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EFFECTS OF BALLISTIC IMPACTS ON SPHERICAL CERAMICS

by

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EFFECTS OF BALLISTIC IMPACTS ON SPHERICAL CERAMICS

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requirements for the degree of

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ABSTRACT

Empirical data suggests that ceramic spheres can serve as front face systems for armor applications, which can improve performance over current monolithic plate design by providing multi-hit fracture resistance and lower costs. Ballistic test results of ceramics composed of AD90, AD995 and sapphire (Al_2O_3) are presented alongside hydro code simulation results. In addition to chemical differences, impact performance between geometric differences is also examined. Performance calculations include (as a function of time) projectile velocity, deceleration, force applied and work applied to the projectile. Shockwave propagation through sapphire targets is observed to be consistent with published sound speeds and is in agreement with hydro code. We found that 1/2" spheres are shown to perform better than 1/2" right circular cylinders. AD90 is shown to perform better under ballistic test conditions than AD995, indicating the feasibility of a low-cost, ceramic sphere-based front facing armor system.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANEOS	analytical equation of state
DoD	Department of Defense
E-SAPI	enhanced small arms protective insert
FBAI	flexible-buoyant armor insert
GUI	graphical user interface
HEL	Hugoniot elastic limit
JH-2	Johnson-Holmquist 2 model for brittle materials
MATLAB	Matrix Laboratory
MTV	modular tactical vest
NATO	North Atlantic Treaty Organization
NIJ	National Institute of Justice
NPS	Naval Postgraduate School
OTV	outer tactical vest
PASGT	personal armor system for ground troops
RCC	right-circular cylinder
RHA	rolled homogenous armor
SAPI	small arms protective insert
SI	système international d'Unités
SNL	Sandia National Laboratory
TEMA	TrackEye Motion Analysis
TIFF	tag image file format
UHMWPE	ultra-high molecular weight polyethylene

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I. INTRODUCTION

We study the performance of ceramic spheres as a front face armor system applied against ballistic threats as a possible replacement to current monolithic ceramic plates. The motivation to investigate ceramic spheres is driven from two directions. First, empirical data suggests ceramic spheres can serve as front face systems for armor applications [1], and second is the improved performance over current monolithic plates by providing multi-hit, fracture resistance and lower construction cost.

Ballistic data from ceramic spheres incorporated as the front face of a composite armor system suggest that the ceramic spheres can provide equal or better mass efficiency as compared to monolithic ceramic plates [1]. An investigation is required to better understand the ceramic sphere response to a ballistic impact.

Through a series of ballistic impacts at a fixed impact velocity (630 m/s) variations in ceramic shape (sphere and right-circular cylinder (RCC)), chemistry and impact location will be used to better understand the performance of each ceramic geometry. Performance of the ceramic systems will be studied through both experimental ballistic impacts and hydro code calculations. Performance calculations will include (as a function of time): projectile velocity, deceleration, applied force and work applied to the projectile.

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II. BACKGROUND

The use and development of personal body armor has been available for thousands of years. Civilizations throughout history have all made significant contributions to armor technology and development [2], [3]. In recent decades that work has continued, integrating cutting edge material science with current terminal ballistic theory and modelling [4], [5], [6], [7]. Ceramics have been intensely researched since the mid-1960s as a candidate material for armor plating. Today, ceramic-based armor systems are in use across the globe. Wilkins authored and coauthored a large body of foundational research into light body armor while at Lawrence Radiation Laboratory in Livermore, CA [8], [9], [10], [11], [12]. Wilkins' paper [13] built upon the work of Tate [14] and established the fundamentals of modern ballistic impact analysis. Current ceramic composite body armor systems incorporate monolithic front face systems backed by an ultra-high molecular weight polyethylene (UHMWPE) textile backing with a mass efficiency around four as compared to rolled homogenous armor (RHA) [15].

This thesis will specifically focus on a new composite ceramic armor for personal body protection using individual ceramic geometries integrated into a front face system.

A. MODERN ARMOR

For the sake of brevity, only a few of the most prominent armor advancements will be discussed by way of introduction. In World War I, almost no effort was made to outfit U.S. combat forces with body armor until a cumbersome attempt was introduced toward the end of the war. Named after its inventor, Dr. Guy Brewster and shown in Figure 1, the Brewster was capable of stopping rounds from a Lewis Gun, but its design and weight made it ultimately ineffective for general use. Brewster body armor was essentially the first attempt by the United States to produce body armor for modern warfare with considerations for bullet impact as well as fragmentation [16].



Figure 1. Brewster Body Armor. Source: [16].

During World War II (WWII) and the Korean War, an early composite armor was used by U.S. Soldiers and Marines that was colloquially known as Doron. Doron was produced by Dow Chemical Company and was a laminate of fibrous glass fabric and plastic with a small percentage of nylon, and is shown in Figure 2. Doron was used extensively during the Korean War, but was only moderately used during WWII, specifically in the last stages in the Battle of Okinawa in 1944 [17]. Doron was shown to be effective at stopping fragmentation, but did not have the ability to consistently stop bullets [18].

The next step forward in body armor came in the early 1980s with the introduction of the aramid fiber-based Personal Armor System for Ground Troops (PASGT) [19]. More commonly known by its trademarked name Kevlar®, this new technology indicated a major shift from using raw-earth materials like steel to synthetic materials. By the year 2005 armor systems were virtually all ceramic based with incorporated Improved Kevlar® and Twaron® fiber-based backing [19]. Around this same time, ultra-high molecular weight polyethylene (UHMWPE) was developed and considered extensively as a possible addition to composite body armor. The incorporation of these new, synthetic materials ushered in current state of modern armor systems based on new materials with unusually

high strength under extreme loading [19]. As threat levels increased alongside weapons development, body armors research advanced in tandem to counter the threat.



“Lt. Rodney M. Brigg of the Body Armor Team, 40th Infantry Division, points to a bruise on Lt. Frank Bassett, Co. G, 180th Infantry Regiment, made by hand grenade fragments. Lt Bassett’s body armor absorbed most of the impact of the blast. 20 June 1952” [17].

Figure 2. Doron Body Armor. Source: [17]

1. Current Armor Systems

After two decades of use, the PASGT was largely replaced by ceramic plate-based armor backed by UHMWPE known as Small Arms Protective Inserts (SAPI) and Enhanced Small Arms Protective Inserts (E-SAPI). An armor system known as the Interceptor incorporated ceramic composite based SAPI plates into the new system ushering in current armor concept designs [20]. Today these SAPI based systems are widely used by militaries across the globe including the U.S. and other NATO allies. SAPI plates are composed of front facing, ~0.89 cm thick Silicon Carbide (SiC) or Boron Carbide (B₄C) backed by around 35 layers of pressed, crisscrossed UHMWPE [20]. There are some differences between SAPI and E-SAPI side and composition, but for purposes of this thesis those will not be discussed. In more recent years, the original Interceptor design has been replaced by newer designs such as the Outer Tactical Vest (OTV) by the U.S. Army and the Modular Tactical Vest (MTV) by the U.S. Marine Corps, but no major design or technology development has taken place [21].

The U.S. currently evaluates and classifies armor based on the National Institute of Justice's (NIJ) performance criteria. Tested armor systems receive a rating from level I to level IV [22]. SAPI and E-SAPI plates are not rated to the same NIJ level of protection; however, for purposes of this study the distinction between SAPI and E-SAPI plates will not be considered nor discussed in detail. The ratings are derived based on the type of projectile the armor is tested as capable of stopping [22]. To eliminate this variable and to study ceramics in a more fundamental way, this thesis will use an identical, chrome-steel projectile shaped as a sphere, discussed further in later sections.

2. Disadvantages to Monolithic Plate Designs

The SAPI and E-SAPI design has its drawbacks and shortcomings. First and foremost, current armor inserts are composed primarily of monolithic ceramic plates with a density greater than water. U.S. combat forces are often required to conduct amphibious operations in contested littoral environments, and the lack of buoyancy in the armor is a known hazard. Attempts to mitigate the inherent danger such as the inclusion of the quick-release strap/handle on the Outer Tactical Vest (OTV) and Modular Tactical Vest (MTV) or the standard operating procedure of wearing standard life jackets underneath armor vests in training environments have been taken [21]. In addition to the lack of buoyancy, the current armor systems are rigid and have no flexibility. This reduces mobility and enables fracturing when the plates are mishandled. Furthermore, monolithic plates are prone to crack propagation after ballistic impact. It is impossible to predict the extent of the cracking post impact because every impact is unique. That said, it is plausible that performance will be degraded with each additional impact due to this crack propagation response.

