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A HYPERVELOCITY EXPERIMENTAL RESEARCH DATABASE (HERD): SUPPORT FOR THE WRIGHT LABORATORY ARMAMENT DIRECTORATE CODE VALIDATION PROGRAM (COVAL)

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Abstract

The Hypervelocity Experimental Research Database (HERD) described in this paper was developed to aid researchers with code validation for impacts that occur at velocities faster than the testable regime. Codes of concern include both hydrocodes and fast-running analytical or semi-empirical models used to predict the impact phenomenology and damage that results to projectiles and targets. There are several well documented experimental programs that can serve as benchmarks for code validation; these are identified and described. Recommendations for further experimentation (a canonical problem) to provide validation data are also discussed.

1.0 Background

The Code Validation (COVAL) Program of the Air Force Wright Laboratory Armament Directorate (WL/MN) is intended to improve and provide more confidence in the predictive capability of analytical or semi-empirical models that are used in the analysis of interceptor systems lethality. The concern of many researchers is that the analytical models are not capable of making accurate predictions of lethality at typical intercept velocities. Some of the intercept velocities are sufficiently high (> 7 km/s) to cause phase changes in many of the materials contained in the targets and kinetic-energy-kill vehicles. The addition of phase change phenomena means that the extrapolation of low velocity data may not be an acceptable assumption. Current experimental capabilities are such that only limited experimental data can be taken at velocities above 7 km/s. The lack of experimental data forces the analytical models to depend on *a priori* (hydrocode) predictions of damage to provide the needed data for curve fits and reference tables.

Fragmentation dynamics dominates the impact physics at impact velocities less than 7 km/s. Fragment size is a continuous function of impact velocity. For example, as impact velocity increases, fragment size typically decreases. Mixed phase (solid and molten) debris clouds have similar dynamics, except for smaller particle size, as solid-only fragment clouds. Secondary impacts and damage, of considerable interest for lethality assessments, can result in further fragmentation. Although progress has been made in fragmentation theory, analytic models rely heavily on experimental data. Debris clouds that contain fragmented solids can be achieved within current light-gas gun capability, but not all lethality estimates will come from experiments due to the expense and time of experimentation. The ability of hydrocodes to describe fragmentation, debris propagation, and the subsequent loading of another structure accurately must be assessed and validated because of the importance of secondary and tertiary impacts.

Hydrocodes are increasingly being used to aid in lethality assessments. Numerical simulations are necessary because sufficient experimental testing cannot be conducted to provide all the necessary information for complete lethality assessment. Besides being very expensive, the full range of impact scenarios cannot be replicated in the laboratory. Additionally, virtually all impact testing must be done at scale in order to achieve a relevant impact velocity with the kinetic energy (KE) interceptor. Thus, hydrocodes are used to provide "expected value" target damage estimates to complement available experimental testing. Examples of hydrocode use include complex ballistic and cruise missile impact simulation, analysis of chemical release and deposition, and high explosive impact initiation.

As noted, the goal of COVAL is to improve the predictive capability of the analytical models. Thus, improving our confidence in the predictive capabilities of hydrocodes in the velocity domain where extensive fragmentation and phase changes take place is important. If the hydrocodes are shown to be accurate in predicting damage, then simulations can be performed to generate numerically derived "experimental" data for incorporation into the semi-analytical models used for lethality assessments. Note that we make a distinction between a damage assessment

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and a lethality assessment. Hydrocodes can be used to predict damage, but additional analysis is necessary for assessing lethality from the damage state.

The word "validation" means the process of building an acceptable level of confidence that a simulation model reasonably approximates the actual process. A large body of phenomenological data exists that can be used to support initial hydrocode validation studies, although, in general, these experiments are not sufficient to fully validate the hydrocodes. Existing experiments tend to have simple geometries and predominantly use low melt-temperature metals as the focus of the experiments. In addition, some of the measurements are inconsistent or incomplete. However, these experiments can and should be used as a starting point. Therefore, the first major task of the COVAL Program is the development of a Hypervelocity Experimental Research Database (HERD). This effort consists of identifying and documenting available experimental impact data in the literature, along with known but unreported data, that can be used in validation studies with the hydrocodes.

The HERD program objectives are to leverage existing data to guide future experimentation and analysis; to develop an understanding of projectile/target breakup, debris cloud characteristics, and debris cloud propagation dynamics; and to evaluate the adequacy of hydrocodes and equation-of-state models to predict damage due to high velocity impacts. Emphasis is placed on experimental data that demonstrates highly fragmented debris or the production of melted and/or vaporized material that results from an impact. In addition, further emphasis is placed on those experiments where the debris cloud interacts with a secondary target.

Three selection criteria were established to assist in the prioritization of the recommended experiments. Experiments should demonstrate phase change or fragmentation phenomena with optical or radiographic diagnostics or both; experiments should involve secondary impacts; and experiments should include some sort of response or time-resolved data. These criteria provided a rational means for selecting experiments for potential code validation studies, although the experiments selected meet these criteria to varying degrees.

2.0 Code Validation

It is not necessary to validate all aspects of a computational tool. Rather, the effort should be the identification of computational specifics that still lack suitable validation. In particular, *two areas that are relevant and important for assessing damage by computational means in hypervelocity impact are related to issues concerning **equation of state** and **fragmentation***. These issues can be subdivided into three areas (Trucano, 1993):

1. accuracy of the numerical hydrodynamics;
2. accuracy of the physical models in the code;
3. adequacy of the physical models in the code.

