UNCERTAINTY CONSIDERATIONS FOR BALLISTIC LIMIT EQUATIONS

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ABSTRACT

The overall risk for any spacecraft system is typically determined using a Probabilistic Risk Assessment (PRA). A PRA determines the overall risk associated with a particular mission by factoring in all known risks to the spacecraft during its mission. The threat to mission and human life posed by the micro-meteoroid and orbital debris (MMOD) environment is one of the risks. NASA uses the BUMPER II program to provide point estimate predictions of MMOD risk for the Space Shuttle and the ISS. However, BUMPER II does not provide uncertainty bounds or confidence intervals for its predictions. In this paper, we present possible approaches through which uncertainty bounds can be developed for the various damage prediction and ballistic limit equations encoded within the Shuttle and Station versions of BUMPER II.

1. INTRODUCTION

Micro-meteoroids and orbital debris (MMOD) are a serious problem for all manned and unmanned spacecraft. Micro-meteoroids are naturally occurring particles that are created from the breakup of asteroids and comets. Orbital debris is human-generated and orbits the Earth. Because these particles are traveling at many kilometers per second, even very small particles can cause loss of critical spacecraft systems or crew (in the case of manned spacecraft).

NASA uses the BUMPER II code to calculate the risk of MMOD impact causing critical damage for each Space Shuttle mission as well as the risk of MMOD penetration for the International Space Station (ISS). BUMPER II has also been used to identify ways of reducing MMOD risk to within established program risk levels through operations, shielding, or other means (Williamsen, 2003). Space Shuttle mission profiles and operations have often been directly affected by risk predictions based on BUMPER II (e.g. its predictions were essential in determining the proper positioning of the payload bay door on STS-73 to provide protection to some otherwise lightly protected pressurized tanks within the payload bay).

2. THE BUMPER II CODE

The original BUMPER code was developed by Boeing under contract to NASA/MSFC for use on the Space Station Freedom program in 1986. In 1991, it was updated to the BUMPER II code, and configuration control was established at NASA/JSC in 1994. BUMPER II is now clearly considered the standard by which other MMOD risk assessment tools are measured—even the European and Russian Space Agencies have used versions of it. Currently, two versions of BUMPER II are maintained, one for the ISS program and one for the Space Shuttle program. The primary differences between the two versions are in the ballistic damage subroutines due to different exterior materials and failure criteria.

While BUMPER II is a powerful tool, it does have limitations. BUMPER II results provide a point estimate of MMOD risk with no assessment of its associated uncertainty. Reporting risk predictions with uncertainty bounds enables those performing the program's probabilistic risk assessments (PRAs) to fold the results into those assessments and put them in perspective with the other risk contributors. Risk predictions can also be used to help prioritize research programs to reduce the highest contributors to risk and uncertainty first. However, the uncertainties associated with underlying BUMPER II input models are still largely unknown.

In this paper, we present and discuss possible approaches through which uncertainty bounds and/or confidence intervals can be developed for the various damage prediction (DP) and ballistic limit (BL) equations encoded within the shuttle and station versions of BUMPER II. The uncertainties in the code's environment models and failure criteria definitions are beyond the scope of this study.

3. NASA PROBABILISTIC RISK ASSESSMENT (PRA) FOR SHUTTLE AND STATION

NASA currently maintains PRAs for the Space Shuttle and the ISS programs. A PRA attempts to determine the overall risk associated with a particular mission by factoring in all known risks (and their corresponding

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uncertainties, if known) to the spacecraft during the mission in the analysis. The threat to mission and human life posed by the MMOD environment is one of the risks.

The primary PRA development application for both the Space Shuttle Program (SSP) and the International Space Station (ISS) is the fault-tree analysis code called SAPHIRE (**S**ystems **A**nalysis **P**rogram for **H**ands-on **I**ntegrated **RE**liability). BUMPER II data are provided to the appropriate PRA model development team (either SSP or ISS) as point values without associated uncertainty distributions. These furnished point values typically represent probabilities over a given mission for the Shuttle and for ten-year on-orbit periods of consideration for the ISS. The next two subsections present a brief overview of the current PRA processes for the shuttle and for the space station.

