Verification and Validation of a Penetration Model for the Design of a Blast Containment Vessel Part I: Validation Experiments

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Model verification and validation (V&V) provides a mechanism to develop computational models that can be used to make engineering predictions and decisions with quantified confidence. Model V&V procedures are needed to reduce the time, cost and risk associated with component and full-scale testing of products, materials and engineered systems. The Los Alamos National Laboratory Dynamic Experimentation (DynEx) program is designing and validating steel blast containment vessels using limited experiments coupled with computational models. This paper describes the testing program for the validation experiments in support of a verification and validation process for an analytical and computational model used to predict the penetration depth of explosively released fragments into the containment vessel structure. The V&V process is described as well as pre-test analytic modeling and validation experiments. Uncertainties in the experiments that may influence model validation are discussed from an uncertainty quantification perspective since there are inherent and subjective uncertainties in the model that must be correlated with the uncertainties from the experiments.

I. Introduction

The Los Alamos National Laboratory Dynamic Experimentation (DynEx) program is designing and validating steel blast containment vessels using limited experiments coupled with computational models. One such vessel is shown in Figure 1 where X-rays are used to image the phenomena through windows consisting of boron carbide ceramic (B4C), beryllium, and aluminum. During explosion experiments the vessel walls and windows are subject to impact from fragments. Successful performance of the vessel is defined when a projectile penetrates less than half the thickness of the outer window layer. The vessel design goal is to minimize window thickness to increase X-ray resolution while withstanding fragment penetration.

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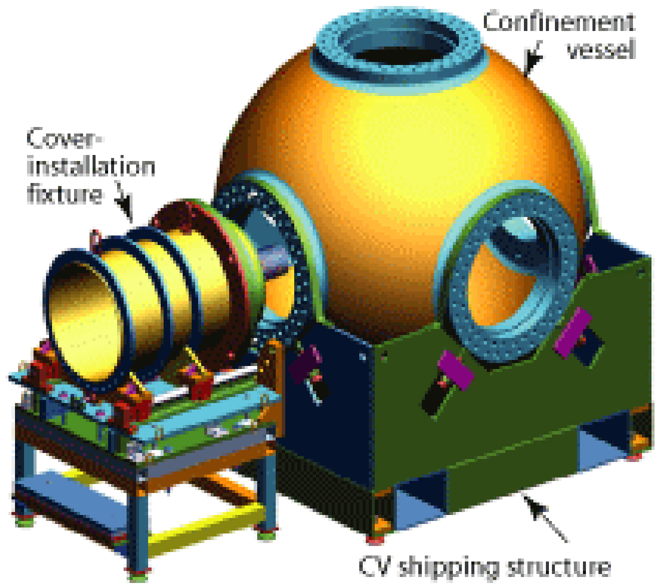

Figure 1. A DynEx containment vessel configuration.

II. Verification and Validation

In situations where full-scale experimental programs cannot be performed, the decision makers must rely on a predictive strategy such as computational models. The key to establishing confidence, or credibility, in model predictions is the development, implementation and practice of a process called model verification and validation (V&V). Model V&V provides a systematic process for building and quantifying confidence in model predictions through the logical combination of focused laboratory experimentation, hierarchical model building, and uncertainty quantification (Thacker, 2005).

The V&V processes is shown in Figure 2 and describes the various activities associated with obtaining high quality experimental results; the parallel and cooperative role of experimentation and simulation; the quantification of uncertainties in both experimental and simulation outcomes, and an objective approach for improving agreement between experiment and simulation.

In Figure 2, the right branch illustrates the process of developing and exercising the model, and the left branch illustrates the process of obtaining relevant and high-quality experimental data via physical testing. The closed boxes denote objects or data, connectors in black solid lines denote modeling or experimental activities, and the connectors in red dashed lines denote assessment activities.

On the experimental side of Figure 2, a physical experiment is conceived and designed resulting in a Validation Experiment. The purpose of a Validation Experiment is to provide information needed to validate the model; therefore, all assumptions must be understood, well defined and controlled in the experiment. To assist with this, Pre-test Calculations can be performed, for example, to identify the locations and types of measurements needed from the experiment. These data will include not only response measurements, but also measurements needed to define model inputs and model input uncertainties associated with loadings, initial conditions, boundary conditions, etc. The Pre-test Calculations link between the experimental and computational branches in Figure 2 also reflects the important interaction between the modeler and the experimenter that must occur to ensure that the measured data is needed, relevant and accurate.