The first area deals with the issues related to truncation errors, etc., resulting from the discretization of a continuum problem. It also deals with whether or not there exists sufficient mesh resolution to encompass the important features that a calculation is intended to model. The second area deals with the ability of the physical models to provide quantitatively correct predictions of experiments. Sometimes this area is not independent of hydrodynamic accuracy. If the numerical calculation is not resolved (that is, it does not have enough computational zones), the physical model may not be able to reproduce the experimental observations; sufficient numerical resolution might give the right results. Equation of state, constitutive models, and fracture models represent some of the physical models in this area. Finally, although a physical model may be accurate for its originally intended purpose, it may not capture the relevant and essential features observed in other types of problems. That is, the physical models that account for certain phenomena may not exist within the numerical framework. Examples include two-phase flow effects and highly fragmented debris propagation.

We wish to make several additional distinctions. *A physical model might not reproduce all the features observed in experiments. However, the key issue is whether the physical models and numerics can replicate accurately the relevant features of an experiment.* In the present study, the concern is the loading and damage as a consequence of hypervelocity impact, particularly that resulting from secondary and tertiary impacts. For example, the critical issue is the subsequent loading and damage of secondary (and tertiary) impacts by a debris cloud, and not whether the features of a debris cloud are replicated exactly by computations.

Trucano makes another observation that is extremely relevant. Large scale experiments and calculations of entire targets are not only expensive, but involve length scales encompassing four to five orders of magnitude, all of which are important to a lethality assessment (Trucano, 1993). Trucano states: "The complexity of the problem forces the ***validation*** of the modeling strategies to be separate considerations of various features of the problem. [...] *Experiments which are directed at the separate phenomena are the most credible means of providing such validation data.*" That is, the overall problem should be divided into pieces that can be analyzed separately. Once the various pieces are validated, then there can be some confidence in the integrated analysis.

3.0 Survey of Literature

A survey of the literature was undertaken to identify documents containing information pertinent to the HERD program goals. Data known to exist to the authors, but not formally documented, were also included in the survey. Of primary interest were documents or data sources that contained sufficient background information to assure a clear understanding of the experiments or study, detailed description of the experimental setup, and documentation of experimental results.

The objective of COVAL is to establish confidence in the use of numerical simulations for lethality studies. Therefore, quantitative comparisons between experimental data and code predictions are needed to assess the predictive capability of hydrocodes. An additional requirement is that these quantitative comparisons be made for critical facets of the lethality engagement scenario. Table 1 provides a summary of the characteristics of relevant experimental studies. In particular, experiments that provide optical or radiographic diagnostics, secondary impacts, and time-resolved impact data (pressure, momentum, etc.) are of high interest.

Several extensive databases with broad scopes have already been gathered under government funding. The present effort concentrated on reporting experimental and computational efforts relevant to code validation. The results of very recent test programs that are highly appropriate for COVAL tasks have also been included. Patterson, (1994) contains a complete listing of more than 100 sources surveyed for the HERD database.

Table 1. Selection Criteria for Experimental Programs

• Debris Cloud Form	
1) Vaporous	*high interest*
2) Molten	*high interest*
3) Solid Fragments	*high interest*
4) Mixed Phase	*high interest*
• Target Layout	
1) Bumper/Breakup plate followed by secondary targets	*most interest*
2) Single thin plates	*interest*
3) Semi-infinite targets	*least interest*
• Diagnostics Used/Data Obtained	
1) X-Ray or Optical Image of Debris Cloud	*high interest*
2) Time resolved pressure, impulse, velocity, etc.	*high interest*
3) Momentum imparted to targets	*high interest*
4) Damage measurements of targets	*high interest*
5) Perforation/no perforation	*interest*

We applied our selection criteria to the experiments and data described in these reports and articles. Table 2 is a summary of the eleven reports/articles that provide most of the desired information shown in Table 1, and thus satisfied the criteria to some degree. Table 2 also indicates areas in which the referenced work might be lacking: for example, little or no information included about damage done to the secondary target plate, or no time-resolved diagnostics such as pressure or momentum. Additionally, the quality of flash X-ray images or photographs is not particularly good in some cases. The next section describes four test programs from among those in Table 2 that we think are suitable for code validation studies.

4.0 Experiments For Code Validation Studies

The following four sets of references contain experimental data that are recommended for comparison to computational simulations. The experiments are well documented and include most of the desired features described in Table 1. Each of these experiments is described in some detail.

4.1 Robert L. Bjork (1990), "Vaporization and SDI Lethality" Experiments with Lead and Molybdenum

There are actually four sets of experiments described in this document. They were all conducted to ascertain the effects of velocity and vaporization upon damage to secondary targets (behind a bumper plate). The predominate projectile material used in these tests was a lead alloy (Linotype) that exhibited vaporization upon impact with a lead bumper shield at speeds near 3.5 km/s. Several other tests used molybdenum projectiles and bumper/breaker plates to compare to the lead results. The molybdenum fragmented into solid pieces at the impact velocities studied in this work (5 km/s and less). Flash X-rays of the debris clouds and postmortem photographs of the damage to aluminum cylinders (which acted as the secondary targets) are provided. Figures 1 and 2 provide a description of the test setup for these experiments; Figure 3 depicts the measured and computed pressure profiles from within the target plates.