3.1. Shuttle Probabilistic Risk Assessment

The current Shuttle PRA is the first Space Shuttle Program (SSP) sponsored PRA of the Shuttle, and is a comprehensive, integrated PRA from launch to wheel stop on the runway. It also represents the first Shuttle PRA to include MMOD as a risk contributor. The primary figure of merit at this time is Loss of Crew and Vehicle (LOCV). Additional figures of merit may be warranted as the Shuttle PRA scope is increased to include ascent abort scenarios, additional on-orbit activities, and safe haven to ISS as a result of possible ascent debris damage.

The Shuttle PRA addresses the five major elements of the Shuttle (Orbiter, SSMEs, SRBs, RSRMs, and ET), the three major phases of a typical mission (ascent, orbit, descent), and the major risk categories (functional failures, crew actions, external events, phenomenological events, and common cause events). It is an integrated model that accounts for dependencies between equipment, systems, mission phases, environment, and humans. The current Shuttle PRA attempts to take into account all reasonable contributors to risk, and then calculates the probabilities of likely combinations of equipment and systems failures that can lead to LOCV (NASA/JSC, 2002). NASA attempts to take into account the uncertainties in the DP/BL equations, the MMOD environment models, and the failure criteria by assuming the BUMPER II point estimate predictions are mean values combined with an assumed "error factor" to generate the corresponding 5^{th} and 95^{th} percentile values.

3.2. Station Probabilistic Risk Assessment

In order to incorporate the as-received data into the SAPHIRE PRA model, BUMPER II data are post-processed using an Excel spreadsheet and @RISK, a third-party commercial product used in conjunction with Excel. The Bumper II data used in this fashion is supplemented by data from MSCSurv, a spacecraft Monte Carlo-based survivability program developed by NASA (see, e.g., Vitali, 2003). Probability uncertainty distributions and conversions to appropriate ISS mission times are generated using Excel/@RISK, and the post-processed data are subsequently incorporated into SAPHIRE for MMOD penetration scenarios leading to loss of science, crew evacuation, and loss of module critical PRA end-states. The results of a previous independent expert panel review of the ISS PRA model included very strong recommendations for regular coordination and integration activities to be conducted between the PRA developers and in-line operational and system engineering experts (IPRP, 2002).

4. REVIEW OF NASA SENSITIVITY ANALYSIS

In an attempt to begin to quantify the uncertainties associated with BUMPER II predictions (with particular emphasis on shuttle analyses), NASA performed a sensitivity study of the dependence of BUMPER II risk prediction on five (5) key parameters using the BUMPER II code (Christiansen, et al, 2004). The code was initially run with baseline assumptions for a Space Shuttle mission. Then additional runs were performed varying only one of the baseline parameters by allowing it to take on either a predetermined low or a predetermined high value. The parameters selected for variation were those whose uncertainties were expected to have the greatest effect on MMOD risk predictions. However, other parameters that were known to have a large potential effect on MMOD penetration—such as MMOD particle shape—were omitted due to a lack of information on how, e.g., MMOD particle shapes might vary on orbit. As such, some of the potentially largest MMOD risk-producing factors still remain to be examined for their effects. Tabs. 1 and 2 show the parameters selected and, where appropriate, the high and low factor or value used in the sensitivity study.