Lastly, high costs are associated with the maintenance of monolithic plate designs via quality control and integrity assurance tests. To be certified as serviceable throughout its entire service life, a SAPI may require multiple inspections. This non-destructive testing is an added cost to the Department of Defense (DoD) beyond the initial plate purchase [23], [24].

3. Flexible-Buoyant Armor Insert

A new type of armor is currently being researched at NPS, specifically designed to address the current issues with the SAPI and E-SAPI plates. The new system, known as the Flexible Buoyant Armor Insert (FBAI), replaces monolithic plate designs with a lattice-based collection of ceramic spheres encapsulated in a flexible, closed-cell polyurea foam and backed by UHMWPE. The design departure from plate or tile centered ceramic toward smaller, spherical geometries is what has initiated the research culminating within this thesis.

B. THESIS ORGANIZATION AND RESEARCH QUESTIONS

This thesis attempts to further ceramic-based armor research by studying behavior of ceramics in different geometries, chemistries and impact orientations under similar ballistic impact conditions (3/8" chrome-steel sphere). Studies will include dwell time for the time period where the different geometries would remain intact prior to fracturing as well as the deceleration, force and work applied by the different ceramic geometries and chemistries.

All studies will include both the experimental investigations using a light gas gun and hydro code modeling. The results from each study are compared.

This thesis is organized into six chapters:

Chapter I	Introduction
Chapter II	Background
Chapter III	Experimental and Computational Set-up
Chapter IV	Data
Chapter V	Data Analysis
Chapter VI	Conclusions

In Chapter I, a basic introduction to the genesis and goals of this paper was presented. Chapter II provided facts on the history of armor development along with a discussion on current armor systems, their shortcomings and proposed improvements via

the new Flexible-Buoyant Armor Insert. Also, past research into composite ceramic-based armor systems were briefly referenced.

Chapter III details the experimental and modelling methods used to assess the ceramic sphere impact conditions. It also describes the computer simulation that will be used to analyze and compare against experimental results. The theoretical equations considered in this research will also be presented.

Chapter IV presents the experimental data and numerical simulations. Chapter V contains data analysis and Chapter VI presents conclusions and suggestions for follow-on work.

Note on units: the numerical simulation software, CTH, is programmed to use non-metric units. CTH is not a true acronym and is not included in the list of acronyms. CTH simply refers to the how the hydro code has expanded geometrically over previous versions. CTH, therefore, is treated in this paper as a proper noun rather than an acronym. For the sake of uniformity, all units, data and graphs will be presented in SI units alongside U.S. customary units when possible.

III. EXPERIMENTAL AND COMPUTATIONAL SET-UP

As introduced previously, this thesis compares data collected from two sources. The first data set is generated from experimental ballistic tests using a light gas gun and recorded with a high-speed camera. Data from the experiments are collected via the program TrackEye Motion Analysis (TEMA), a program produced by Image Systems, which allows for data collection from raw video footage. The second set is generated by a computer simulation using CTH. CTH is a hydro code program developed by Sandia National Laboratory and is a controlled U.S. resource. In an effort to keep this thesis an unlimited distribution document, any discussion about the program or the simulation results will be at the unrestricted level.

A. GAS GUN EXPERIMENTS

The primary experimental equipment for this thesis is a light gas gun with a 1 inch (2.54 cm) smooth bore. There are many benefits to conducting this experiment with a gas gun. First and foremost, the velocities can be controlled very accurately when launching projectiles with compressed air vice powder cartridges. Also, there is no heating of the barrel, no excess debris or discharge from the barrel and lower costs to operate. In this section, the various main components of the gun will be illustrated and described. In addition, several experiment specific components purposely designed for this experiment will be discussed.

1. Gas Gun Components

The light gas gun is designed to compress dry air enabling impact velocities up to 4000 fps (1220 m/s). The gas gun incorporates a 6000 psi (41.4 MPa) breech with a 13 ft. (3.96 m) barrel. A regenerative breech is used to enable a fast release of the breech pressurized gas. Figure 3 shows the complete light gas gun system in the NPS ballistics research laboratory. The main components include the breech, 1 inch bore barrel, and the impact chamber. Not shown in Figure 3 are the air compressors, air storage tanks, air pressure valve schemes and computer control systems which are all required for the gun to operate as a complete system. Figure 4 shows the 3/8 inch (0.9525 cm) chrome steel ball

bearing utilized as the projectile for the experiments. The light gas gun contains a 1 inch (2.54 cm) smooth bore barrel which requires the use of a sabot to launch projectiles. The sabot pictured in Figure 2 was 3D printed at NPS. 3D printing greatly reduces the operational costs of firing the light gas gun.

Figure 5 shows a closer view of the light gas gun breech and the systems of valves that control the system air pressures. The breech consists of multiple chambers that controls the motion of a piston and plunger, which enables the release of the gas behind the projectile. Compressed air is fed into the breech and reset compartments via the system of control valves. This takes place after a sabot/projectile set, as seen in Figure 4, have been loaded into the end of the exposed barrel and the breech has been secured onto the barrel. When triggered, the breech piston releases compressed air from the breech down the barrel which drives the sabot and projectile toward the impact chamber.



Figure 3. Light Gas Gun



Figure 4. Chrome Steel Projectile and Sabot

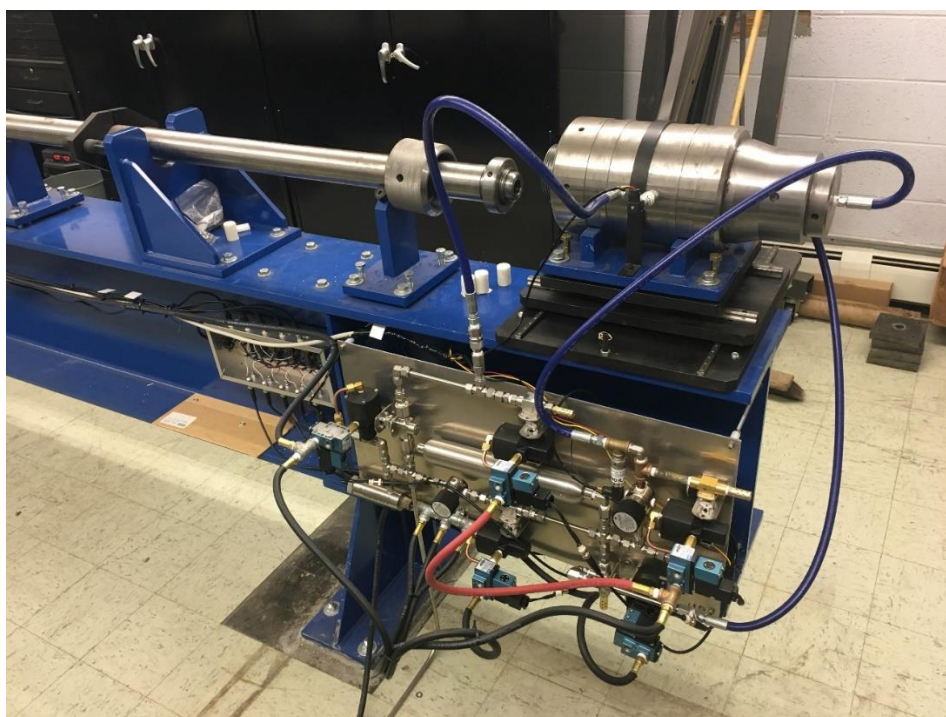


Figure 5. Gas Gun Breech and Pressure Control Scheme

Figure 6 shows the first half of the impact chamber within the light gas gun. On the left side of Figure 6 you can see the barrel that leads to the breech. There are several port windows shown which will be discussed in more detail in the next section. Contained within this half of the chamber, for this experiment, are a triple laser velocimeter, a sabot stripping plate, a trigger wire mount (for camera flash and record) and a target mounting plate. Some of these components will be detailed later.

The impact chamber is designed to pull a vacuum, but for purposes of this experiment no vacuum conditions were required.

Figure 7 shows the second half of the impact chamber. This acts as the stopping system to catch all projectiles and fragmentation from the post impact event. The catch tank contains 20, 0.25" thickness mild steel plates hanging from an I-beam with a separation of 1" between plates.

Figures 8 and 9 show the air compressor and air storage tank that fuel the light gas gun. The compressor fills the tank to a total of 6500 psi (44.8 MPa). The valve shown on top of the tank can be let open to allow air flow from the tank into the gas gun breech via the presser control valves as shown in Figure 5.