Table 2. Summary of Selected Experimental Investigations

Source	Impact Velocity (km/s)	Material	Debris State F=fragmented M=molten V=vaporous	Debris Cloud Images	Witness Damage Measured	Additional Diagnostics	Comments
Hopkins, *et al.* (1972)	1.0-7.0	Al→Al Cd→Cd	F V	None	perforation only		classic paper
Bjork (1990)	1.5-5.0	Pb→Pb Mo→Mo	F M V	X-Ray	perforation, damage	pressure-time response	hard to match debris cloud photo with specific experiment, scaling of X-rays not provided
Mullin, *et al.* (1989)	2.8-6.8	Al→Al Zn→Zn Cd→Cd	F M V	X-Ray	damage	momentum, pressure-time	good pictures
Piekutowski (1992)	3.8-7.2	Al→Al	F M	X-Ray	none		t/d study - very good debris cloud pictures
Konrad, *et al.* (1993)	~5	Zn→Zn	M V	X-Ray	perforation, damage	need analysis of witness	no velocity dependence
Chhabildas, *et al.* (1993)	5.0-11.0	Al→Al	M V	X-Ray	perforation		important work time-dependent hole growth only diagnostic
Mullin, *et al.* (1993)	7-11	Al→Al Zn→Zn	M V	X-Ray	perforation	PVDF gages	data needs analysis
Ang, *et al.* (1992)	7.1-9.8	Al→Al	M V	optical	perforation	time-resolved perforation	holographic data
Stilp, *et al.* (1990)	2.3-4.5	Steel→Steel	F	X-Ray	perforation, damage	measured velocity elements of fragments	t/d study
Schmidt, *et al.* (1993)	1.4-6.0	Cd→Cd	F M V	X-Ray	perforation, damage		ballistic limit thickness studies
NASA (MFSC & JSC) many sources	3.0-7.0	Al→Al	F	None	perforation, some damage		ballistic limit thickness studies

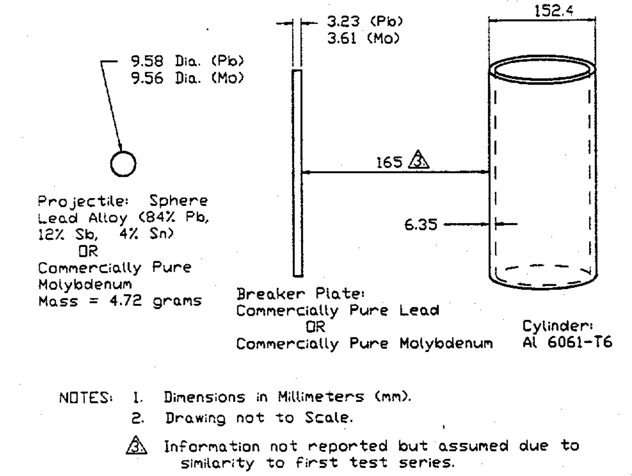


Figure 1. Experimental Setup for Second Test Series of Bjork (1990)

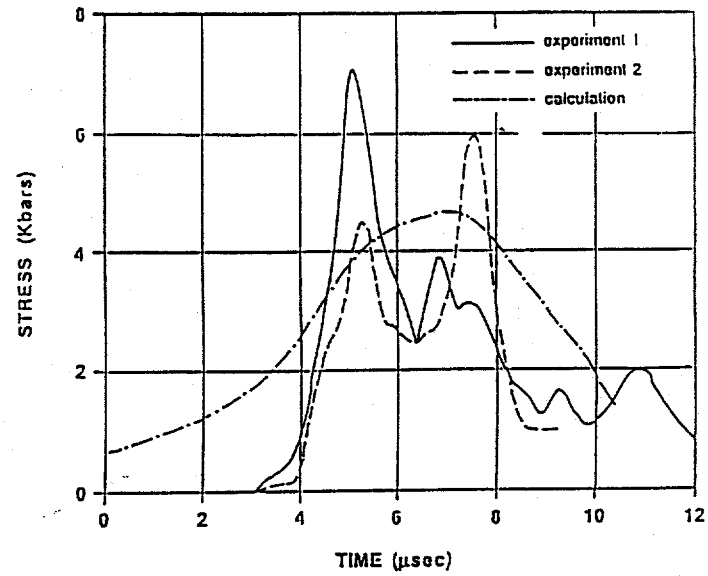


Figure 3. Comparison of measured and computed stress histories, Pb on Pb at 5 km/s, from Fourth Test Series of Bjork (1990)

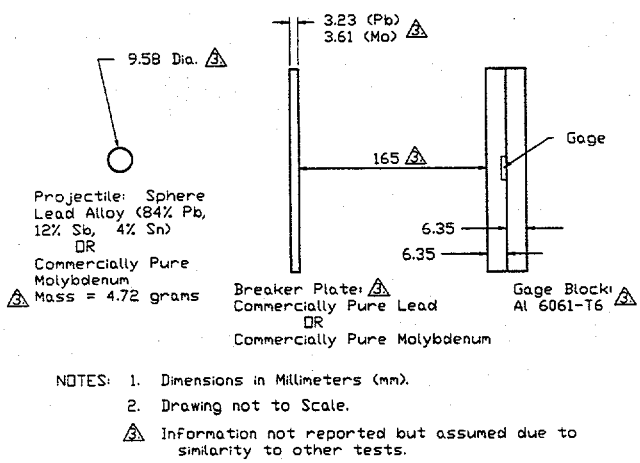


Figure 2. Experimental Setup for Fourth Test Series of Bjork (1990)

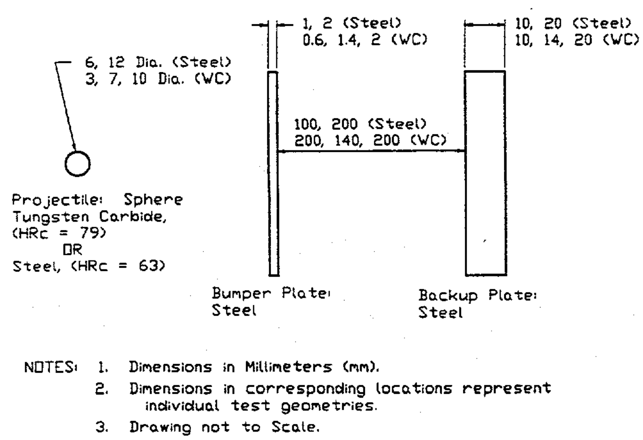


Figure 4. Experimental Setup for Test Series of Stilp, *et Al.* (1990)

4.2 Stilp, *et al.* (1990), "Debris Cloud Expansion Studies" Experiments with Steel and Tungsten Carbide

This document describes a series of 38 impact tests with tungsten carbide and steel spheres designed to provide fragmentation and debris cloud data. The projectiles were shot through relatively thin steel bumper/breaker plates, with the debris then impinging upon a thicker steel second plate. Figure 4 depicts the test geometry. The impact velocities (2.3 - 4.5 km/s) are such that the debris is predominantly solid, although some minor melting is reported in impact craters on the second plate. Measurements of velocity components of the debris cloud are reported for all tests. The test results are depicted in graphs, some of which are reproduced in Figure 5.