Table 1. Orbital Debris Sensitivity Study Variables (Christiansen, et al, 2004)

Study Parameter	Higher Risk Value	Baseline Value	Lower Risk Value
Density (gm/cu.cm.)	7.9 (steel)	2.8 (aluminum)	1.0 (water/ice)
Flux Factor	1.6	1.0	0.9
BL Eqn Prediction Mult Factor	0.8	1.0	1.2
Failure Criteria	Minimum Failure Criteria	Baseline Failure Criteria	Maximum Failure Criteria
Velocity Distribution	Maximum Velocity Option	Baseline Velocity Option	Minimum Velocity Option

Table 2. Meteoroid Sensitivity Study Variables (Christiansen, et al, 2004)

Study Parameter	Higher Risk Value	Baseline Value	Lower Risk Value
Density (gm/cu.cm.)	1.9	1.0	0.5
Flux Factor	2.0	1.0	0.5
BL Eqn Prediction Mult Factor	0.8	1.0	1.2
Failure Criteria	Minimum Failure Criteria	Baseline Failure Criteria	Maximum Failure Criteria
Velocity Distribution	Maximum Velocity Option (Long Period Comets)	Baseline Velocity Option	Minimum Velocity Option (Asteroidal)

The results of the sensitivity assessment are shown in Tab. 3. These results do not include the velocity parameter variation runs because the meteoroid runs had not yet been performed at the time of the completion of the study. The dramatic swings in the predicted MMOD risks shown in Tab. 3 demonstrate the importance of developing the capability to include overall uncertainty bounds as part of the results of MMOD risk assessments performed in support of future shuttle missions.

5. BUMPER II UNCERTAINTY ANALYSIS -- SHUTTLE VERSION

The shuttle version of BUMPER II uses a variety of equations to predict damage to shuttle components in terms of an impacting particle's density, velocity, and angle of impact. Some equations are developed by simply drawing a curve through fail/no-fail test data (the so-called ballistic limit, or BL, equations), while others are developed by performing statistical curve-fits to empirical data (the damage predictor, or DP, equations). Considering the different approaches used to derive them, the DP equations and BL equations in the shuttle version of BUMPER II belong to two different classes of empirical equations. These equations and their uncertainty considerations are discussed in this section.

Table 3. Sensitivity Study Results (Christiansen, et al, 2004)

Case		Expected Number of Orbital Debris (OD) and Meteoroid (M) Penetrations (N)			Probability of No Penetration	MMOD Penetration		% Change
		OD	M	MMOD Total	MMOD Total	Risk	Odds	From Baseline N
0	**Baseline**	0.00215	0.00205	0.00420	0.99581	0.419%	1 in 239	-----
1	**Max Flux**	0.00344	0.00410	0.00754	0.99249	0.751%	1 in 133	80%
	Min Flux	0.00194	0.00102	0.00296	0.99704	0.296%	1 in 338	-30%
2	**Max Vel**							
	Min Vel							
3	**Max Den**	0.00954	0.00518	0.01471	0.98539	1.461%	1 in 68	250%
	Min Den	0.00046	0.00090	0.00136	0.99864	0.136%	1 in 734	-68%
4	**Max Eqn**	0.00103	0.00102	0.00204	0.99796	0.204%	1 in 490	-51%
	Min Eqn	0.00466	0.00457	0.00923	0.99081	0.919%	1 in 109	120%
5	**Max Fail**	0.00087	0.00091	0.00178	0.99822	0.178%	1 in 561	-58%
	Min Fail	0.01224	0.01198	0.02422	0.97607	2.393%	1 in 42	477%

5.1. Damage Predictor Equations

The DP equations are curve-fits to empirical data, that is, they are the results of statistical regression analyses of available test data. As such, uncertainty bounds and/or confidence intervals can be obtained at the time that the regression analyses are being performed to form the DP equations. A review of the literature referencing the various DP equations in BUMPER II revealed that while an R^2 value for a DP equation may have been occasionally provided, information regarding uncertainty bounds and/or confidence intervals was not (R^2 values can be used as a metric to quantify how well a regressed curve fits the data on which it is based). Considering the sophistication of modern statistical analyses packages and the availability of the test data in electronic format, obtaining this information would be a relatively straightforward task that would involve redoing the original regression analyses.