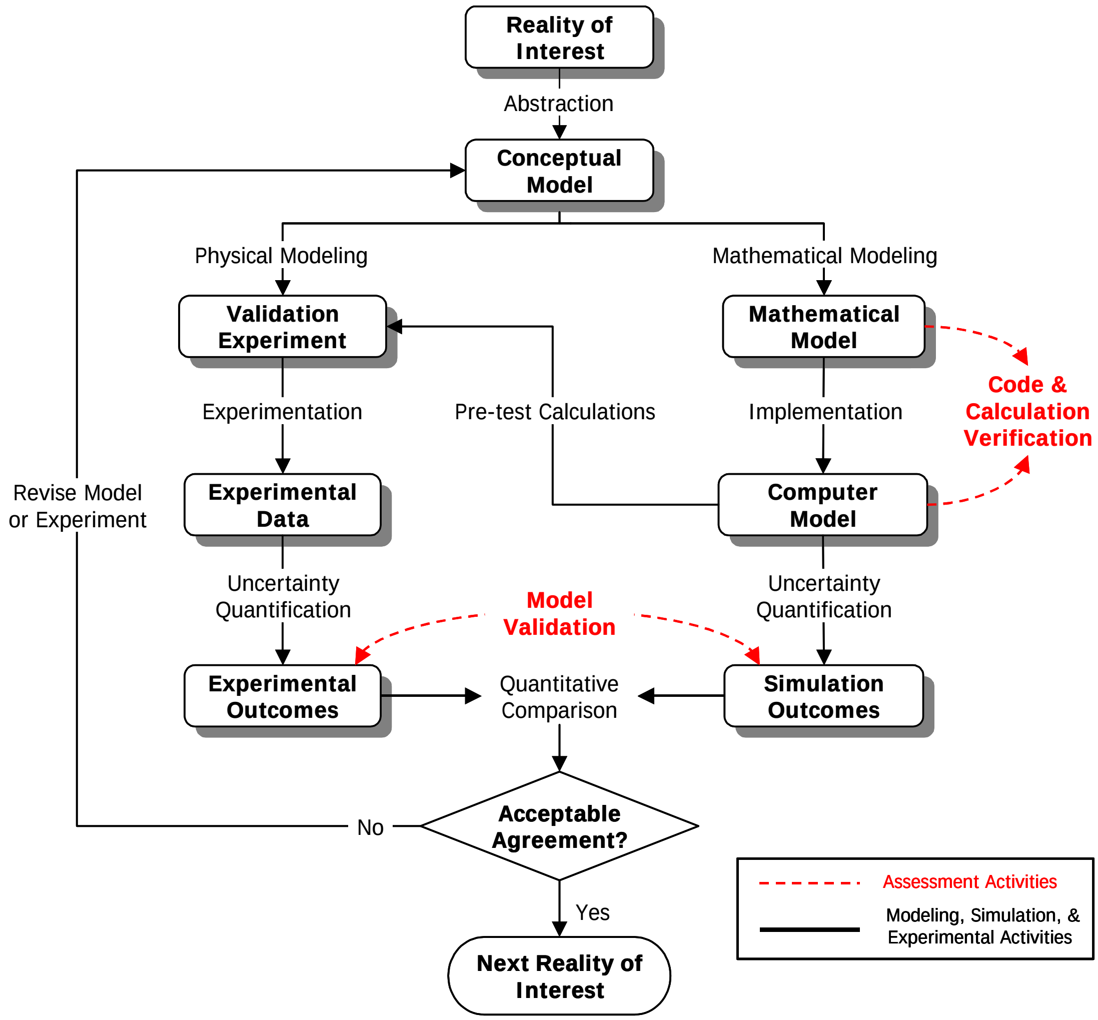

Figure 2. Detailed model development, verification and validation process.

Experimentation involves the collection of raw data from the various sensors used in the experiment (flash X-rays, ultrasonic scans, etc.) to produce Experimental Data such as impact velocity, projectile pitch, depth of penetration, etc. Uncertainty quantification is then performed to quantify the effect of measurement error, design tolerances, as-built uncertainties, fabrication errors, and other uncertainties on the Experimental Outcomes. To support the quantification of experimental uncertainties, replicate experiments are generally required to quantify the lack of repeatability due uncontrollable variability. Experimental Outcomes will typically take the form of experimental data with error bounds as a function of time or load.