4.3 Mullin, *et al.* (1989, 1990), "Dissimilar Material Velocity Scaling Relationships for Hypervelocity Impact" Experiments with Cadmium, Zinc, and Aluminum

The experiments and analysis reported in this document were performed to support the velocity scaling concept. Experiments were conducted with spherical zinc, aluminum, and cadmium projectiles impacting into double wall targets. The first wall acted as a bumper/breakup plate, and the second target plate served as a witness plate and a ballistic pendulum. A ballistic pendulum was also hung in front the bumper plate to measure the momentum of the ejecta that splashed back from the initial impact. On some of the impact tests, pressure-time traces were obtained from carbon gages imbedded in the witness plate. Figure 6 depicts the test setup.

The impact velocities were selected to provide debris clouds of either solid, molten, or vaporous form. Flash X-ray images are available for most of the tests. Momentum was measured for both the ejecta and the main debris cloud. Damage to the witness plate (extent of cratering, and a qualitative description of damage magnitude, since there were no perforations) is provided. Figure 7 shows the measured resulting momentum onto the backwall (witness) plate. The results of this study provide the loading response onto a witness plate over a range of impact velocities that produced fragmented, molten, and vaporous debris.

4.4 Mullin, *et al.* (1993), Konrad, *et al.* (1993), Chhabildas, *et al.* (1993) Experiments with Zinc and Aluminum

These experiments are very recent and have not been fully analyzed or reported. The references indicated above describe portions of the test program. Velocity scaling experiments were conducted with zinc over the velocity range of 2.35 - 6.78 km/s, which corresponds to 4.5 - 14 km/s impacts for aluminum. Three different projectile shapes were launched: disks, spheres, and rods. Flash X-rays were obtained of the debris cloud and of the back wall plate during perforation by the debris. Velocity and extent of the debris cloud were measured. Postmortem damage to the back wall plate was also measured. Most of the impacts generated debris clouds with significant melt or vaporization, but some tests were conducted such that the debris was composed primarily of solid fragments. The test setup is depicted in Figure 8. These data provide some of the most complete information corresponding to the requirements in Table 1.

Impact tests were also conducted with aluminum disks and rod-like projectiles launched from 7.4 to 11.4 km/s using specialized launch techniques, the inhibited shaped charge (ISC), and the three-stage light-gas gun hypervelocity launcher (HVL). The zinc tests described previously were designed to be similar to these aluminum tests, with the objective to further verify velocity scaling principles. The test setup for the aluminum tests was similar to Figure 8, and is shown in Figure 9. Fewer flash X-rays were made of the aluminum tests, and no images are available of the back wall plate during perforation by the ISC projectiles. However, the pressure-time profiles that resulted from the impact of the debris into a gage block were recorded on two of the ISC tests. A trace from one of these tests is shown in Figure 10.

5.0 Code Validation Study: Recommendations

5.1 Issues in Code Validation

The four test programs described in the previous section represent those that can be used for code validations. However, it is not necessary to simulate all of the experiments. A reasonably good exercise of code capabilities can be obtained by simulating a subset of the mentioned experiments. Table 3 lists issues related to code validation. The specific experiments chosen for simulations were selected to address these issues.

5.2 Existing Data

5.2.1 Computational Matrix

Twelve of the experiments would be simulated. The first two simulations replicate the Bjork experiments of lead into lead, and molybdenum into molybdenum. The original simulations were performed with a first-order accurate advection algorithm. Bjork (1990) demonstrated relatively good agreement for the moly impact test, but very poor agreement with the lead impact tests. The current state-of-the-art hydrocodes not only have second-order accurate advection algorithms, they also have improved interface reconstruction algorithms. Therefore, it is of interest to re-evaluate our ability to reproduce these two experiments and the pressure-time response data. In particular, the lead impact data show a double hump in the pressure-time response, and it is of interest to see if this can be replicated in the numerical simulations. Because there were two lead-into-lead tests, some statistics of expected experimental variability exist.

The next two sets of experiments involve impacts of zinc into zinc. The first set, from Mullin, *et al.* (1989), covers a velocity range that gives fragmentation, melt, and vaporization. Pictures exist of the debris clouds that loaded the ballistic pendulum. Repeat tests indicate that there is little test-to-test variation in the response parameters that were measured, such as the dispersion of the debris cloud and the total momentum to the witness plate. There is some information on witness plate damage, and the witness plates are available to take more measurements.

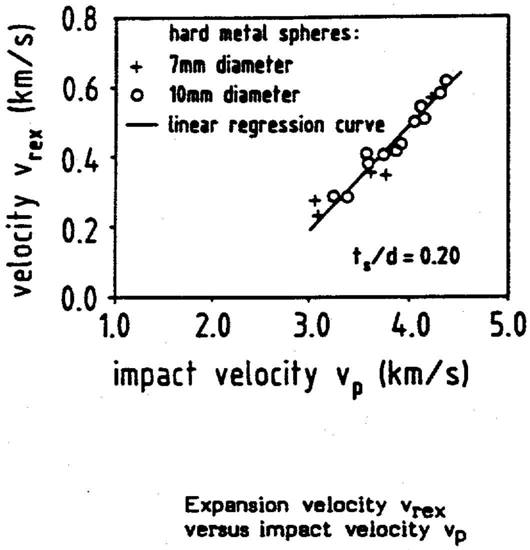


Figure 5. Examples of Experimental Data from Test Series of Stilp, *et al.* (1990)