Figure 6. Impact Chamber (Front Half)



Figure 7. Impact Chamber Catch Tank (Back Half)



Figure 8. Primary Air Compressor



Figure 9. Compressed Air Tank

2. Test Methodology

Specific to this set of experiments, several components were added to the light gas gun. This section will present figures and additional descriptions to the testing process.

All images were captured using a Shimadzu HPV-X2 as shown in Figure 10. The camera position is perpendicular to the impact trajectory. The aforementioned viewing ports on the impact chamber are used to supply both a high-powered light system and enable the high-speed video camera to view and record all impact events. The camera is triggered using a Whittner model 1000 trigger box (not shown) and interfaced to a desktop computer using HPV proprietary software used to control the Shimadzu HPV-X2 operation.

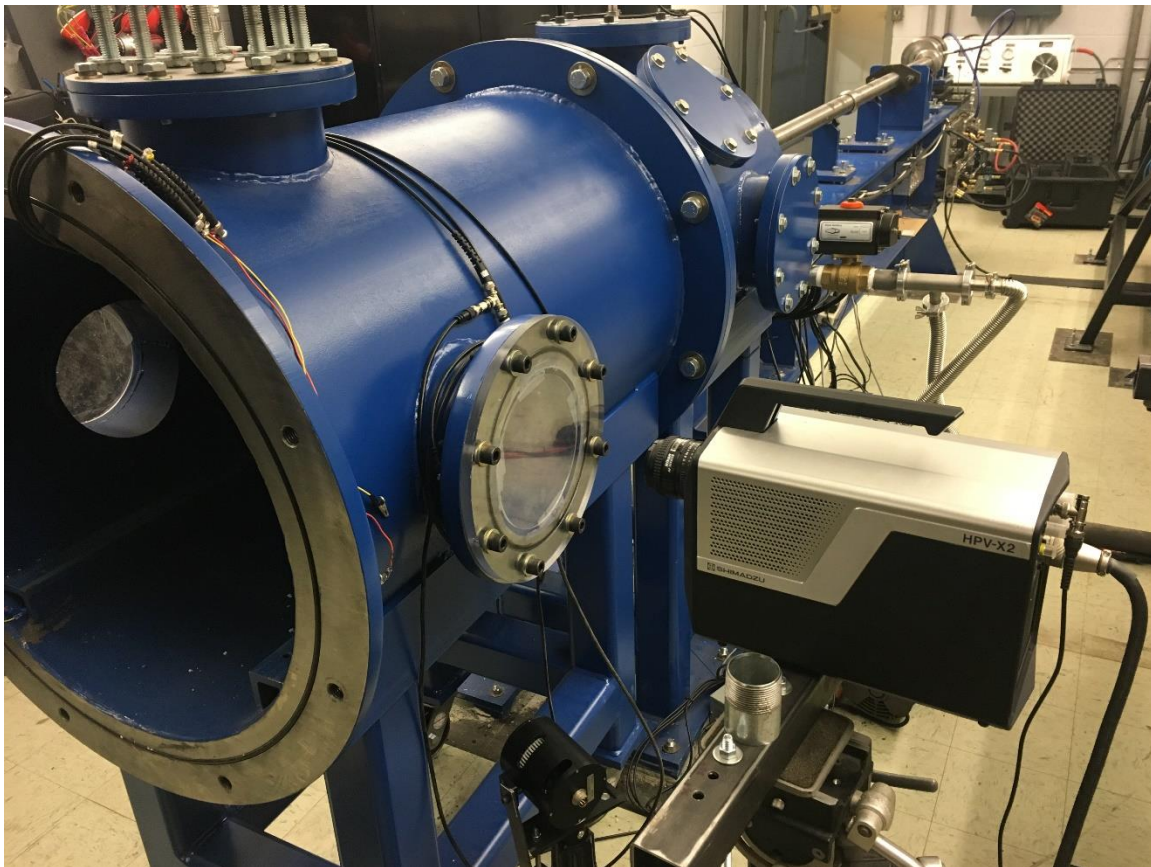


Figure 10. Camera Orientation for Impact Analysis

Figure 11 presents a view from the back side of the middle section of the impact chamber. The large circular plate is the sabot stripper plate which helps provide full separation of the four sabot pieces from the projectile during flight. The velocimeter (not shown) is located directly after the muzzle of the barrel. It consists of 3 solid state lasers that are collected by three opposite fiber optic cables. The three lasers/fiber optic cables are separated by 3/4" along the flight path. As the projectile travels out of the barrel, its velocity is measured using both the known separation distance between each laser/fiber optic system and measured time for the projectile to travel between each laser channel. This information is fed into the LabVIEW software where the muzzle velocity is computed.



Figure 11. Sabot Stripper Plate and Wire Camera Trigger Mount

As shown in the foreground of Figure 11, a thin wire is stretched and secured taut on a trigger wire mount. The two ends of the wire leads are connected to the two input

leads inputted to the trigger control box. The trigger control box will generate a 10V square pulse when the projectile breaks the trigger wire. The camera is triggered once the wire is broken. Delay times can be set based on the separation distance between the trigger wire and target.

Figure 12 shows the target mounts used in the experiment. Ceramics of various chemistry, geometry and size were adhered onto the 3D printed mounts. The 3D printed mounts were fastened to the circular mount plate as shown in Figure 13. Figure 13 also shows the 3D printed mount with a 3/8 inch (0.9525 cm) sapphire sphere adhered onto the end of the mount which is then affixed by small screws to the emplacement plate.

Figure 14 shows the complete impact set-up as seen from the opposite viewport of the Shimadzu camera. On the left is the wire camera trigger mount. Centered in the figure is the viewing port with the camera positioned perpendicular to the flight path of the projectile (high-powered lights not shown). Finally, on the right is the target mount plate with the target and 3D mount in their final position. With these conditions properly aligned, the catch tank can be bolted to the center tank section. At this point the tank system is ready for the ballistic impact experiment.

Figures 15 and 16 show both the firing system and data acquisition equipment to control and measure events within each ballistic test. The top of Figure 16 shows the firing trigger (white button) and associated safety cable. Both figures show the computer monitor displaying the Graphical User Interface (GUI) that allows the operator to control the gun system operation. Figure 15 also shows the data acquisition cards and associated hardware to safely and accurately control and monitor the full functionality of the gas gun.

