A COMMENT ON THE USE OF SIMULTANEOUSLY LAUNCHED PROJECTILES IN THE DEVELOPMENT OF BALLISTIC LIMIT CURVES FOR MULTI-WALL TARGETS

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ABSTRACT

The traditional shield design for a spacecraft that is to operate in the MMOD environment consists of a bumper that is placed at a small distance from the inner wall. Shield performance is characterized by a ballistic limit equation (BLE), which is obtained through impact tests using light gas guns. Traditional firings employ only one projectile per launch package; however, some facilities have taken to launching multiple projectiles in a single package. In light of the significant role played by a BLE in risk assessment, a study was performed to examine whether this method of simultaneously launching projectiles would provide results consistent with the traditional single-firing approach. This concern was that multiple particle impacts, especially at oblique angles, can result in interference between debris clouds created by particles that have already struck the bumper, and those that have not. The objectives were to attempt to duplicate a set of multiple-projectile test results using hydrocode modeling of test firings with single projectiles, and to determine if results obtained using those two approaches were consistent. The study focused on the BLE used by NASA for the International Space Station (ISS) Service Module (SM) small diameter cylinder radiator wall. This BLE was chosen because the TsNIIMASH facility in Moscow, Russia recently performed tests on this wall system using simultaneously launched projectiles and, based on the results of those tests, had suggested that some adjustment to the NASA SM BLE may be warranted.

1 INTRODUCTION

Multi-wall shield designs for spacecraft have been studied extensively in the last four decades as a means of reducing the perforation threat of the near-Earth micro-meteoroid and orbital debris (MMOD) environment over equivalent single-wall structures. The performance of an impact shield is typically characterized by its ballistic limit equation (BLE), which is obtained through high-speed impact tests that typically use spherical projectiles fired in light gas guns (LGGs). These BLEs are typically drawn as lines of demarcation between regions of rear-wall perforation and no perforation (P / NP) in two-dimensional spherical projectile diameter-impact velocity space and when graphically represented, are often referred to, in this form, as ballistic limit curves (BLCs). The high-speed impact testing that provides data for the development of these BLEs and their BLCs typically use spherical projectiles fired in light gas guns at impact velocities between 3 and 7 km/s. These data are then fitted with scaled single-wall equations below approx. 3 km/s, and with theoretical momentum and/or energy based penetration relationships above approx. 7 km/s to obtain three-part BLCs that cover the full range of impact velocity of interest for MMOD spacecraft protection design, that is, from approx. 0.5 to 16 km/s.

Traditional LGG firings employ only one projectile per launch package. However, some facilities were developed to launch multiple projectiles of different sizes in a single launch package (see, e.g. [1, 2, 3]); recently, this advanced technology was used in the testing of candidate spacecraft wall systems and in the development of BLEs for those wall systems. In light of the significant role played by a BLE in risk assessment, a study was performed to examine whether or not this method of simultaneously launching several projectiles at a single target could give rise to some issues which may compromise the impact test data obtained in this manner.

This study was motivated by the realization that multiple particle impacts, especially at oblique angles, could result in interference between the debris clouds created by particles that have already struck the bumper shield and those particles that have not yet hit the target, thereby reducing the damage potential of the particles about to strike the bumper. As such, the objectives of this study were to attempt to duplicate a set of recent high speed multiple-projectile impact test results using hydrocode modeling of test firings with single projectiles, and to determine if results obtained using those two approaches were consistent. The study focused on the BLE used by NASA for the International Space Station (ISS) Service Module (SM) small diameter cylinder radiator wall. This BLE was chosen because the TsNIIMASH facility in Moscow, Russia recently performed tests on this wall system using simultaneously launched projectiles and, based

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on the results of those tests, had suggested that some adjustment to the NASA SM BLE may be warranted.

2 OVERVIEW OF EXPERIMENTAL RESULTS

The BLE currently used by NASA for the International Space Station (ISS) Service Module (SM) small diameter cylinder radiator wall configuration is given in Ref. [4] and is based on high-speed impact tests performed by NASA/JSC and at the TsNIIMASH test facility in Moscow, Russia. Recently, some additional tests have been performed on this wall system at the TsNIIMASH facility where, in each test, three different aluminum projectiles were simultaneously fired in a single launch package – effectively "three tests" per shot. Figures 1 and 2 show the SM BLEs for 0-deg and 60-deg impact obliquities, as well as the new TsNIIMASH test results. The BLEs shown in these figures have been adjusted from the actual SM BLEs in Ref. [4] to account for the thinner inner walls used in the TsNIIMASH tests (the NASA BLEs have a hard-wired inner wall thickness of 0.160 cm, whereas the TsNIIMASH tests were performed using a thickness of 0.142 cm).