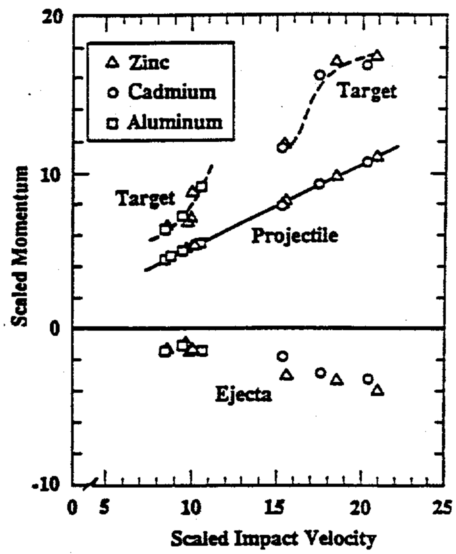


Figure 7. Scaled Momentum from Mullin, *et al.* (1989)

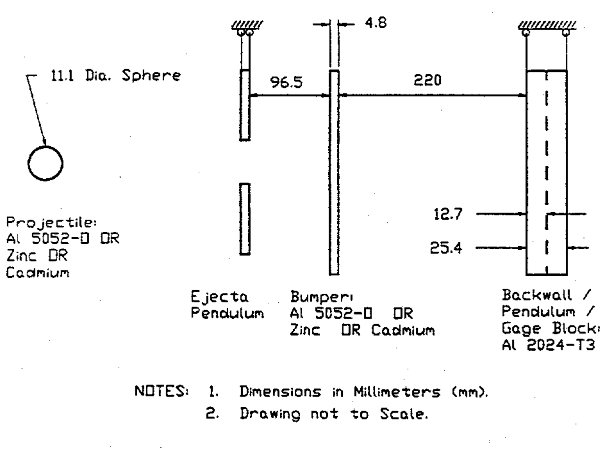


Figure 6. Experimental Setup for Test Series of Mullin, *et al.* (1989)

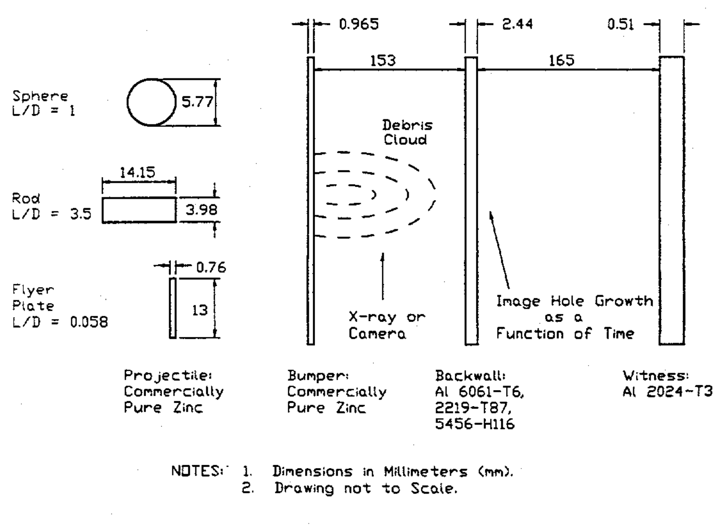
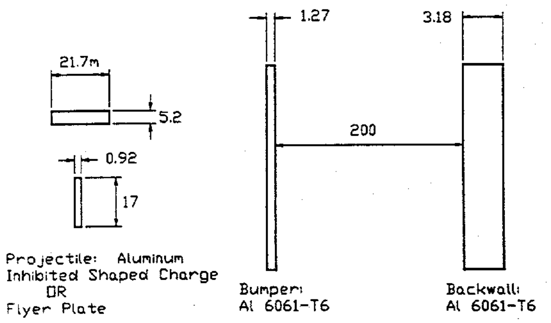


Figure 8. Experimental Setup for Mullin, *et al.* (1993); Konrad, *et al.* (1993)



NOTES:
1. Dimensions in Millimeters (mm).
2. On 2 tests, the backwall was replaced with an aluminum gage block.
3. On 1 test, the backwall was replaced with two 3.18 mm plates 100 and 200 mm from the bumper rear.
4. Drawing not to Scale.

Figure 9. Experimental Setup from Mullin, *et al.*(1993); Chhabildas, *et al.* (1993)

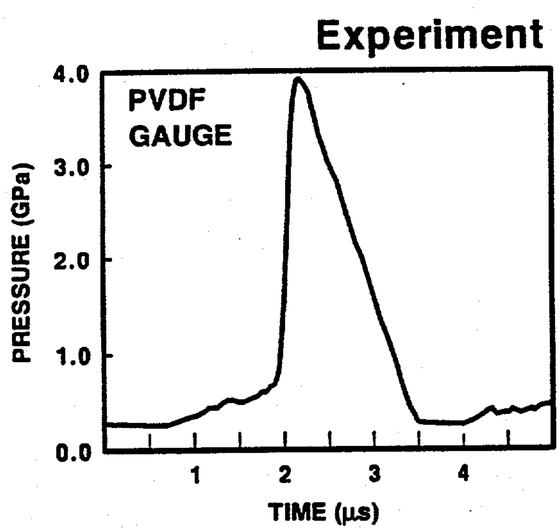


Figure 10. Pressure-Time Trace from an Instrumented ISC Test
Experimental Setup from Mullin, *et al.* (1993)

Table 3. Issues in Code Validation

Phase Changes
- EOS
- Mixed phase flow (flow separation)
- Cloud propagation
- Loading of next plate

Fragmentation
- Impact of first plate
  - fragment generation
  - fragment propagation in numerical grid
  - mesh resolution

↓

- Impact of next plate
  - local response
  - synergistic response
  - impulsive loading
  - plate failure
  - fragment generation

Velocity causes changes in geometric scale size of fragments

Table 4. Philosophy of Computational Code Validation Study

Coarse zoning to scope problem

- gross features
- physical time scale of important features

↓

"Resolved" simulation

- numerical accuracy
- agreement w/experiment

↓

What is the minimum zonal resolution that gives acceptable answer?