5.2. Ballistic Limit Equations

Unlike the DP equations, the BL equations are not statistically based. They are *not* curve-fits, but are rather simply lines of demarcation between regions of penetration and non-penetration. As a result, and also *un*like the DP equations, it is simply *not* possible to obtain uncertainty bounds and/or confidence intervals as part of the current procedure that is used to derive the BL equations. Alternative, innovative approaches must be developed to either (i) obtain the required uncertainty information from existing BL equations and the data on which they are based, or (ii) rederive the BL equations using a statistics-based approach so that uncertainty information is forthcoming out of the analyses along with the equations themselves. Both of these options are briefly discussed in the following paragraphs.

(a) Uncertainty Modeling Using Existing BL Equations and Data

As discussed previously, considering the manner in which the existing BL equations are derived, it is impossible to state that any existing BL equation is accurate to within +/-X% with a confidence of Y%. However, it may be possible to develop a quantitative measure that would indicate, at least at some level, the accuracy of a BL in separating the region of perforating projectile diameter-impact velocity combinations from non-perforating combinations. We can consider, for example, the use of **specificity and sensitivity ratios**, which are used in the medical world to distinguish between false positives and false negatives. For example, if we designate a penetration event as the event we are testing for, then a penetration might be considered as a "positive reading" and a non-penetration might be considered as a "negative reading". In this case, the following definitions could be applied for any given BL equation:

Sensitivity = (Actual penetrations predicted as penetrations) / (Actual penetrations predicted as penetrations + Actual penetrations predicted as non-penetrations) (1)

Specificity = (Actual non-penetrations predicted as non-penetrations) / (Actual non-penetrations predicted as non-penetrations + Actual non-penetrations predicted as penetrations) (2)

By using these ratios we would get a first-order quantitative assessment of whether or not a given BL equation tends to be conservative or non-conservative (at least in the tested areas). For example, a low specificity value (i.e. more non-penetrations predicted as penetrations) and a high sensitivity value (i.e. fewer penetrations predicted as non-penetrations) would tend to demonstrate a conservatism in the BL equation whereas a high specificity and a low sensitivity would tend to demonstrate non-conservatism. If both values were relatively high, that would indicate a fairly accurate curve, whereas if both values were fairly low, that might demonstrate a problem with the testing method or with test repeatability.

As an example, consider the BUMPER II subroutine TPSBELPERF, which calculates the critical particle diameters that will cause threshold perforation of an underlying 2024-T81 aluminum plate or honeycomb sandwich panel using the BL equations given in Christiansen and Friesen (1997). The perforation/no-perforation data on which these equations are based can be found in Friesen and Whitney (1996). The data used to generate the BL equations in this subroutine were obtained from tests on five (5) different tile configurations using spherical steel and aluminum projectiles fired at varying trajectory obliquities.

The vast majority of the tests fired used aluminum projectiles and target configuration consisting of a ceramic tile backed by a thin aluminum plate. When the data for this particular TPS target type are plotted against the corresponding BL equation (Christiansen and Friesen, 1997), the correlations appear to be very favorable (see Fig. 1). However, for other target types, with which significantly fewer tests were performed, the comparisons were not always as favorable.

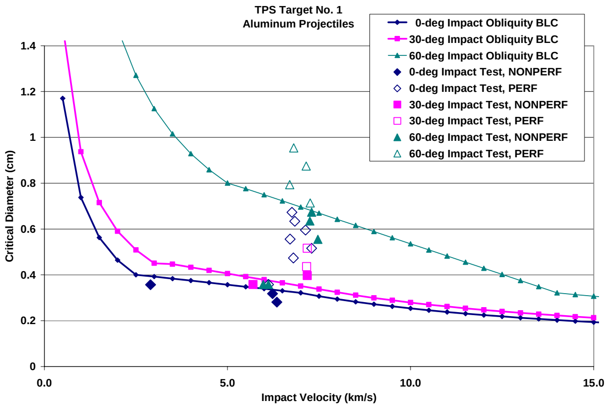

Figure 1. Comparison of Ballistic Limit Curves and Test Data, Basic TPS Target Type

Tab. 4 below shows a summary of how correct (C) or incorrect (IC) the TPSBELPERF BL equation is in predicting penetration (P) or non-penetration (NP) events over the limited velocity ranges at which the tests were performed.