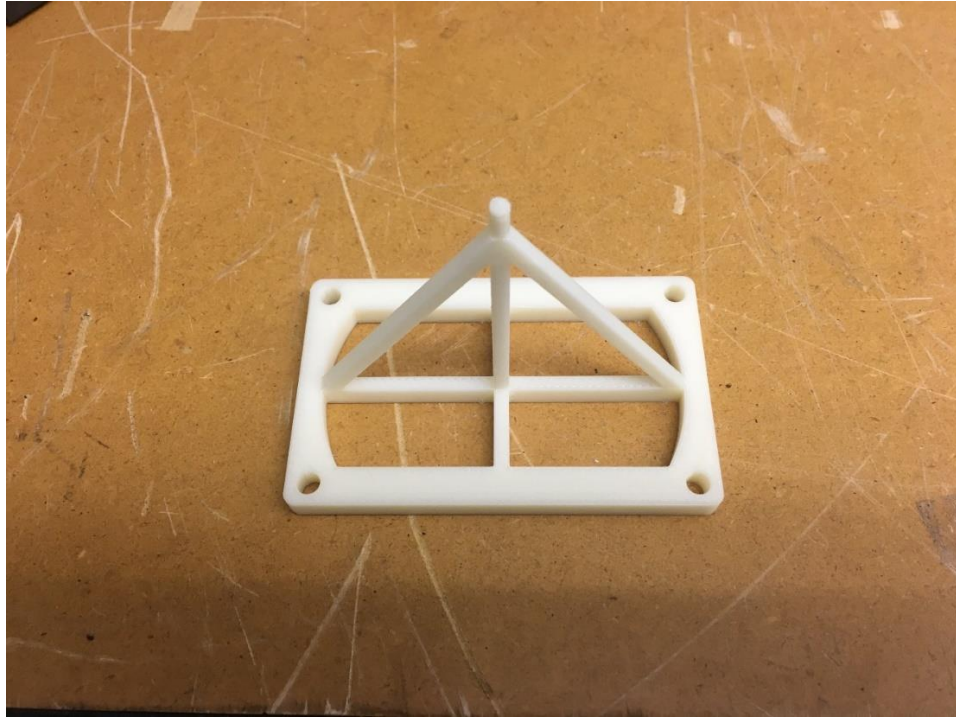


Figure 12. Target Mount



Figure 13. Target Emplacement Plate



Figure 14. Experimental View Opposite Camera

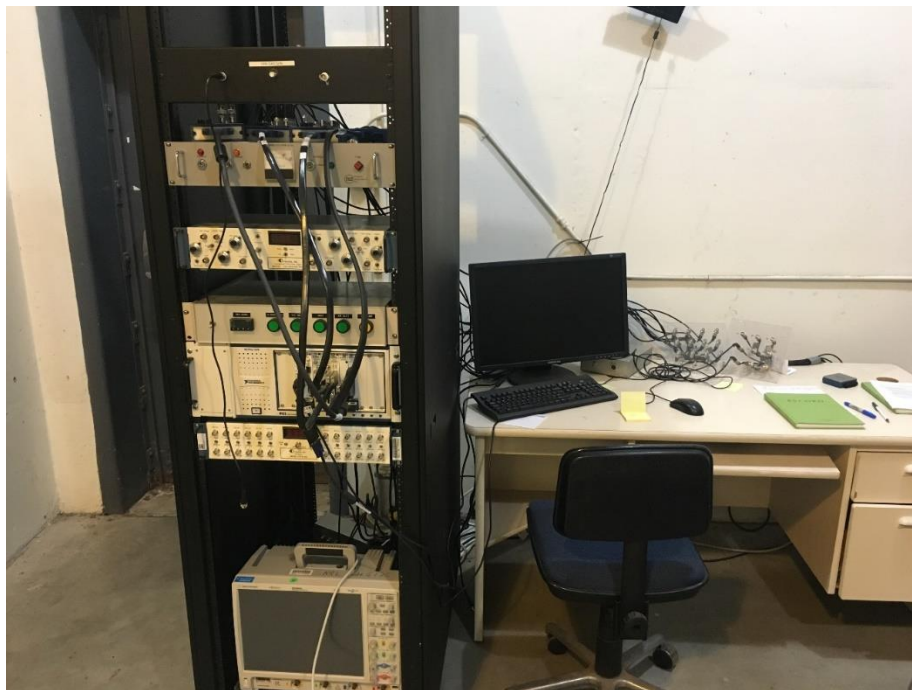


Figure 15. Testing Control Station



Figure 16. Testing Control Computer

3. TEMA

The Shimadzu HPV-X2 is capable of taking images in 100 ns increments which is equivalent to 10 million frames per second. Many of the experiments were recorded at this frame rate, but the Shimadzu software does not incorporate measurement of dynamic variables including particle velocity and material expansion. Figure 17 displays an example frame of an impact of a 3/8" steel sphere with a 3/8" AD995 alumina sphere.

A video of 256 images (Figure 17) is collected for each impact event. The videos can then be formatted to a TIFF file and loaded into TEMA. TEMA allows users to set tracking points on the image and uses pixel color association to follow a given point throughout the duration of an uploaded video. Using this program experimental data was collected tracking deceleration of the back of the projectile as well as lateral expansion of the target perpendicular to the plane of impact.



Figure 17. Example Image from Shimadzu Camera during Test Displaying a 3/8” Steel Sphere Approaching a 3/8” AD995 Alumina Sphere

Each test video is individually analyzed with the TEMA software and both position and velocity are collected as a function of time. The data collected through TEMA will be presented and discussed within Chapters IV and V.

B. CTH SIMULATION

Sandia National Laboratory (SNL) developed a program for simulation of terminal ballistics and explosives known as CTH. It is a hydro code that allows a user to test a wide array of materials under specified conditions to test performance. For this thesis, a combination of tabulated analytical equation of state (ANEOS) data and the Johnson-Holmquist 2 (JH-2) model for brittle (i.e., ceramic) materials were used for these simulations [4]. The various material properties that CTH draws from are contained in a standardized digital library maintained by SNL. Simulation for single crystalline, ~99.9% pure Al_2O_3 , also known as sapphire, required ANEOS input parameters for modelling. AD90 and AD995, respectively ~90% pure and ~99.5% pure Al_2O_3 . This section will detail the basic program set-up and an overview of the theoretical equations contained in the JH-2 model.

1. Diatom Set-up

Cylindrical symmetry was imposed within a 2D geometric design that was input into CTH. Within the modeling, the target is initially at rest with the projectile given an initial velocity similar to that of the experimental tests. The input configuration is known as the diatom input. The geometry and positioning of the studied materials can be adjusted to match the configurations of the experimental testing enabling a simulation to physical experiment comparison.

The circles on Figure 18 would be treated as spheres during the modeling due to the cylindrical symmetry programmed into CTH. The lower circle (sphere) is set with an initial velocity of 670.56 m/s in the y-direction and is composed of 4340 Alloy Steel to simulate the projectile. Unfortunately, the CTH database does not include chrome steel and 4340 Alloy Steel was considered the closest match for modeling purposes. The upper circle is stationary to simulate the target ceramic and is composed of either sapphire, AD90 or AD995 depending on the test. The dark line behind the upper circle simulates the mount and is made of plexiglass.

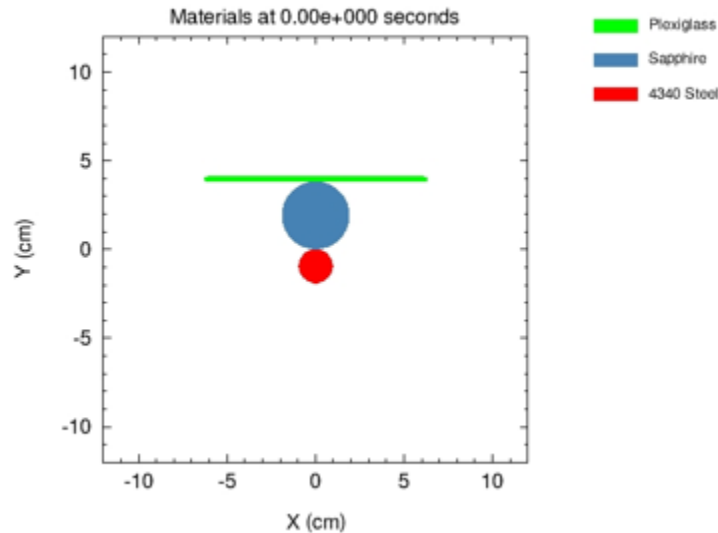


Figure 18. Initial Diatom Figure (CTH)

Testing for RCC targets required a simple diatom geometry change for the target from a 2D circle to a box. The cylindrical symmetry then allowed it to be computed through CTH as a cylinder.

2. Models

As previously discussed, no theoretical model for sapphire exists in the CTH database outside of tabulated ANEOS values. For purposes of this section it will not be discussed further and a full description of the JH-2 model will be presented. The JH-2 model was proposed by Johnson and Holmquist in 1994, [25] and is considered one of the best models for simulating brittle materials such as ceramics in terminal ballistic scenarios. Figure 19 shows a general overview of the model based on several assumptions and parameters defined by the authors.

The material begins to soften when the damage begins to accumulate ($D > 0$). This allows for gradual softening of the material under increasing plastic strain. The strength and pressure are normalized by the strength and pressure components of the Hugoniot Elastic Limit (HEL), which allows for many of the constants to be dimensionless. This can be very helpful when comparing different materials, and when estimating constants for materials which have an insufficient data base to determine constants. The strength and damage are analytic functions of the pressure and other variables. This allows for parametric variation of the constants in a more systematic manner. The strength generally is a smoothly varying function of the intact strength, fracture strength, strain rate, and damage. [25]