- *depends upon metric*

"fine zoning" required for state variables
"coarse zoning" for time-integrated variables

Although not extensively analyzed, stress measurements were taken during the loading of the plate at several different radial positions, thereby providing time-resolved loading data. This set of calculations tests the ability of the hydrocode to reproduce features of the debris clouds and resultant loading data over a range of impact velocities and physical states (fragments, melt, vapor, and various mixed phases). It is of particular interest to see if the code simulations can reproduce the observed experimental changes in load response with impact velocity.

The second set of zinc into zinc experiments (Konrad, *et al.*, 1993) permits an examination of projectile shape effects (sphere, plate, rod, cylinder), all at the same velocity. Witness plates were used to record the damage, but further analysis is required to quantify this damage.

5.2.2 Scope of Study

Twelve experiments were suggested for code validation. But these experiments represent more than twelve numerical simulations. First, a coarsely zoned problem should be run to scope the computational problem, i.e., provide gross features of the problem and the physical time scale of these features. Issues related to mesh size and numerical resolution will require several computational runs to establish the requirements for a fully "resolved" simulation to provide the "best" agreement with experiment. Hydrocodes also have a number of "switches;" for example, how to treat the thermodynamics of mixed cells, and how to treat the strength in mixed cells. Although a preferred approach has developed over the past few years on mixed cell thermodynamics, no such consensus has evolved for the constitutive treatment of mixed cells. Several different runs may have to be performed to see which hydrocode options provide the best agreement with experiment.

A separate but equally important issue is the minimum zonal resolution necessary to give an acceptable answer. Unfortunately, this latter issue is dependent upon the metric being used for comparison. For example, "fine" zoning is required for state variables such as the stress or pressure. If damage (or initiation) criteria are based on a maximum (peak) stress, then the zoning must be sufficiently detailed to resolve the stress. On the other hand, if the metric is a time-integrated variable, for example, impulse, then coarser zoning can be used to produce reasonably good agreement with experiment. Table 4 summarizes the overall approach for performing the simulation and code validation study.

5.3 New Experiments

5.3.1 Canonical Problem

It is useful to discuss some of the concerns and features surrounding the COVAL program in terms of a canonical problem. The canonical problem was chosen to illustrate interactions typical of a kinetic energy interceptor striking a complex target. From the previous discussion, it should be clear that code validation requires relatively simple (but carefully chosen) experiments that reflect the key physical processes of the actual (but complex) interactions.

Figure 11 is a schematic of the canonical problem for code validation over a range of impact velocities. This sketch shows a projectile (shown here as a sphere, but it can be any simple shape) impacting a plate. The initial impact will produce a debris cloud whose state will depend on the impact velocity and material characteristics. The debris cloud will then traverse a void space and impact will occur with a second plate. The secondary impact will also produce a debris cloud whose state will now depend on the characteristics of the initial debris cloud, the secondary impact velocity, and material and geometric characteristics. It should be expected that the secondary debris cloud will have different characteristics than the first cloud. The secondary debris cloud will also traverse a void space and impact a third plate.

In this scenario, the projectile represents a simplified kinetic energy kill device; the first plate represents the outer skin of a typical target. The second plate represents some internal structure of the target, and the third plate represents the internal component that must be disabled to render the complex target inoperable. The spacing (void space) simply represents the gaps between internal components typical in complex targets of interest to the COVAL program.

5.3.2 Instrumentation

Instrumentation must be set up so as to capture diagnostic information at each step of the experiment. X-ray and optical (holographic) data should be acquired to characterize the debris cloud as it traverses the void space. In addition, PVDF gauges should be used to provide time-dependent data for the plate loading phase. The instrumentation is chosen to capture the maximum amount of information that can be used in a code validation exercise. A mix of instrumentation is shown in Figure 11; the appropriate systems would be chosen when test plans are developed. Repeat tests are essential to characterize the statistical variability of measured responses. Repeat tests may also be required since some types of diagnostic information may be mutually exclusive, or may interfere with the subsequent time evolution of the experiment (e.g., a mirror position to record hole growth with time).

5.3.3 Impact Phenomenology as a Function of Velocity

A key aspect of impact-induced fragmentation is that as the velocity increases, the size distribution of the resulting debris cloud changes. At relatively low impact velocities, the size distribution is skewed towards a few large particles with no very small particles. As the velocity increases, the number of large particles decreases and the number of small to very small particles increases. The size of the largest particle also decreases as the total number of particles increases. This progression has interesting ramifications for our canonical problem as is illustrated by the following.

At low impact velocities, a few large fragments are created by the initial impact. This scenario can be visualized in Figure 12. Here large fragments refer to objects much larger (fully resolved) than the computational mesh. The dynamics of the initial impact are dominated by tensile failure phenomena. In this regime, both the hydrocodes and the analytical models should do an adequate job of modelling the generation and trajectories in the first void space. The secondary impacts are characterized by discrete impacts with little or no synergism. A smaller number of spall-generated fragments may be ejected from the back of the second plate. Some of the original fragments will be stopped by the second plate, but the larger, high velocity fragments will perforate the plate and additional fragments will be generated.