Figures 1 and 2 also show possible "upward adjustments" to the NASA SM BLE that may be warranted based on the new TsNIIMASH data. If these adjustments were made, then the resilience of the SM against damage from MMOD impacts would be rated higher than it is now, and risk assessments performed using such "upwardly adjusted" BLEs would return assessed penetration risk values lower than those being calculated using the current SM BLEs.

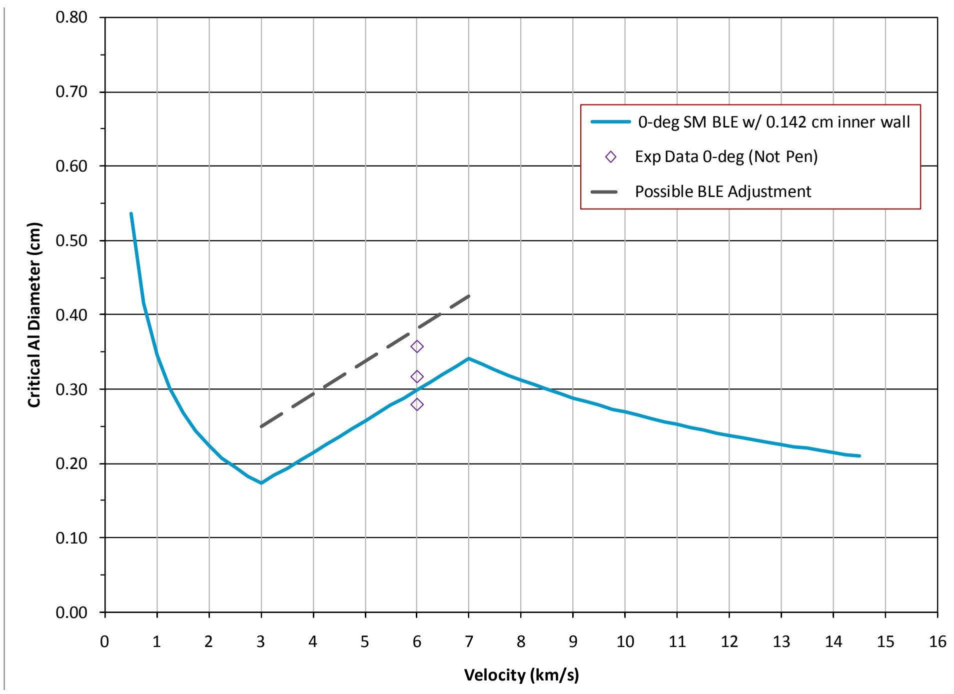

Figure 1. Comparison of Modified SM BLE, TsNIIMASH Test Results, and Possible Attendant Adjustment to the BLE, 0-deg

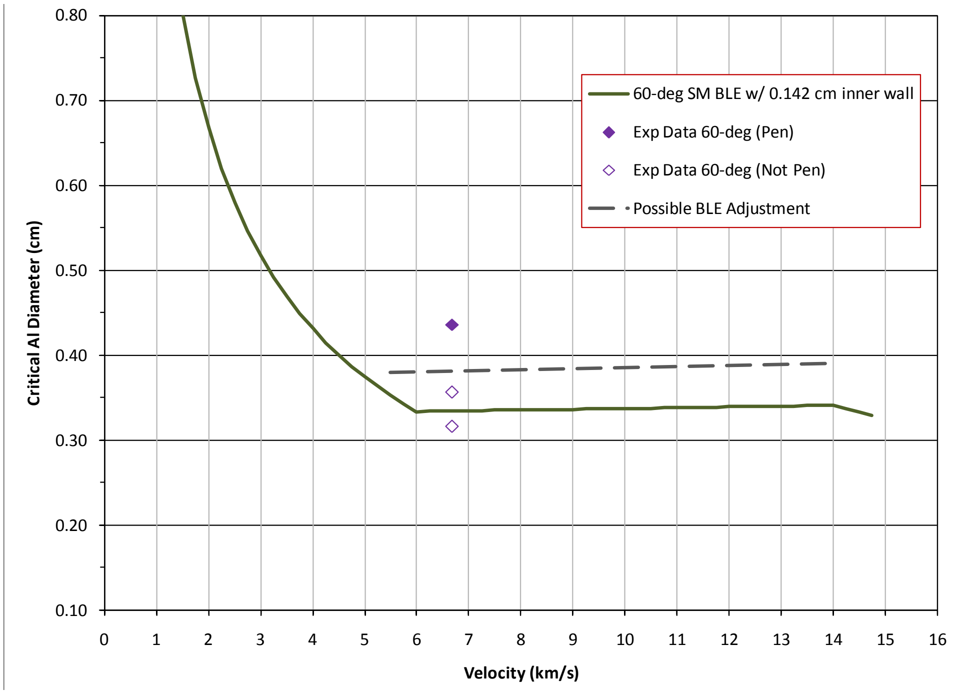

Figure 2. Comparison of Modified SM BLE, TsNIIMASH Test Results, and Possible Attendant Adjustment to the BLE, 60-deg