As shown in Figure 19, there are several main equations that CTH incorporates into its modeling. First, normalized equivalent stresses are proposed in the general form,

$$\sigma^* = \frac{\sigma}{\sigma_{HEL}}. \quad (1)$$

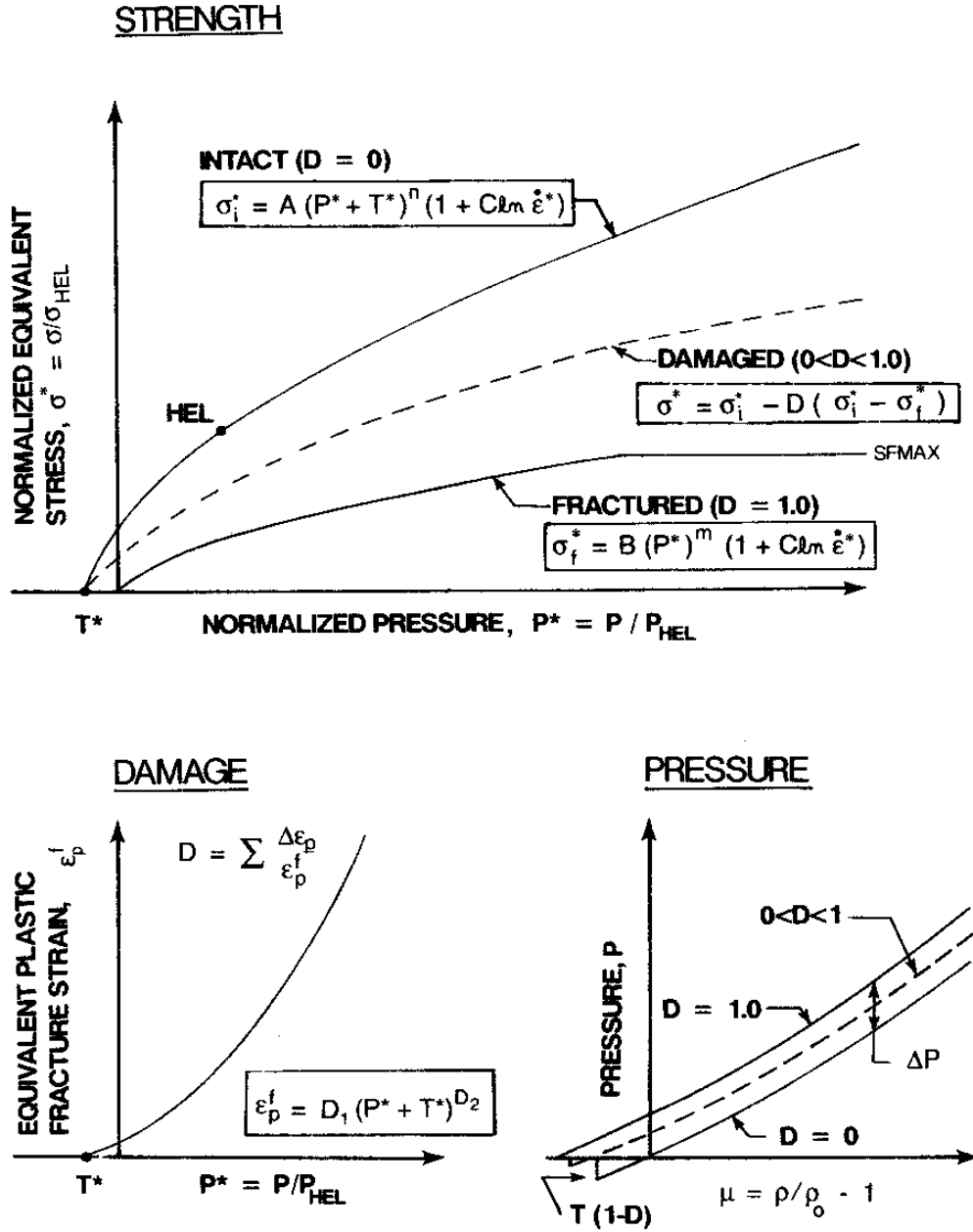


Figure 19. A General Overview of the JH-2 Model. Source: [25]

Next, the normalized intact strength and normalized fracture strength are given by

$$\sigma_i^* = A (P^* + T^*)^N (1 + C \cdot \ln(\dot{\epsilon}^*)), \quad (2)$$

and

$$\sigma_f^* = B(P^*)^M (1 + C \cdot \ln(\dot{\epsilon}^*)), \quad (3)$$

respectively. A, B, C, M, N are all material constants. P^* and T^* are normalized by dividing by P, and T by P_{HEL} , respectively. The dimensionless strain rate is $\dot{\epsilon}^* = \dot{\epsilon} / \dot{\epsilon}_0$, where $\dot{\epsilon}_0$ is a reference strain rate 1.0 s^{-1} . Moreover, damage for fracture is expressed as

$$\epsilon_f^p = D_1 (P^* + T^*)^{D_2}, \quad (4)$$

and pressure is expressed as a function of density,

$$\mu = \frac{\rho}{\rho_0} - 1, \quad (5)$$

where ρ_0 is initial material density. Here, D_1 and D_2 are material constants and μ is a variable of convenience. With the inclusion of the material's elastic moduli, the final main equation can be derived and is presented here in its final form,

$$\text{HEL} = K1 \cdot \mu_{\text{HEL}} + K2 \cdot \mu_{\text{HEL}}^2 + K3 \cdot \mu_{\text{HEL}}^3 + \frac{4}{3} G \left(\frac{\mu_{\text{HEL}}}{1 + \mu_{\text{HEL}}} \right), \quad (6)$$

where K1 is the bulk modulus and G is the shear modulus. The full JH-2 model equations and derivations can be found in their paper, but equations (1) through (6) are sufficient for the purposes of this thesis.

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IV. DATA

As detailed in Chapter III, we conducted both numerical simulations and physical experiments. Collected data was processed via TEMA, HPV-X2, Origin 6.1, LabVIEW and MATLAB. Curves were fitted to raw data via Lorentzian peak-fitting and are expressed in Figures 20 and 22 through 26.

A. HALF-INCH SPHERE COMPARISON

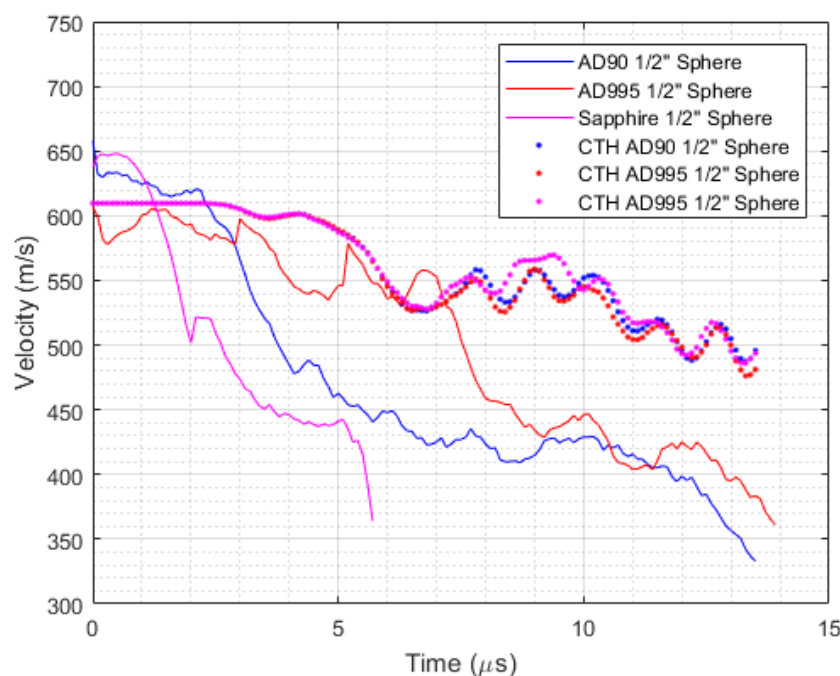


Figure 20. Deceleration of Projectile after Impact (1/2'' Ceramic Targets)

The average mass of the 3/8'' steel projectile was 3.52 ± 0.02 g. This value was multiplied by the changes in velocity as presented in Figures 20 and 24 with the resulting calculated forces over time presented in Figures 22 and 25. Values for force were further solved for work via measured incremental changes in distance and are presented in Figures 23 and 26. Figure 21 illustrates the impact obliquity of the projectile on the 1/2'' targets.