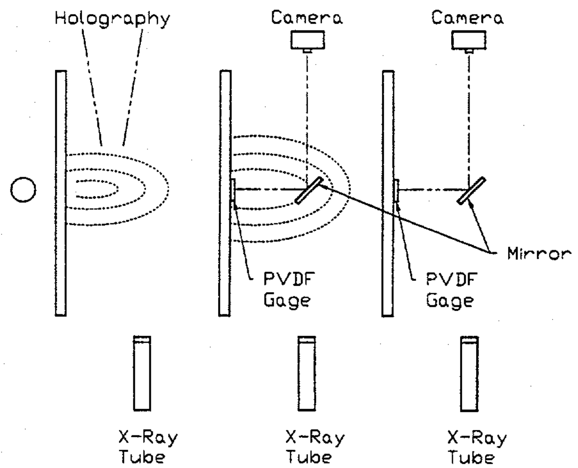


Figure 11. Canonical Problem Description

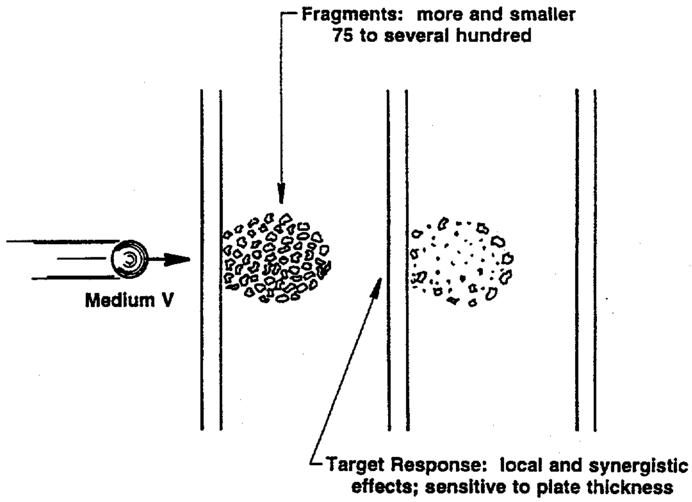


Figure 13. Medium Velocity Impact Phenomena

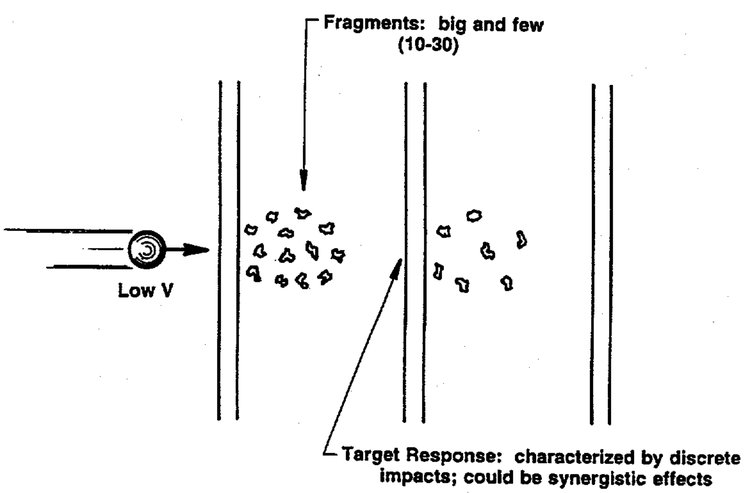


Figure 12. Low Velocity Impact Phenomena

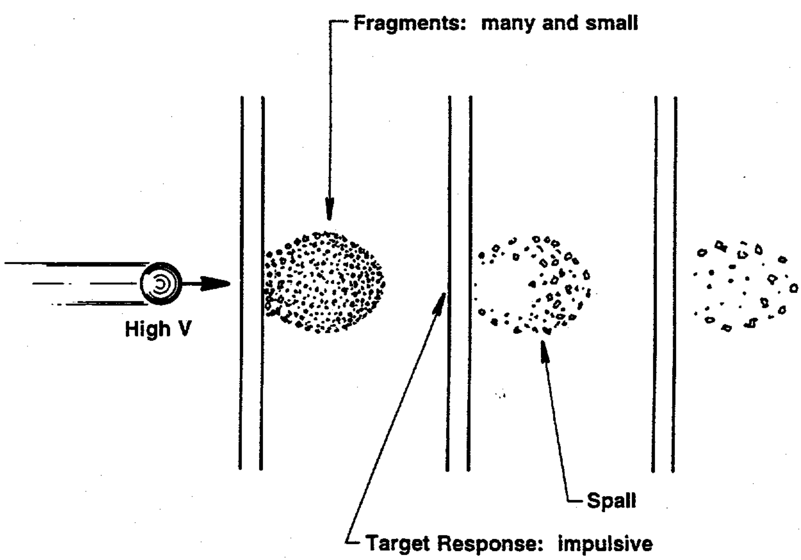


Figure 15. High Velocity Impact Phenomena

The tertiary impacts are very few, and damage at the third plate is dominated by strength rather than hydrodynamics. We would expect that both hydrocodes and analytical models should do an adequate job of modelling the complete range of dynamics for this impact scenario.

As the velocity increases, the initial debris cloud is characterized by more and smaller fragments. This scenario can be visualized in Figure 13. Here the fragments are not larger than the computational mesh, but comparable in size (marginally resolved). The failure regime is still dominated by tensile phenomena, but the process is determined statistically and only averages of size and trajectory have meaning. Depending on material characteristics, the initial debris cloud may contain some molten material along with discrete particles. The hydrocodes have been shown to have some validity in this regime, but it is not clear if the agreement is real or simply serendipitous. The comparisons to date have been single experiments, not comprehensive studies. The secondary response is determined by a combination of local and synergistic effects. The secondary debris cloud may consist of a spall-produced fragment due to the discrete impacts along with particles that survived perforation, or the secondary debris could be a spall plug due to impulsive loading.

Loading of the third plate now resembles secondary loading for lower velocity initial impact. It is not clear how well the hydrocodes and analytic models would do in predicting the complex, total response of this scenario. We are confident that some parts of the complex experiment can be modeled accurately, but less so for the integrated interactions.