Uncertainty quantification is shown on both left and right branches of Figure 2 to underscore its important role in quantifying the uncertainty and confidence in both the experimental and simulation outcomes. Uncertainty quantification plays a key role in model V&V. Nondeterminism refers to the existence of errors and uncertainties in the outputs of computational simulations due to inherent and subjective uncertainties in the model. Likewise, the measurements that are made to validate these simulation outputs also contain errors and uncertainties. While the experimental outcome is used as the reference for comparison, the V&V process does not presume the experiment to be more accurate than the simulation. Instead, the goal is to quantify the uncertainties in both experimental and simulation results such that the model fidelity requirements can be assessed (validation) and the predictive accuracy of the model quantified. The role of non-determinism in model V&V is more fully discussed in Thacker et al., 2004.

III. Analytical and Computational Models

Before the development of the analytic model for layered armors, pre-test estimates were used for guidance for the experimental design and test matrix. To accomplish this, an empirical approach was taken that modeled the ceramic and the backing window materials (aluminum or beryllium; assumed for this analysis phase to be semi-infinite). The threat projectile was a depleted uranium (DU) rod. These computations were performed using the Walker-Anderson model (Walker and Anderson, 1995) for the penetration for the semi-infinite material, with the amount of projectile erosion based on the experimental work with tungsten from Orphal, et. al (1997) and Orphal and Franzen (1997). Recall that the maximum allowable depth of penetration for the DynEx program was half the thickness into the vessel or viewport wall. This analysis predicted the depth of penetration, and led to the conclusion that ceramic armor was required to limit the penetration to the desired depths. Boron carbide (B4C) was chosen and thus added into the test matrix. The results of this analysis are shown in the subsequent section, compared to the experimental results.

IV. Validation Experiments

We were tasked to analyze the penetration threat from three different sizes of DU rod-shaped projectiles. The rods were 5mm in diameter; three lengths were used: 10, 30, and 50mm. These projectiles were manufactured by LANL, in the alloy designated U6Nb. For all tests the impact velocities were nominally 2.0 km/s. The main concern from a confinement perspective is fragment impact into the two X-ray windows made of Al 7050-T7451 and beryllium S-65C. In the tests the Al target was a simple rectangular block 6.0 inches square and 2.0 inches thick, shown in Figures 3 and 4. The Be target was more complex. The Be core was actually a truncated conical section, slightly larger in diameter on the impact side (diameter = 1.75 inch) than the rear side (diameter = 1.64 inch), and 1.75 inches thick. It was press fit into the center of the 9-inch square, 1.9 inch thick steel support assembly. Two rubber O-rings were placed into grooves cut into the center hole of the steel plate to help hold the Be disk in place. On the impact side of the target a steel plate was screwed that helped support the ceramic armor disks and the edge of the Be piece (Figure 5). On the rear side of the Be target assembly an aluminum plate was placed that covered the rear of the Be disk. This aluminum plate thickness directly behind the Be disk was 0.24 inches. The Be target assembly with this rear aluminum plate removed can be seen in Figure 6.

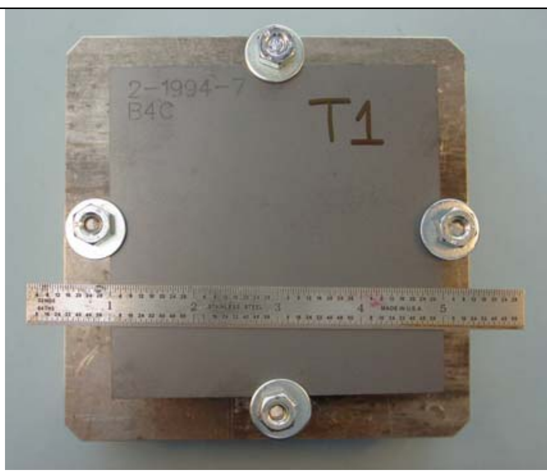

Figure 3. Impact side of the Al target, showing the B4C ceramic armor disks.

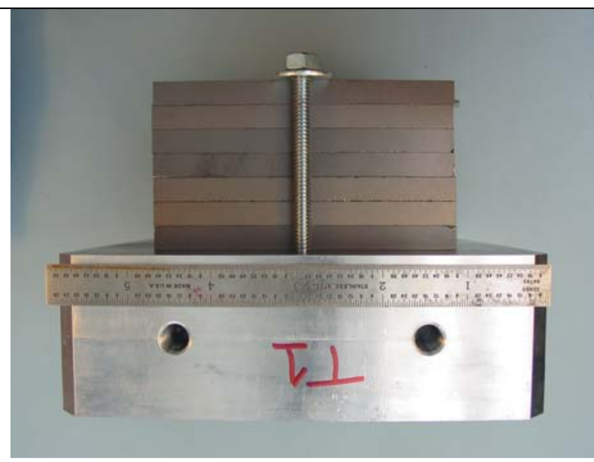

Figure 4. Top view of an Al target, showing the stack of B4C armor disks before impact (Test 1).