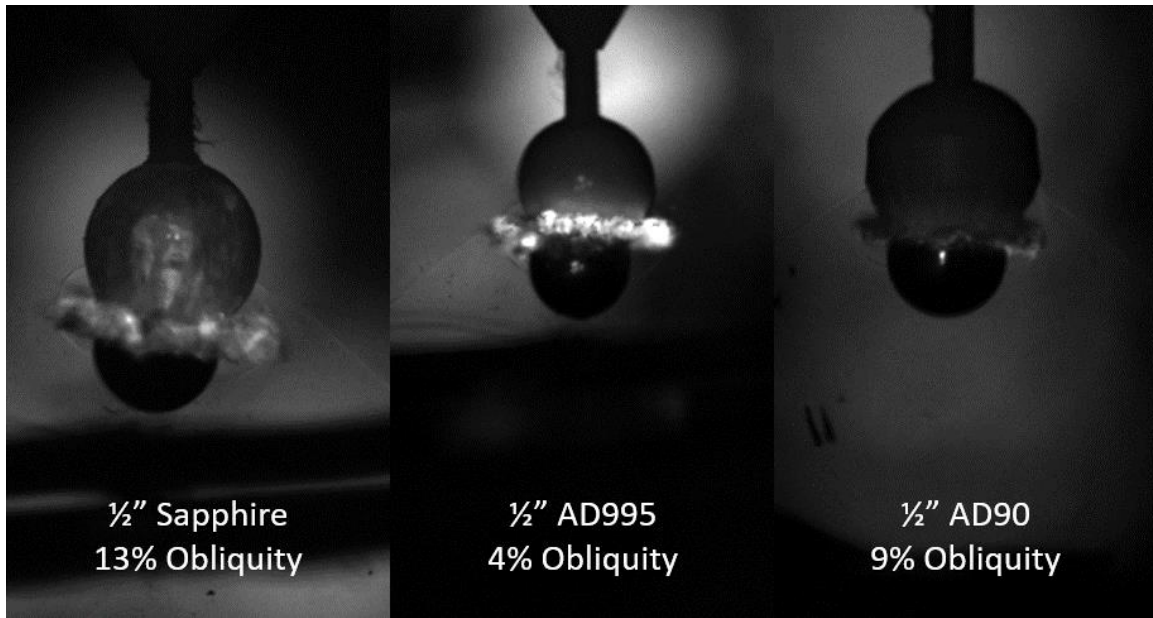


Figure 21. Image Capture after 5.5 μ s on 1/2" Targets

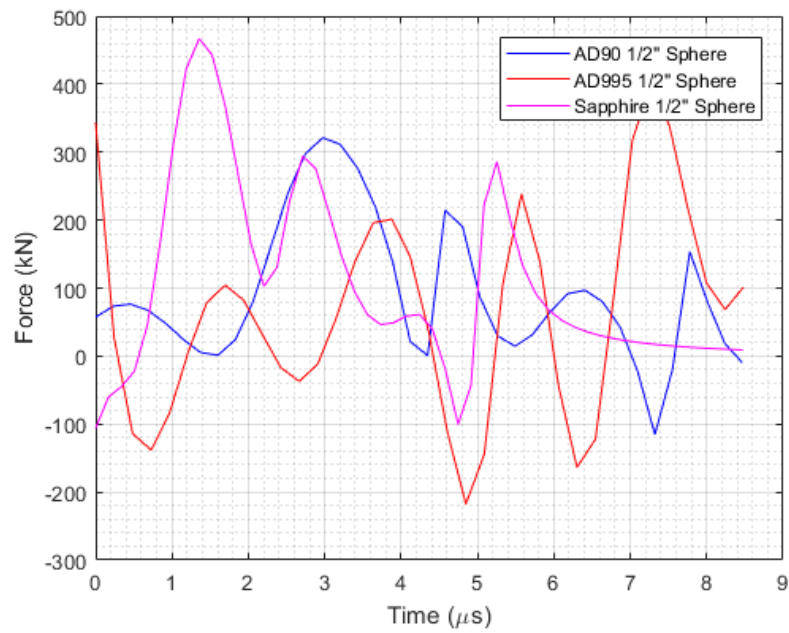


Figure 22. Force Required to Decelerate Projectile (1/2" Ceramic Targets)

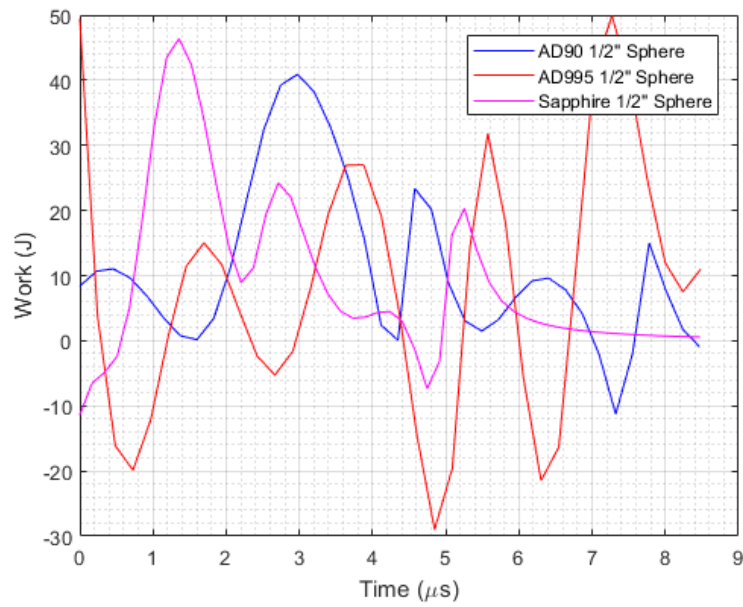


Figure 23. Work Required to Decelerate Projectile (1/2'' Ceramic Targets)

B. AD90 SIZE AND GEOMETRY COMPARISON

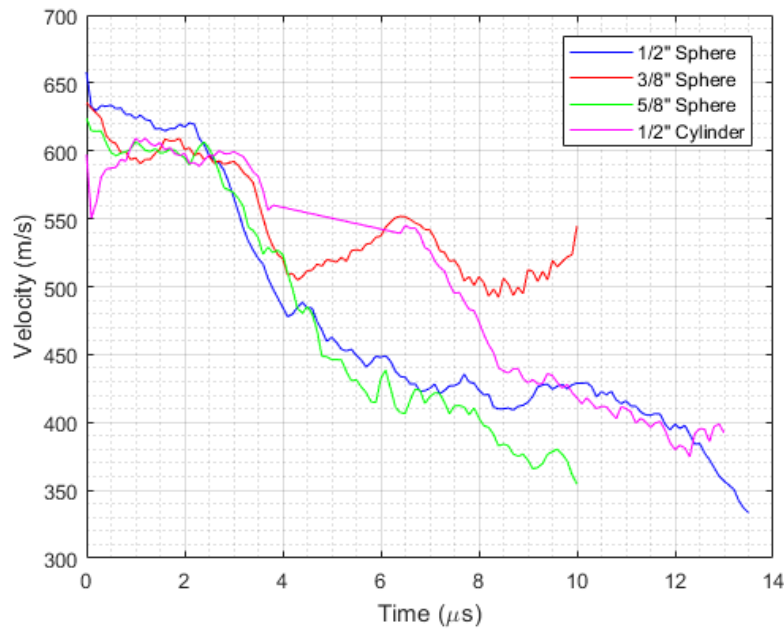


Figure 24. Deceleration of Projectile after Impact (AD90 Ceramic Targets)

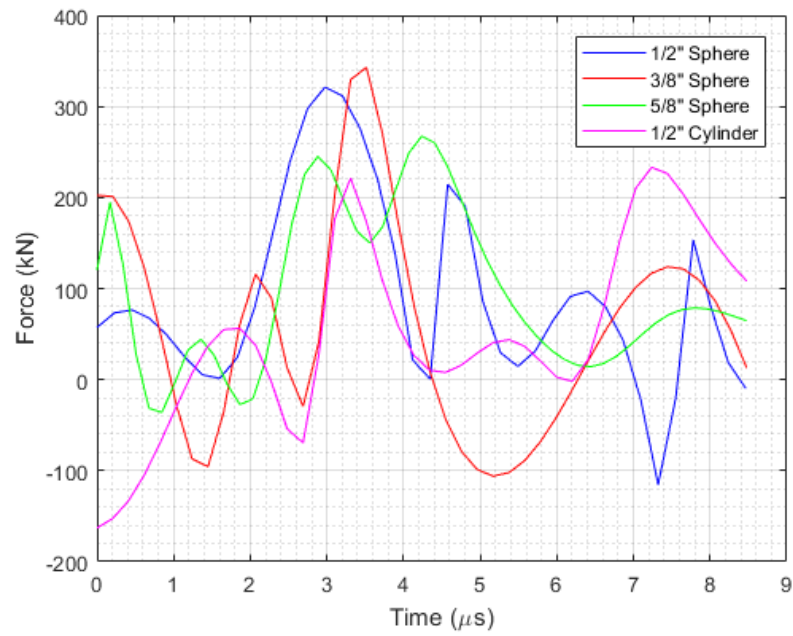


Figure 25. Force Required to Decelerate Projectile (AD90 Ceramic Targets)