The response of the second plate (actually, the response of all the plates) depends upon the loading conditions, material properties, and plate thicknesses. The cartoon shown in Figure 14 represents various types of plate response as a function of plate thickness. Although discrete responses have been shown in Figure 14, response is really a continuum.

As the velocity increases again, the initial debris cloud is characterized by many and very small fragments, molten debris, or vapor. This scenario is visualized in Figure 15. Here the fragments are much smaller than the computational mesh and are being treated as a continuum of material by the hydrocodes.

The failure regime is dominated by tensile phenomena, but the process is statistically determined and only distribution and shape of the debris cloud have meaning. Depending on material characteristics, the initial debris cloud will contain some molten material, some vapor, and some solid particles. Depending on what portion of the experiment we are trying to replicate, the hydrocodes have been shown to have *some* validity in this regime, but overall agreement tends to be poor. The secondary target response is principally determined by impulsive loading. The secondary debris cloud will consist of "more and smaller" fragments and should be similar to the initial debris cloud of a medium velocity impact. Loading on the third plate now resembles secondary loading for a medium velocity initial impact. It is not clear how well the hydrocodes and analytical models would do in predicting the complex total response of this scenario. We have less confidence that some parts of the complete experiment can be modelled accurately and much less so for the integrated interactions.

It should be clear from the above discussion that code validation for high velocity initial impacts has a critical link to lower velocity phenomena.

5.3.4 Experimental Variables

Several experimental series should be considered to aid in the understanding of the key physical phenomena. For all of the experimental series, the assumption is that one or at most two parameters will be varied in any given set, although due to overlap, a single experiment may be part of several series. In approximate order of importance, these experimental series are as follows.

The initial impact velocity should be varied from approximately 1 to 7 km/s. This range, depending on materials, will provide data on fragmentation, discrete particle loading, impulsive loading, and mixed phase energy partitioning in both the initial and secondary debris cloud, and secondary and tertiary impacts. This test series will provide a wealth of useful data for both hydrocodes and analytical models.

The projectile shape should be varied. A test series consisting of spherical projectiles, long rods (l/d ~ 5), and disks (l/d ~ 0.2) should be considered. The spherical projectile is not of particular interest by itself as a possible kill device, but it is simple to use experimentally. Rods and disks may be more typical of components of a kill vehicle and should be studied for that reason alone. Velocity variation for each of the projectiles should also be considered to add to our understanding of the fragmentation and phase change phenomena.

The plate thickness, spacing, and materials should be varied. Because of the complexities of the potential targets, this series of experiments will provide data more typical of actual encounters. As such, this series is somewhat ambitious and may require additional time to complete. Obviously, a parallel effort in numerical simulations is needed to complement the experimental effort.

5.4 Summary

A large body of data exists for hypervelocity impact into a spaced plate array (most of these data consists of a bumper and a back plate). Various types of measurements have been taken by different researchers, and the types of data collected and the quality of the documentation varies considerably. A review of this literature has resulted in the selection of several experimental tests series that are applicable to code validation studies. A subset of the experiments was designated for potential code validation studies; data from these experiments will permit a quantitative evaluation of the ability of numerical simulations to predict impact loading of multiple plate targets.

The best way to perform a validation study is to compare code results against relatively simple experiments that tend to isolate separate but relevant phenomena. In particular, we have identified experiments that permit an evaluation of effects from fragmentation, melt, and vaporization, and the subsequent loading of a second plate (impact velocity is the variable). In the experiments, quantitative measurements were made of the plate response. Additionally, effects of projectile shape can be studied at a constant impact velocity.

We showed that the phenomenology changes with impact velocity. As the phenomenology changes, particularly with respect to fragment size and phase transformations, the ability to resolve all the details numerically decreases. This raises questions concerning the ability of hydrocodes to calculate correctly the subsequent loading of the next plate in the target array. Sufficient data to evaluate the ability of hydrocodes to reproduce secondary and tertiary impact response do not currently exist. A canonical experiment is recommended to collect the appropriate data.

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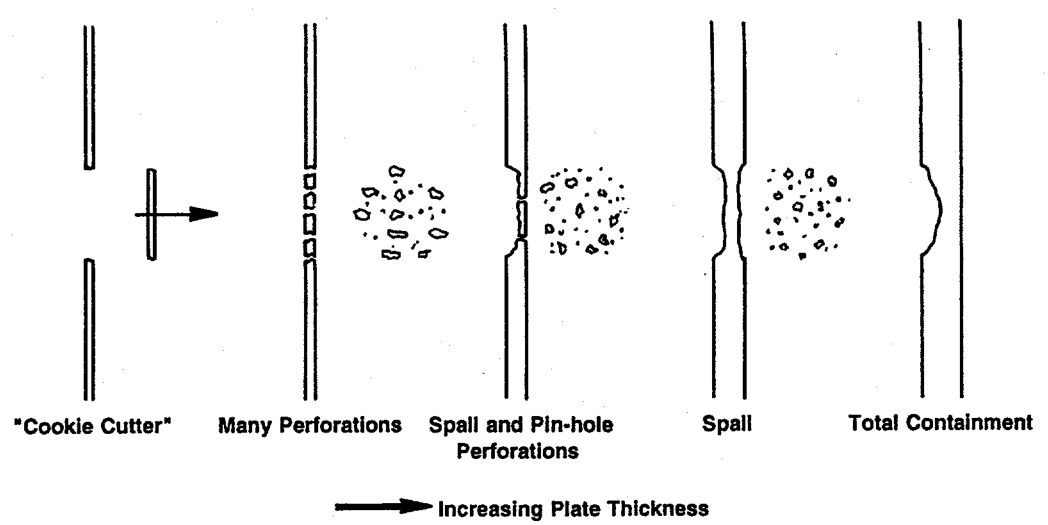

Figure 14. Failure Modes of Loaded Plates