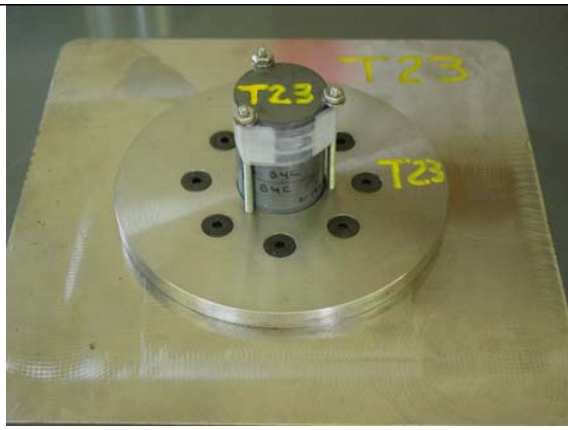

Figure 5. View of the front of a Be target showing the stack of B4C armor tiles (above the impact side of the Be piece).

Figure 6. View of the rear of a Be target with the rear aluminum plate removed, showing the back side of the Be disk.

The B4C ceramic armor was formed by a pressure assisted densification (PAD) process to achieve a uniform density and material properties. The tiles used as armor for the Al targets were 4.0 inches square and 0.317 inches thick. For the Be targets, the B4C tiles were cylinders 1.45 inches in diameter and 0.318 inches thick. In many cases several of these tiles were stacked together to form thick armoring. The projectiles were fired to their required velocities using a high performance 30mm powder gun. The gun is mounted onto an I-beam that runs continuously from the gun through the area of the flash X-ray (FXR) stations. Projectile velocity, pitch, and yaw are computed from these radiographs. The target area lies beyond the X-ray station.

Pusher-type sabots, shown in Figure 7, were designed to support the smooth projectiles during their acceleration down the gun barrel. The sabot body was made from aluminum and the obturator was delrin.

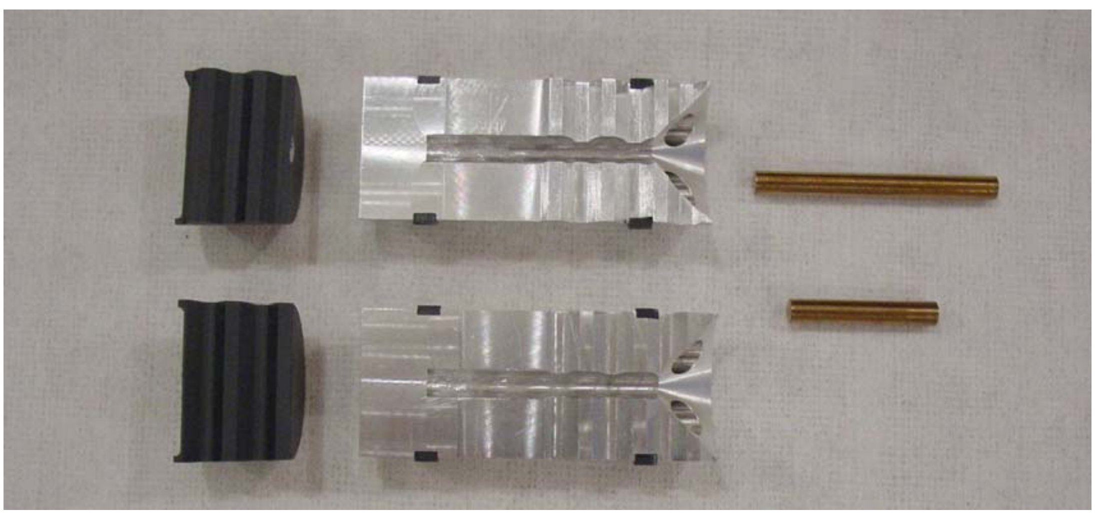

Figure 7. Photo of the 2-piece sabot and the 50mm and 30mm length rods.

V. Experimental Results

A total of 31 data shots were fired against these targets. Repeat shots were taken as often as possible, either 2 or 3 for each condition, so that variability or uncertainty could be evaluated. All tests were fired as close to 2.0 km/s as possible. The DU rod size and the number of B4C armor tiles was varied from test to test. The experimental results are shown graphically in the following Figures 12 and 13.