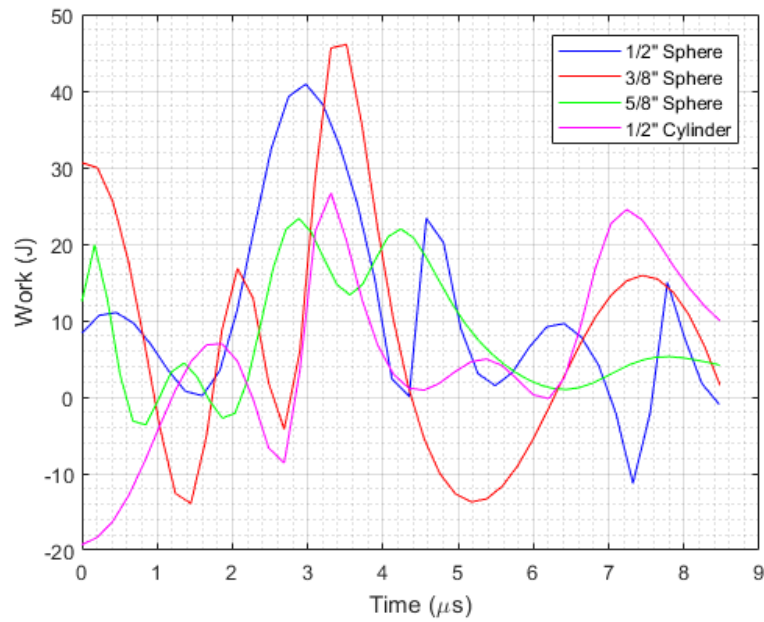


Figure 26. Work Required to Decelerate Projectile (AD90 Ceramic Targets)

Table 1 presents net integrated area under the work curve that was calculated as described. The values presented are the net total work found for this time span by taking total positive work and subtracting the negative.

Table 1. Work (J) by Target on Projectile for Initial 8.5 μ s

Target	Work (J)
1/2" Sapphire Sphere	459
1/2" AD995 Sphere	301
3/8" AD90 Sphere ^a	344.5
1/2" AD90 Sphere ^a	420
5/8" AD90 Sphere ^a	413.4
1/2" AD90 Cylinder	261
1/2" AD90 Cylinder (Off-axis) ^b	212

^aAD90 Spherical Targets contained a small geometrical variation from perfect spheres in the form of a small flat band

^bImpact took place at $\sim 45\%$ obliquity

C. SHOCKWAVE COMPARISON

Images from the impacts of the steel projectile on 1/2" and 3/4" sapphire are presented alongside matching time interval images from the simulation as Figures 27 and 28.

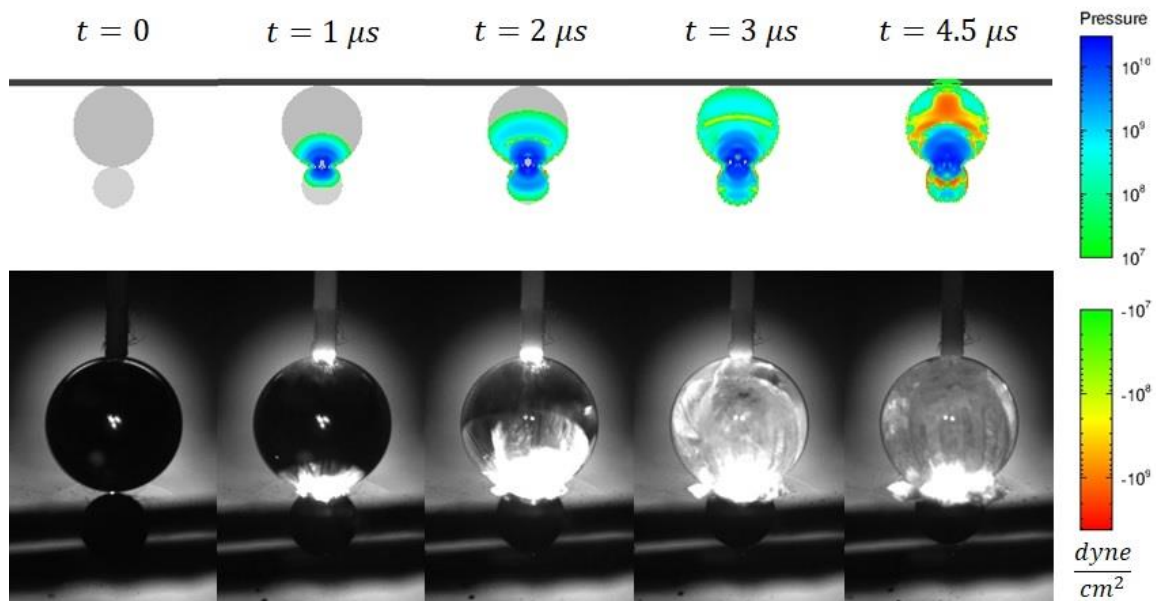


Figure 27. Simulation vs. Experimental Shockwave Comparison of 3/4" Sapphire

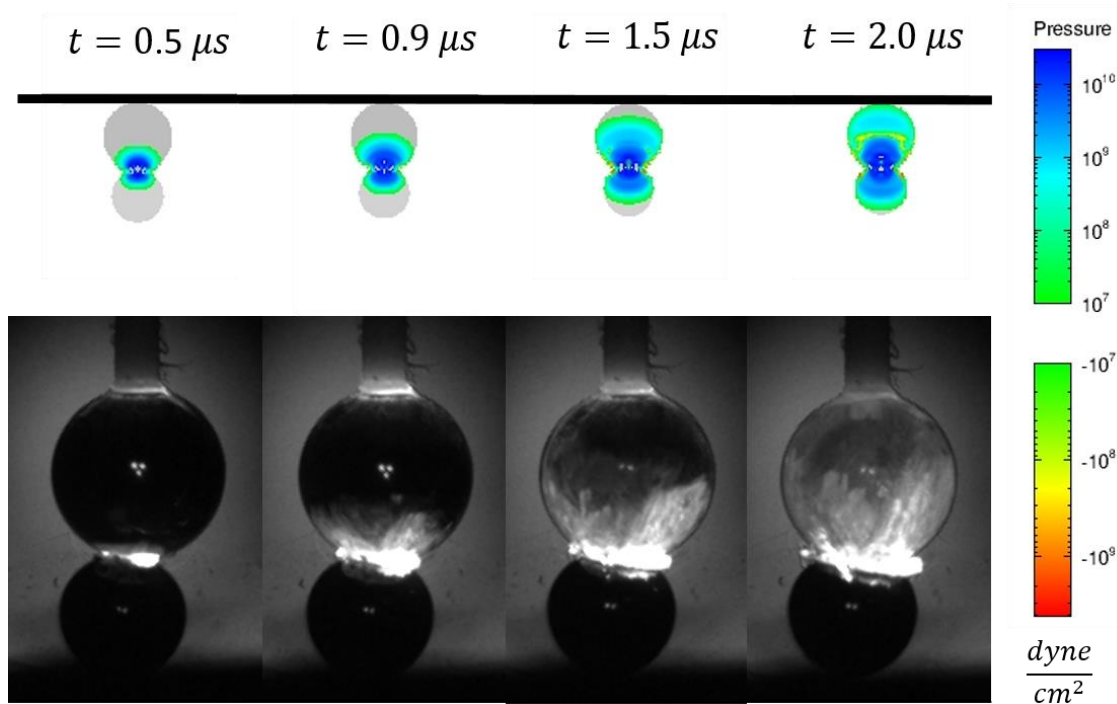


Figure 28. Simulation vs. Experimental Shockwave Comparison of 1/2'' Sapphire

D. TARGET EXPANSION

Times of lateral expansion perpendicular to the direction of impact is presented in Table 2.

Table 2. Elapsed Time from Impact to 5% Lateral Expansion

Target	Experimental Data (μ s)	CTH Data (μ s)
3/8'' Sapphire Sphere	5.8	9.52
1/2'' Sapphire Sphere	6.1	16.4
3/4'' Sapphire Sphere	16	48.7
3/8'' AD995 Sphere	3.9	9.11
1/2'' AD995 Sphere	6	15.4
3/4'' AD995 Sphere	15.8	82.5
3/8'' AD90 Sphere ^a	4.4	8.91
1/2'' AD90 Sphere ^a	6.7	15.8
5/8'' AD90 Sphere ^a	8.9	25.9
1/2'' AD90 Cylinder	6.5	10.4
1/2'' AD90 Cylinder (Off-axis) ^b	7.5	-

^aAD90 Spherical Targets contained a small geometrical variation from perfect spheres in the form of a small flat band.