Table 4. Overview of Penetration Event Prediction for Subroutine TPSBELPERF

Targ #	Proj Matl	θ_p (deg)	# P (C)	# P (IC)	# NP (C)	# NP (IC)
1	Steel	0	3	2	2	0
1	Aluminum	0	7	0	3	0
1	Aluminum	30	2	0	1	1
1	Aluminum	60	4	0	5	0
2	Aluminum	0	2	0	0	1
3	Aluminum	0	1	3	0	2
4	Aluminum	0	3	0	4	1
4	Aluminum	60	n/a	n/a	3	0
5	Aluminum	0	1	0	0	2

Tab. 5 presents the specificity and sensitivity ratios for the entire dataset used to develop this BL equation as well as for some subsets of it. As can be seen from the relatively high overall ratio values in Tab. 5, overall, the TPSBELPERF BL equation is able to discriminate fairly well between penetration and non-penetration events. If only steel projectiles are considered, the relative values of the specificity and sensitivity ratios indicate a non-conservatism in the BL equation when used for impact scenarios involving steel projectiles.

Table 5. Sensitivity and Specificity Ratios

	Sensitivity Ratio	Specificity Ratio
Overall	82.14%	72.00%
ST PROJ	60.00%	100.00%
AL PROJ	86.96%	69.57%
AL, 0-deg	82.35%	53.85%
AL, non-0-deg	100.00%	90.00%

However, if only aluminum projectiles are considered, the relative values of the specificity and sensitivity ratios indicate a conservatism in the BL equation. This conservatism for aluminum projectiles is seen again by the relative values of these ratios in the 0-deg dataset as well. While some level of conservatism is appropriate, especially for mission systems that support the presence of humans in space, an exceedingly high amount of conservatism may actually be detrimental to other mission aspects. If BUMPER II results are being represented as the best point estimates of MMOD risk at this time, an effort should be made to eliminate any unreasonable conservatism where it might exist.

(b) A Statistics-Based Approach to Uncertainty Modeling for BL Equations

The approach presented in the preceding section produces a result that, at best, really only measures, albeit in a quantitative fashion, the scatter (or repeatability) of the tests or, perhaps, the reliability of the BL equation based on the tests. It does not provide enough information to allow one to make the statement that a given BL equation is accurate to within +/-X% with a confidence of Y%. In order to be able to make this statement, the BL equations must be rederived using a consistent, statistics-based approach. Such an approach was proposed and used by Williamsen and Jolly (1992) to develop preliminary BL curves for the Space Station Freedom manned module multi-wall orbital debris shields.

In Williamsen and Jolly (1992), data were regressed to develop an empirical equation that defined a **penetration parameter** P_m in terms of impact parameters for a given set of target material properties and geometry, that is,

$$P_m = f(d_p, V_p, \theta_p) = \alpha d_p^{\beta} V_p^{\gamma} \cos^{\delta}\theta_p + \varepsilon \qquad (3)$$

In eqn (3), α through ε are coefficients obtained through a standard nonlinear regression of P_m data. In its simplest form P_m may be visualized as a measure of the depth of penetration through an entire multi-wall shield system. It includes crater depth data prior to perforation of a critical target region as well as witness plate data after the perforation of a critical target region.

In the context of a multi-wall shield, if the impact event results in a perforation of the bumper, but no penetration of the pressure wall, P_m=0. If the pressure wall is penetrated, then $P_m = t_w$, the thickness of the pressure wall. If the first witness plate is also perforated, then $P_m = t_w + t_{wp1}$, where t_{wp1} is the thickness of the first witness place; if the second is perforated, $P_m = t_w + t_{wp1} + t_{wp2}$; etc. If the pressure wall is cratered, but not perforated, then $0<P_m=d_c<t_w$, where d_c is the depth of the deepest pressure wall crater. Setting the penetration parameter equal to a predetermined value (i.e. t_w) allowed Williamsen and Jolly (1992) to solve for critical diameter in terms of impact velocity that would result in just barely perforating the pressure wall. That is, using a statistics-based approach, the authors were able to arrive at a BL equation for a variety of multi-wall systems. It is important to note that this approach could be easily modified to include rear side spall considerations in the calculation of P_m if appropriate for the target type being considered.