The primary data taken from each experiment is the depth of penetration (DOP) into the base metal (aluminum or beryllium). Deposits at the crater bottom prevented accurate DOP measurements using downward probing mechanical calipers. Two non-destructive methods were used to provide more accurate measurements, with accuracies on the order of 1mm. Ultrasonic scans were used on the rear and sides of the aluminum targets. Signals received from the ultrasonic device delineated the location of the penetration hole, locating it in three dimensions. Figure 8 shows an example of the ultrasonic investigation of the target shown in Figure 9. Ultrasonic scans were attempted for the Be targets, but their complexity, plus the high sonic velocity of the beryllium material, did not allow for clean signals. The size of the Be target assembly did not allow an X-ray source to penetrate through it, so the targets were cut with a hole saw. This resulted in a cylindrical piece, the outsides of which were steel, surrounding the Be core. The cut was slowly and carefully controlled to avoid disturbing the Be sample, which had a brittle appearance and behavior after impact. Figure 10 shows the piece cut out from Test 18, and the X-ray image in Figure 11.

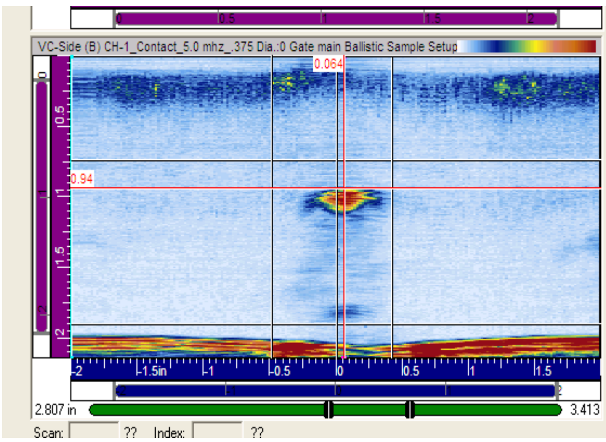

Figure 8. One view from the Ultrasonic C-scan indicating the depth of the crater and a residual projectile piece.

Figure 9. Picture of the Damage to the Aluminum Target in Test 8.

Figure 10. Picture of the drilled-out core taken from Be Test 18, showing the Be disk surrounded by the cut-out steel layer.

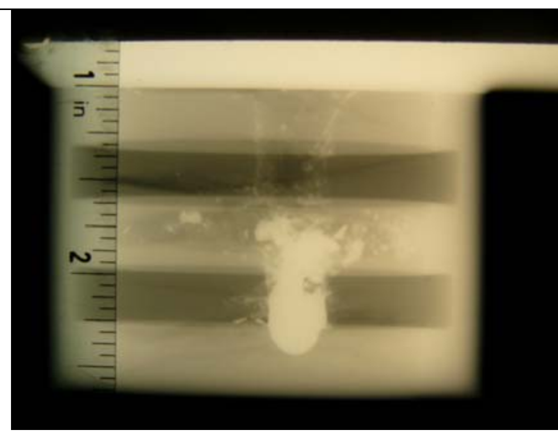

Figure 11. NDE X-ray image taken from Test 18 (Be). A tungsten plate used to locate the top of the target; the dark horizontal bands are due to the O-ring grooves. The light image deep in the target is the residual DU rod.

Figure 12 shows the aluminum DOP data as a function of the B4C tile thickness, for all different rod sizes. The vertical lines on the graph depict the total thickness of the aluminum portion (solid) and the ½ thickness (dashed). Only one perforation of the entire target occurred, that being Test 11 with a 30mm rod. Tests were conducted with a variety of armor thicknesses and projectile types to provide as much information as practical for the validation process. The spread in the depth of penetration for a given ceramic thickness indicates the experimental variation between repeat tests with "identical" conditions. his spread is an important factor in the V&V analyses of the computational simulations. Testing over a wide range of the variable of interest provides more comparison points for the computational analyses, and, assuming good agreement, more confidence for its capabilities.

Figure 13 shows the same kind of data for the experiments with beryllium. It can be seen that there was more variation seen with the repeat tests; this is believed to be due to the greater complexity of those target systems.

The analytic prediction of the B4C thickness required to reach the ½ penetration level is seen to be quite good in all situations. The analytic model developed in this program to help design the experiments also becomes another element in the V&V process, the "mathematical modeling" shown in Figure 2.