^bImpact took place at ~45% obliquity. Not modelled in CTH

V. DATA ANALYSIS

A. SIMULATION VS. EXPERIMENT

There is good agreement between experiment and simulation in the shockwave velocity as shown in Figures 27 and 28. The transparency of the sapphire targets offers some additional clues about the mechanics that occur inside the sphere after impact. These images are not completely conclusive evidence due to complex light behavior through the sapphire's crystalline structure. However, the measured speed of the apparent propagating wave through the sapphire in Figures 27 and 28 is approximately $\sim 11,000$ m/s which is consistent with published literature [26]. Wave speeds were also observed in the 3/8" sapphire sphere, but no figure is presented here. For all three sized spheres, the CTH simulation agreed very closely with experimental observations.

Conversely, Figures 20 and 22 through 26 immediately indicate that there is a disparity between the experimental and simulation results. CTH yields a slower, smoother deceleration of the incident steel sphere projectile over time and a longer time to 5% lateral expansion. This could be a consequence of the differences between 4340 steel that CTH has in its library and the chrome steel that was used in the experiments. Another explanation is that we used best estimate values for some of the JH-2 variables due to their absence from the CTH library and from published literature. Additionally, the JH-2 may be better suited for traditional, monolithic plate or tile analysis rather than smaller spherical or cylindrical analysis.

Both experiment and simulation show an expected pattern of deceleration/acceleration peaks after impact due to the reflected shock waves altering the particle velocity of the incident projectile. As compression and relief waves propagate repeatedly through the projectile, the deceleration, taken as a change in velocity from a point particle at the rear of the projectile as oriented toward the impact, would be expected to be non-linear. The variations in deceleration due to the shock wave reflections can be seen in Figures 20 and 24.

The CTH simulation also indicated a longer period between impact and the onset of projectile deceleration. Again, this could be a result of differences in the sound speed of 4340 Steel and the chrome steel used in the experiment; but for purposes of this study, the general rate of deceleration after onset appears to be significantly faster in the experiments than in the simulation.

B. CHEMICAL COMPARISON

Figures 20 through 24 illustrate the differences in performance of 1/2" spheres between AD90, AD995 and sapphire. Unfortunately, the results do not allow for a perfect comparison. Variations included video recording speed 5 million frames per second vs 10 million frames per second, impact delay timing and impact obliquity. However, some interesting trends were still observable between the sapphire and the two aluminas (AD90 and AD995).

Between 3 and 9 μs there is a significant increase in deceleration with the AD90 compared to the AD995. Table 2 presents the time to 5% lateral expansion for AD90 at 6.7 μs while AD995 is only 6 μs . One explanation could lie in the wave speeds of either medium. AD90 has a measured wave speed of ~ 9000 m/s and that of AD995's is $\sim 10,700$ m/s. The material can only react to ballistic impacts as fast as the shock wave travels through the ceramic. As the AD90 has a slower wave speed enabling the period that the ceramic remains intact could allow for the material to resist penetration for a longer period of time compared to AD995 and Sapphire. This notion is also supported by the similarities in the 5% expansion times for AD995 and Sapphire which are presented as 6 and 6.1 μs respectively. This is also true for the expansion times for the 3/4" sphere tests, which list times at 15.8 and 16 μs , respectively. No 3/4" AD90 spheres were available for testing. The time to reach 5% expansion for the 1/2" AD90 is 6.7 μs . If we take a ratio of the wave speeds comparing AD995 to AD 90 and comparing the time difference between the 5% expansion, only a 5% difference is observed. This supports the wave speed can be correlated to the time period required for the sphere to expand 5%. A similar difference is observed for the time of expansion between the 3/8" AD995 and AD90.

As presented in Table 1, there is a ~40% increase in work done by AD90 on the projectile during the initial 8.5 μ s over that of AD995. This is true despite the lower percentage of obliquity for the AD995 impact versus the AD90 impact. Again, this could be explained by the differences in wave speed. Both are polycrystalline structures so they are a better pair for comparison than single-crystal sapphire. As expected, the sapphire outperforms both polycrystalline materials by doing 459 J of work on the projectile, but it is impractical as a candidate for armor due to high cost.

C. SIZE AND GEOMETRIES COMPARISON

Figures 24, 25, and 26 present data for only AD90 targets. The deceleration shown in Figure 24 indicate that there is a significant increase in performance for spheres between 3 and 9 μ s over cylinders. The small, smooth portion of the 1/2" cylinder data is due to a small obscuration in the camera view from 3 to 7 μ s, but the over-all trend is visible when compared to the 1/2" sphere. The cylinder target also reaches 5% expansion sooner than the sphere, albeit by a smaller margin with a difference in time of only 0.2 μ s. The cylinder only does 261 J of work on the projectile compared to the work on the sphere of 420 J. This could be explained by the boundary conditions that the cylinder introduces over the sphere. The perpendicular orientations of the cylinder's edges maximize the potential for localized damage as shock waves propagate through the medium.

The results also suggest early failure by the 3/8" spheres that suggests that they are below a mass relative to the projectile necessary for strong armor performance; however, more research and testing is required to confirm this. Interestingly, there are similarities in the deceleration profiles for the 1/2" and 5/8" spheres shown in Figure 24. Both the total amount of projectile deceleration and the deceleration rates are very close and suggest that there is only marginal performance increase with larger size ceramic spheres once a certain critical threshold has been met. It would appear as though the 3/8" spheres fall below that threshold, but that 1/2" meet or exceed it. This is only relative for the 3/8" chrome steel projectile here, but it is worth additional testing across a range of projectile types to verify or deny. This could allow armor designers to reduce weights to meet minimum required safety levels easier.

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VI. CONCLUSIONS

In this study we investigated the performance of ceramic spheres as a front face armor system against ballistic threats. We presented data for shock wave velocity, deceleration, force and work done by targets to decelerate incident projectiles as well as target lateral expansion rates (up to 5% expansion).

Within the observed shockwave propagation through the sapphire spheres, observed wave speeds were consistent with published data and with CTH simulation. This was expected due to the well-established EOS for sapphire within the CTH library. Wave speeds were observed to be consistent across all sized sapphire spheres. The transparency of sapphire allowed us to observe some inner mechanics of not only wave propagation, but also crack propagation.

Calculation of the work by the target applied to the incident projectile is measured in terms of deceleration of the projectile and equated to force and displacement. In comparison of the different ceramic chemistries, results indicate that AD90, though a lower compression strength as compared to AD995, performed better under ballistic impact conditions. Within the geometry studies, the spheres performed better than cylinders. As expected, we observed lower performance when the cylinder was impacted “off-axis” or at ~45% obliquity. Lastly, in comparison of the different sphere diameters for AD90, the larger diameter sphere applied more work. This offers some insight to design requirements for future incorporation into a functioning body armor system. There appears to be agreement between the experimental data and the simulation in some variable aspects, but not all.

For future testing, the following revised testing is suggested:

1. lengthening the impacting projectile
2. properly orienting the camera to maximize un-obstructed viewing angles would allow for longer ranges of time for presentation and comparison

Furthermore, more candidate geometries exist for comparison. Future studies may include comparisons between cubic and/or other strong geometric candidates with special attention paid to their boundary conditions. Moreover, alumina is not limited to AD90 and AD995. More purity levels with differing material properties exist and should be studied. Other chemical compounds such as Silicon Carbide or Boron Carbide could be considered as well for complete comparison.

With regards to CTH, future studies may want to investigate more than the JH-2 model and should attempt to match all physical experiment materials to those that exist in the CTH library. Also, additional consideration and simulation specifically attempting to better understand damage mechanics and propagation would greatly improve over-all understanding of candidate ceramic performance.

APPENDIX. CTH INPUTS

Parameter	AD995	AD90
K1	2.31E12	1.62E12
K2	-1.6E12	-1.41E12
K3	27.74E12	10.47E12
ρ_0	3.89	3.625
G	1.52E12	1.13E12
P_{HEL}	0.657E11	0.57E11
T	-2.62E9	-2.21E9
A	0.88	0.93
B	0.28	0.28
C	0.007	0.007
M	0.06	0.6
N	0.64	0.64
D1	.001	.001
D2	0.7	0.5
v	0.25	0.228

Note: Values listed are in CTH standard units: cm, dyne/cm², etc.

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