3 HYDROCODE MODELING OF RECENT TSNIIMASH TEST RESULTS

The impact scenarios of the 0-deg and 60-deg TsNIIMASH tests were modeled using the SPHC hydrocode by "firing" one particle at a time against the target dual-wall system. The target wall geometries in the hydrocode runs were identical to those in the TsNIIMASH tests: 0.95mm thick AMg6 bumper, 50 mm stand-off distance, and 0.142 cm thick AMg6 rear-wall. Material data for the AMg6 were obtained from http://www.matweb.com/ for AL5456-O, with density adjusted to 2.63 g/cm^3, and yield strength adjusted to 35 ksi. All of the simulations used a Mie-Gruneisen equation of state, incorporating physical phase changes dependent on the material parameters, and an elastic/plastic strength model with strain hardening.

Three 0-deg hydrocode runs were performed using 3.57 mm, 3.17 mm, and 2.8 mm projectiles; in each hydrocode run, the impact velocity was 6.05 km/s. The hydrocode results showed that when fired independently at 0-deg, the impacts by the two larger projectiles resulted in rear-wall perforations, while the impact by the smallest projectile did not. The results for the larger two projectiles appear to differ from the non-penetration results obtained in the recent TsNIIMASH tests at 0-deg, which showed that no rear-wall penetrations were observed for any of the projectiles.

The independent hydrocode runs at 60-deg were performed using 4.36, mm, 3.57 mm, and 3.17 mm projectiles, respectively. In each of these hydrocode runs, the impact velocity was 6.73 km/s. The 60-deg hydrocode simulations showed that when fired independently, none of the three projectiles resulted in rear-wall perforations. These results are different from those obtained by TsNIIMASH, which showed no rear-wall penetrations at 60-deg for the smaller two projectiles, but did show a perforation by the largest one.

Figures 3 and 4 show the hydrocode results from a penetration / non-penetration (P / NP) perspective for the independent runs, the TsNIIMASH test results shown previously, and the NASA SM BLEs (modified for a 0.142 cm rear-wall) for the 0-deg and 60-deg impact scenarios, respectively. Figure 4 also contains two data points from tests performed by NASA in the development of its current SM BLE.

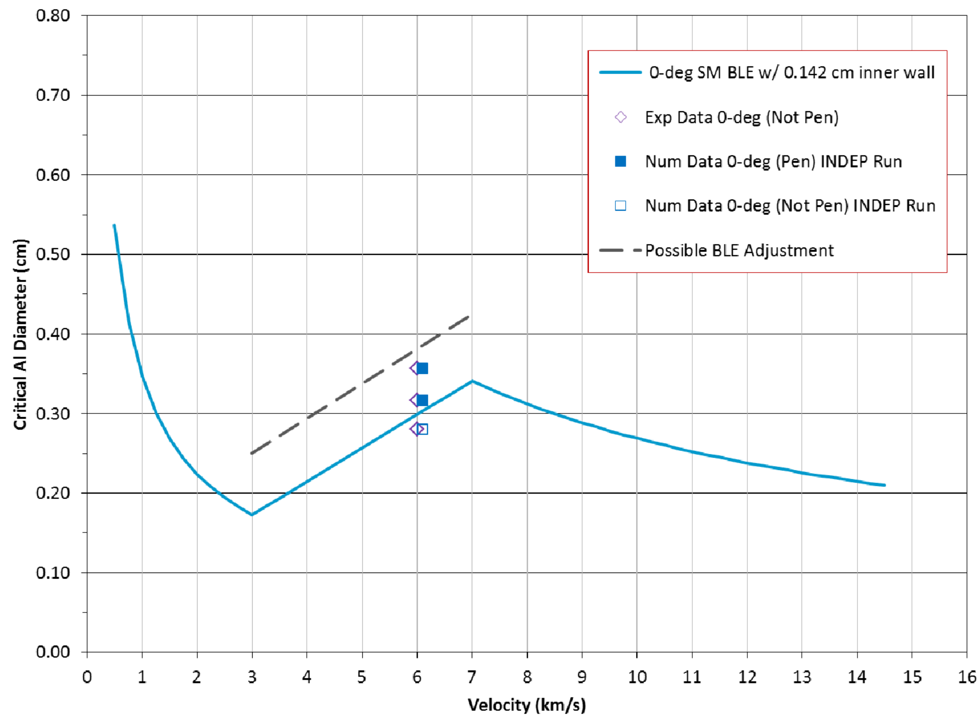

Figure 3. Comparison of Hydrocode Results from Independent Runs, TsNIIMASH Test Results, and NASA SM BLE, 0-deg Impact Scenario