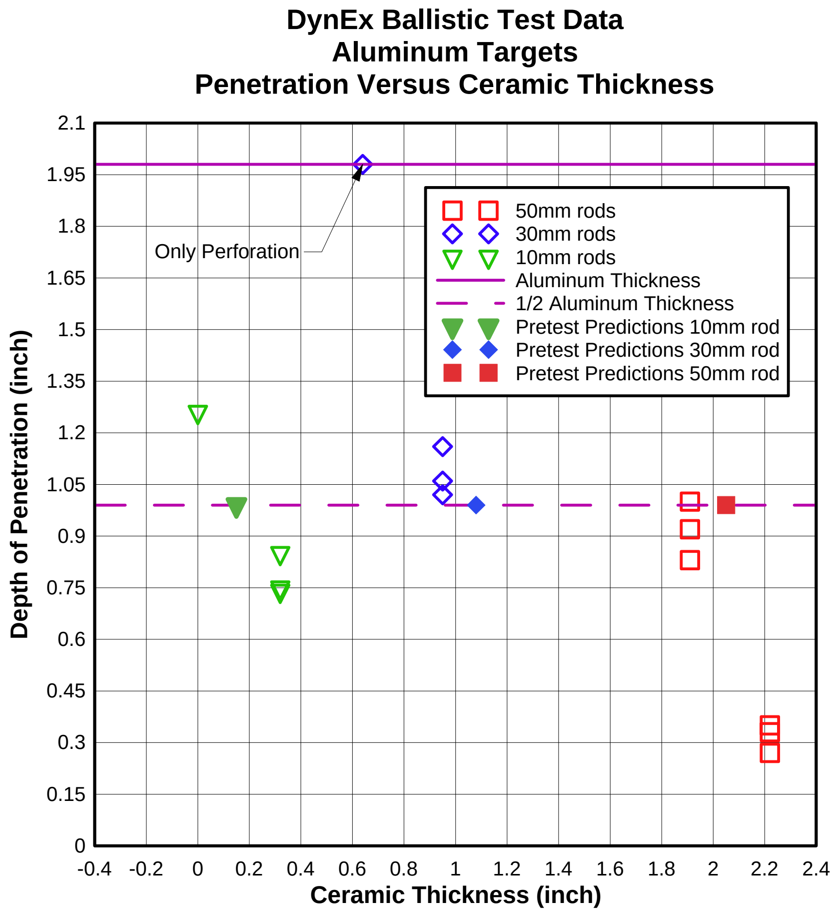

Figure 12. Results of the experiments with aluminum targets. Note the solid figures that indicate the pre-test analytic model predictions.

