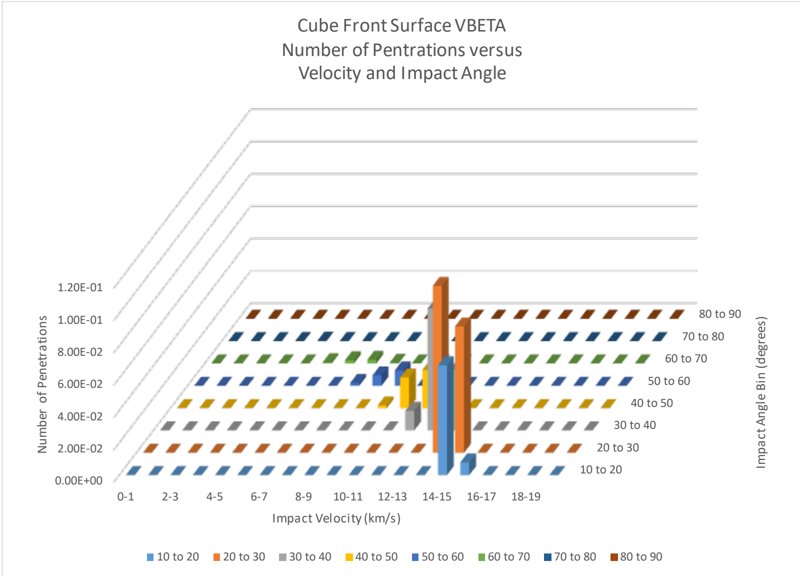

Fig. 8. VBETA Results for cube front surface (EID Range 1000, 1099) shown in 3D graphical format.

9.3 Contour:

The Contour color risk "heat" map runs within the Shield module and outputs a text file containing the probability of impact or penetration per square meter per year (as a percent) for each shield element. This information can then be applied to the original FEM to produce images like those shown in Fig. 9. These were produced in our modeling software by importing the spacecraft (cube) FEM, then importing and overlaying the Contour text file from Bumper. Note that the colors in this example are set to show high risk as red and low risk as blue with other colors for intermediate risk values. The color-risk scale is linear with 10 evenly-spaced segments, but can be tailored to other scales and higher resolution. Spacecraft orientation is the same as specified in the earlier FEM images. These images show that the front of the cube is highest risk from both debris and meteoroids. Note that these two sets of results can be combined to produce a composite overall risk color contour image.

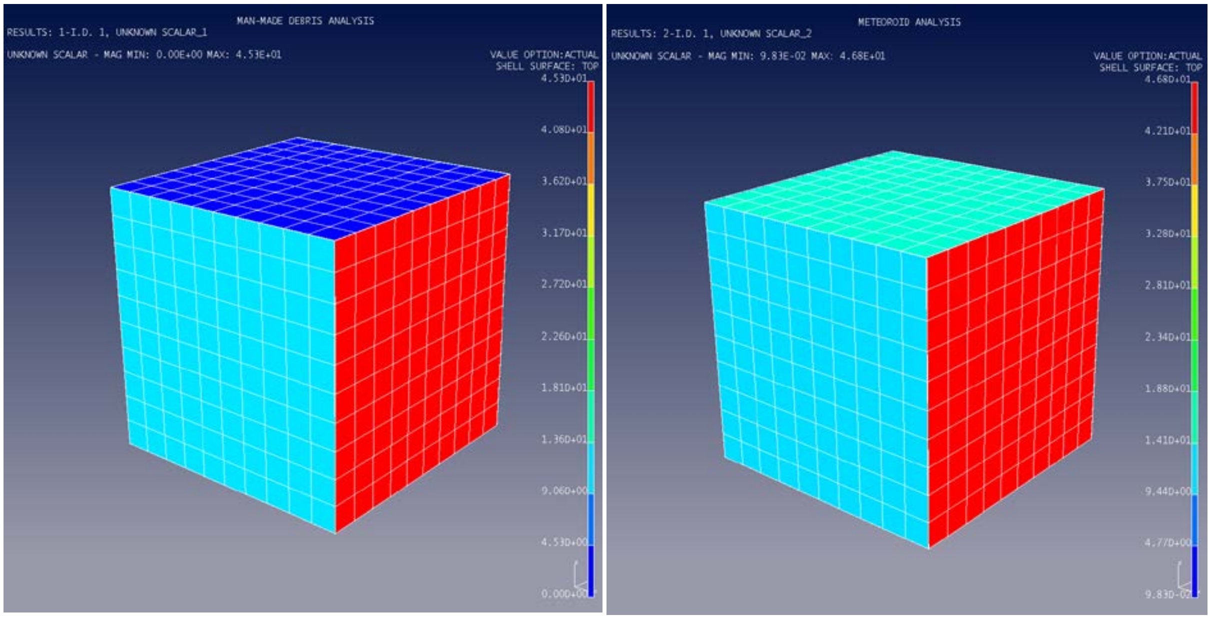

Fig. 9. Color Risk Contour images for debris (left) and meteoroids (right).

10 BUMPER AVAILABILITY

A copy of the Bumper executable can be requested by contacting:

NASA Johnson Space Center
Technology Transfer & Commercialization Office
2101 NASA Parkway
Mail Code: XP
Houston, TX 77058
Website: https://technology-jsc.ndc.nasa.gov
Email: jsc-techtran@mail.nasa.gov
Phone: (281) 483-3809

11 CONCLUSIONS

This paper described the Bumper MMOD risk analysis program and the associated risk analysis process. Since its creation over three decades ago, the Bumper program has been maintained and updated by the NASA JSC Hypervelocity Impact Technology Bumper Configuration Control Board. During that time, Bumper has been used to reduce MMOD risk to many spacecraft including ISS, Space Shuttle, Orion, as well as numerous satellites and space probes. Commercial space companies have been using Bumper to reduce risk as well. Future spacecraft such as Gateway and Mars Sample Return are being developed using Bumper as well.

12 REFERENCES

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