Figure 3 shows that the hydrocode predictions do reasonably well in matching the current NASA SM BLE (as adjusted for rear-wall thickness) for 0-deg impacts, and highlights the differences between the simultaneous TsNIIMASH test results, the NASA SM BLE, and the independent hydrocode run results.

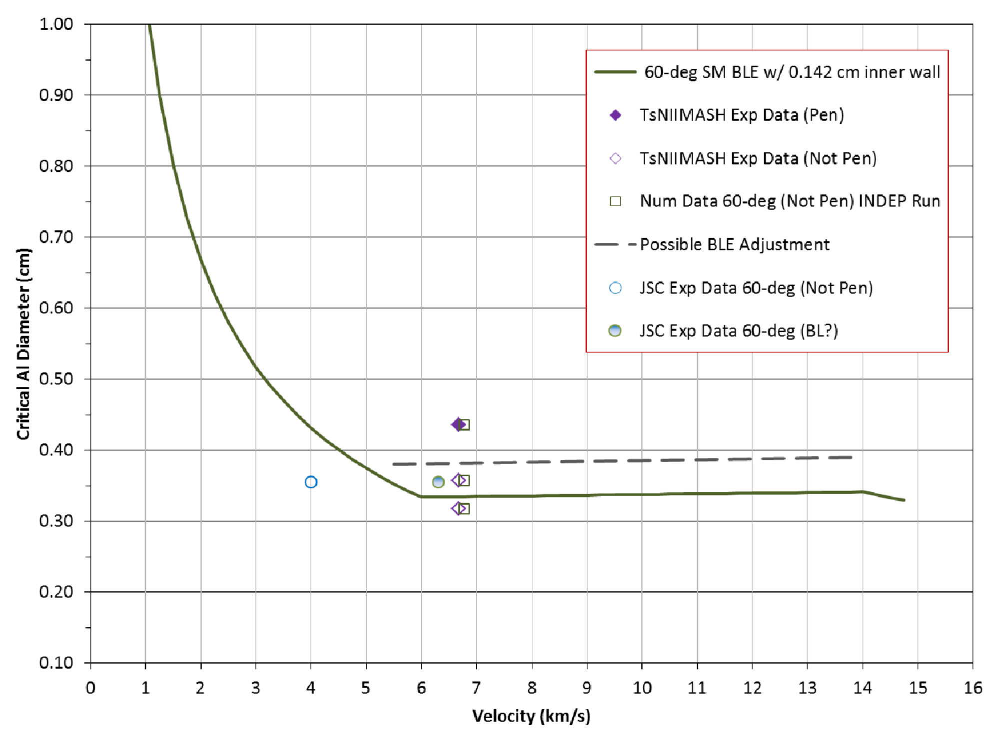

Figure 4. Comparison of Hydrocode Results from Independent Runs, TsNIIMASH Test Results, JSC Test Results, and NASA SM BLE, 60-deg Impact Scenario

In Figure 4 we see that the results from the two JSC tests match the BLE fairly well, but the hydrocode predictions indicate that the flat middle portion might be conservative regarding whether or not the rear-wall of the dual-wall target system is penetrated. That is, because of its position (and in particular, the flatness of the middle portion of the curve), the BLE predicts more rear-wall penetrations to occur than indicated by the hydrocode results obtained as part of this study. However, in both figures it is again evident that the hydrocode P / NP results do not appear to match those of the new TsNIIMASH tests that used simultaneously launched projectiles.

4 CONCLUSIONS

A study was performed to examine whether the method of simultaneously launching several projectiles in a light gas gun at a single target might result in some issues which may compromise the impact test data that are obtained in this manner. When TsNIIMASH multiple-projectile test results and the results of single-projectile hydrocode simulations were plotted against the current NASA SM BLE, it was found that the hydrocode predictions matched the BLE for 0-deg impacts reasonably well, while the TsNIIMASH test results did not. For the 60-deg impacts it was evident from both hydrocode and TsNIIMASH results that the middle portion of the BLE might be conservative regarding rear-wall penetration. However, sufficient evidence was found to indicate that simultaneously firing multiple projectiles could yield results different from independent firings of the same projectiles under the same conditions.

5 ACKNOWLEDGEMENT

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