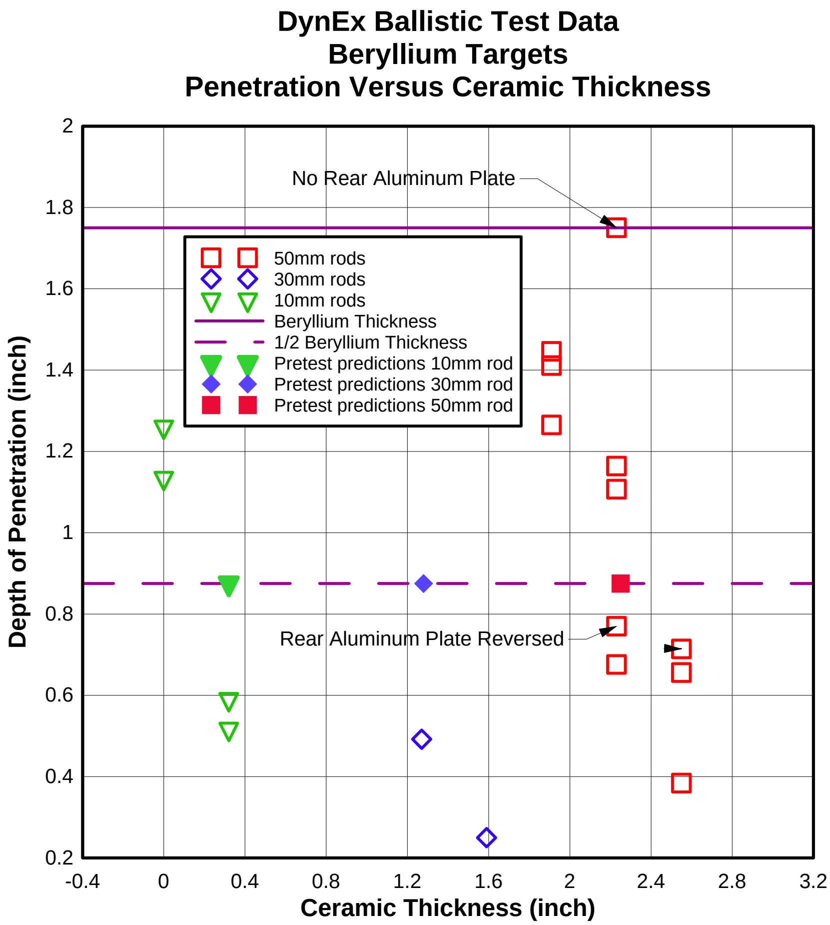

Figure 13. Results of the experiments with beryllium targets. Note the solid figures that indicate the pre-test analytic model predictions.

VI. Uncertainty Analysis

Uncertainty can enter into the experimental results in many areas. These are discussed below, and, where possible, estimates or calculations are provided to put numerical bounds on the uncertainty. The parameters focused upon are those that are deemed important to the penetration process. After the discussion section, the uncertainty of the most important parameters is summarized in Table 1.

Material Properties: The material properties of the DU rods, the B4C armor tiles, and the target pieces are very important in determining final penetration depth. In the most simplified sense, the density and strength (best represented by the dynamic stress-strain constitutive behavior) are important for the DU and the Aluminum. For the B4C and the Be, being brittle hard materials, characteristics which describe their fracture toughness or post-fracture commutated strength are probably important, as is their density. Our knowledge of these parameters and associated uncertainty is discussed below.

- **DU, Be, Al:** All the target pieces and rods were supplied by LANL and we assume that QA controls were in place to insure that all the materials came from the proper alloy, heat treating/forming processes, etc., to insure uniformity and control of strength, constitutive behavior, and density. The rod alloy is designated U6Nb, which has a handbook value of ρ = 18.5 g/cm^3, and an ultimate strength σ = 185,000 psi. The Al alloy is 7050-T7451, which has handbook values of ρ = 2.83 g/cm^3, an ultimate strength σ = 76,000 psi, and a failure strain of 11 %. The Be alloy is unknown; pure Be has handbook values of ρ = 1.84 g/cm^3, an ultimate strength σ = 53,700 psi, and a failure strain of 3 %. We cannot assign uncertainty to those values because SwRI did not measure them.

- **B4C Tiles:** All the B4C tiles were supplied to SwRI by CERCOM under a QA compliant manufacturing process. Included with that material is standard documentation of values for the Pressure Assisted densification (PAD) B4C material: ρ = 2.485 g/cm^3 and flexural strength σ = 65,000 psi. Personal communication with Cercom about their material obtained information that CERCOM performs flexural strength test on batches of their material every year, with the flexural strength varying from 56,000 to 72,000 psi, but "most" data lies near 65,000 psi. This provides a spread in the expected results, but not a real measure of the statistical variance. We performed ballistic testing to help understand and qualify the ballistic resistance of the B4C tiles. In that work we were not able to define an exact variance in "ballistic resistance" due to size effects with the different tiles. At best, using a curve fitting technique, we were able to determine a nominal "ballistic resistance" curve that can be compared to future materials. Looking solely at the maximum variation in residual velocity between tests that should provide identical results, we determined a variance of 7 percent. We were able to investigate the variance in the density values. We found that the B4C disks averaged density ρ = 2.50 g/cm^3 and the B4C squares ρ = 2.52 g/cm^3. The standard deviations were small, approximately 0.01 g/cm^3.

- **Other Target Materials:** The Be targets were complex assemblies that confined the Be disks in a steel plate, and backed up the Be disk with an aluminum plate. The type of material used in these areas is unknown, so we again assume that LANL took the required QA steps to obtain uniform, known material properties.

Target Assembly: The construction and geometric controls over the target assemblies can affect their ballistic performance. This is true to a lesser degree with the Al targets, because they are relatively simple assemblies, with the B4C tiles held flat to the impact face with small screws. The Be targets are more complex, and the response noted during impact makes this of more concern. The Be disk in these targets is press fit into a bored-out opening in the steel plate, with 2 O-rings used to insure a tight fit. Grooves are cut into the steel to accept these O-rings. The disk itself is not cylindrical, but rather has a slight taper that is larger on the impact side. The Be disk could be pushed out with moderate finger pressure in the pre-impact condition. After all the impact tests it was noted that the Be disks were pushed backwards into the assembly, and were jammed in so tight that light weight mechanical presses could not budge them. Stronger presses were not used for fear of shattering the Be disk. In many of the tests the Be disk also pushed hard enough against the back aluminum cover plate to shear out a thin disk. So, the geometry (relative diameters) of the Be disk and the hole would seem to be very important, as would the thickness of the rear aluminum cover plate. And the strength of those materials is also important to ballistic performance. The authors do not know values of these parameters.