If this approach were to be adapted to shuttle TPS configurations, two important results would follow. First, we would be able to develop statistics-based (and not simply hand-drawn) BL equations for shuttle TPS configurations. Second, we would be able to obtain, for each BL equation so derived, the statistics-based uncertainty information that would allow us to make the statement that a given BL equation is accurate to within +/-X% with a confidence of Y%. Since this is the type of information that is needed to develop overall uncertainty bounds for MMOD predictions, it would appear that this approach is the appropriate one to take.

6. BUMPER II UNCERTAINTY ANALYSIS -- STATION VERSION

The subroutines in the station version of BUMPER II consist exclusively of BL equations. These equations are again simply lines of demarcation between regions of penetration and non-penetration and are not statistically based. As such, considering the manner in which the existing station BL equations were derived, it is impossible to state that any existing BL equation is accurate to within +/-X% with a confidence of Y%. Again, alternative, innovative approaches must be developed to either (i) obtain the required uncertainty information from existing BL equations and the data on which they are based, or (ii) rederive the BL equations using a statistics-based approach so that uncertainty information is forthcoming out of the analyses along with the equations themselves. Based on the discussions in subsections (a) and (b), it would appear that the latter is the preferred option. In addition, a similar approach should be followed in determining uncertainty bounds and/or confidence intervals for the ballistic limit curves beyond the testable regime.

7. CURRENT NASA PLANS FOR FUTURE BUMPER II UNCERTAINTY ANALYSIS

As BUMPER II is the accepted code for MMOD risk assessments for the Space Shuttle and the ISS, NASA also plans to use BUMPER II as the engine for running Monte Carlo type analyses (which form the backbone of current PRAs). BUMPER II is generally run using script files which basically provide the responses an interactive user would otherwise provide. In order to perform a Monte Carlo style analysis, many script file commands would have to be in place in order to run through the Response and Shield modules of BUMPER II many times. A preprocessor is currently being developed to create the necessary script file(s) to run these many iterations of BUMPER II. Within the script file(s), the iterations would contain parameter values which would be varied from iteration to iteration based on random numbers drawn against user-specified distributions.

After completion of the BUMPER II runs, the postprocessor to BUMPER II (also being developed) will be run to read expected failure numbers from the shield summary files that BUMPER II provides for each iteration, calculate the mean and user-specified high and low percentile values, and write the results for all iterations along with the mean, and high and low percentile values to a single, Excel-compatible file. The postprocessor will also calculate certain key convergence statistics to allow the user to assess whether convergence has been achieved. Note: the postprocessor will be designed to run independently of BUMPER II, so this is not a stop-when-convergence-is-met capability.

8. CONCLUSIONS

The BUMPER II code is currently used by NASA and other space agencies to calculate the risk of MMOD impact causing critical damage for each Space Shuttle mission, and the risk of MMOD penetration for the International Space Station (ISS). While BUMPER II is a powerful tool, it does have limitations – it provides a point estimate of MMOD risk, but without any assessment of its associated uncertainty. In this paper, we have presented several possible approaches through which uncertainty bounds and/or confidence intervals can be developed for the various damage prediction (DP) and ballistic limit (BL) equations encoded within the shuttle and station versions of BUMPER II.

While specificity and sensitivity ratios can be used to provide a quantitative measure that would indicate the accuracy of a BL in separating the region of perforating projectile diameter-impact velocity combinations from non-perforating combinations, these ratios, at best really only measure the scatter (or repeatability) of the tests or, perhaps, the reliability of the BL equation based on the tests. To determine actual confidence bounds, the BL equations in BUMPER II must be rederived using the consistent, statistics-based approach described herein.

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