- **Tile Attachment Screw Torque:** For all tests the screws that held on the stack of B4C armor tiles were tightened to a torque of 5.0 in-lb, using a calibrated torque wrench. This wrench was noted by the Cal lab to have a deviation of 0.2 in-lb. It is the opinion of the authors that the torque values applied to the screws is a secondary factor in the DOP results, because the penetration event is so fast the tiles cannot appreciably move while they are penetrated and destroyed.

Physical Dimensions: All the dimensions taken in the test program, which includes the length and diameter of the projectile, the thickness and size of the B4C tiles, and the outer dimensions of the targets (except the Be assemblies) were made with calibrated calipers. The outer size of the Be assembly was large enough to definitely not affect the penetration event, so it was measured with a tape measure. The calipers were accurate to less than 0.001 inch.

Mass Measurements: Several elements of the test program were weighed before each test. These include the sabot and obturator pieces, the projectile, the gunpowder charge, and the powder in the "spit tube". All these measurements were made with calibrated scales that were accurate to 0.2 grams.

Velocity: The primary measurement for the projectile velocity is the flash X-ray system. The conservative confidence level of the measurements made from the X-ray and digitizer measurement system of distances, lengths, angles, etc is stated to be 95%. This is stated even though static measurements indicated standard deviations in linear measurements of 0.002 inches and, for angles, 0.04 degrees. The 95% confidence level applied to the 2.0 km/s goal velocity for this test program would indicate an uncertainty of 0.1 km/s, but this seems very high when the standard deviation of all the data obtained herein is 0.03 km/s, which, considering the possible velocity variations caused by powder loads, sabot geometry, timing circuits, and other variables should make this standard deviation larger than 0.1 km/s. Therefore the authors recommend that an uncertainty in velocity of 0.03 km/s sounds reasonable. This is further substantiates when the velocity data taken with the make screens (a secondary velocity system) is compared to that obtained with the flash X-ray system. In most all cases the difference between the two independent measurements is less than 10 m/s.

Pitch and Yaw: Pitch and yaw are also measured with the flash X-ray system, so, following the argument just presented for the velocity, it seems reasonable to assume that these angles can be measured with the accuracy stated in the trial cases, namely, 0.04 degrees.

Impact Normal: The impact orientation for the experiments was defined as normal, meaning that the velocity vector of the projectile would be perpendicular to the face of the target plate (or actually the B4C tiles on the front). This condition was checked in the experiments by use of a laser that is bore mounted in the muzzle of the gun, and indicates the impact location on the target face. (This assumes the laser beam is perfectly aligned with a perfectly straight gun bore, neither of which is truly correct). The target alignment is checked before each test by placing a small flat mirror on the face of the target, which shines the beam back onto the laser face. A perfect normal condition is obtained when the beam shines back onto itself. In actual practice, the beam points to a location that can be as much as 1/3 inch from ideal, over a distance of 14 feet. This results in an angle of 0.11 degrees. Given the other imperfections involved, a reasonable uncertainty would be to double this value, to 0.22 degrees.

Table 1. Summary of Uncertainty Estimations

Parameter	Uncertainty	Notes
Material Properties (B4C Tiles Density)	0.01 g/cm^3	Averaged from many measurements
Material Properties (B4C Tiles Ballistic Resistance)	7%, but can not be absolutely quantified	Data taken from analysis of the certification ballistic tests indicates this as a maximum
Material Properties (DU, Be, Al)	unknown	LANL might have this data
Physical Dimensions	0.001 inch	Form calibrated calipers
Mass Measurements	0.2 grams	From calibrated scales
Tile Screw Torque	0.2 in-lb	Not considered very important
Velocity	0.03 km/s	From X-Ray measurement system
Pitch and Yaw	0.04 degrees	From X-Ray measurement system
Impact Normal	0.22 degrees	From laser pointer measurements

VII. Summary

The role of validation experiments is described in the overall V&V procedure. This paper focuses upon the experimental results, the use of pre-test predictions to guide the development of the experimental program, the use of repeat tests to establish experimental variation, testing over a wide range of the variables of interest to increase the confidence of the simulations, and the estimation of uncertainty in the experimental variables.

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