ARMY RESEARCH LABORATORY

The Current Capabilities on Dynamic Impact Testing

By Jian H. Yu, Peter G. Dehmer, and James M. Sands

ARL-TR-4496 **July 2008**

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14. ABSTRACT
This report describes the equipment and the operating procedure for the dynamic impact tester. It is used to evaluate armor materials and systems, such as composites, ceramics, transparent armors, and helmets. The dynamic impact system is capable of launching a projectile at speeds ranging from 50 to 1000 m/s at a target and capturing the history of impact events, such as the speed of projectile, the strain and strain rate on the target during the impact, and the spall pattern.

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1. Introduction

This report documents the current dynamic impact testing equipment capabilities and operating procedures for the evaluation of armor materials and systems, including composites, ceramics, transparent armors, and helmets. The dynamic impact testing equipment at the U.S. Army Research Laboratory (ARL) has the state-of-the-art testing equipment and high-speed image capturing capability. The impact phenomenon and history on the target material and the impactor can be captured and analyzed. The data collected serves not only as an evaluation tool for the ballistic performance of materials, but also aids in the development of new armor designs.

2. Equipment

2.1 Fragment-Simulating Projectile (FSP) Launching Apparatus

The design of the launching apparatus is based on a similar device developed by Joseph Rogers[1]. It consists of a smooth bore barrel, a high pressure gas reservoir, and a solenoid valve that can rapidly release the compressed gas from the reservoir to barrel. There are different barrels available for launching 0.22 and 0.15 caliber (CAL) fragment simulating projectiles (FSPs). The barrels can be fitted with a sabot stripper for launching sub-caliber projectiles, as small as a 2 grains (0.130 g) projectile in a sabot carrier.

2.1.1 Assembly for the 0.22 CAL Barrel

Figure 1 shows an exploded view of the 0.22 CAL launching assembly. Detailed computer-aided design (CAD) drawings are provided in the appendix of this report. The 0.22 CAL barrel consists of three stainless steel barrel sections that are coupled together by brass couplings. The total length of the barrel is 224.79 cm (88.5 in.). The barrel is securely fastened on a supporting rail with brackets. An optional sabot stripper can be attached at muzzle end of the barrel for projectiles that require a sabot for launching.

[1] Rogers, J. M. *Development of a High-Pressure Medium Velocity Helium Gun for Firing 17-Grain Fragment Simulator*. Army Materials and Mechanics Research Center, Watertown, Massachusetts, AMMRC TR 72-11., March 1972

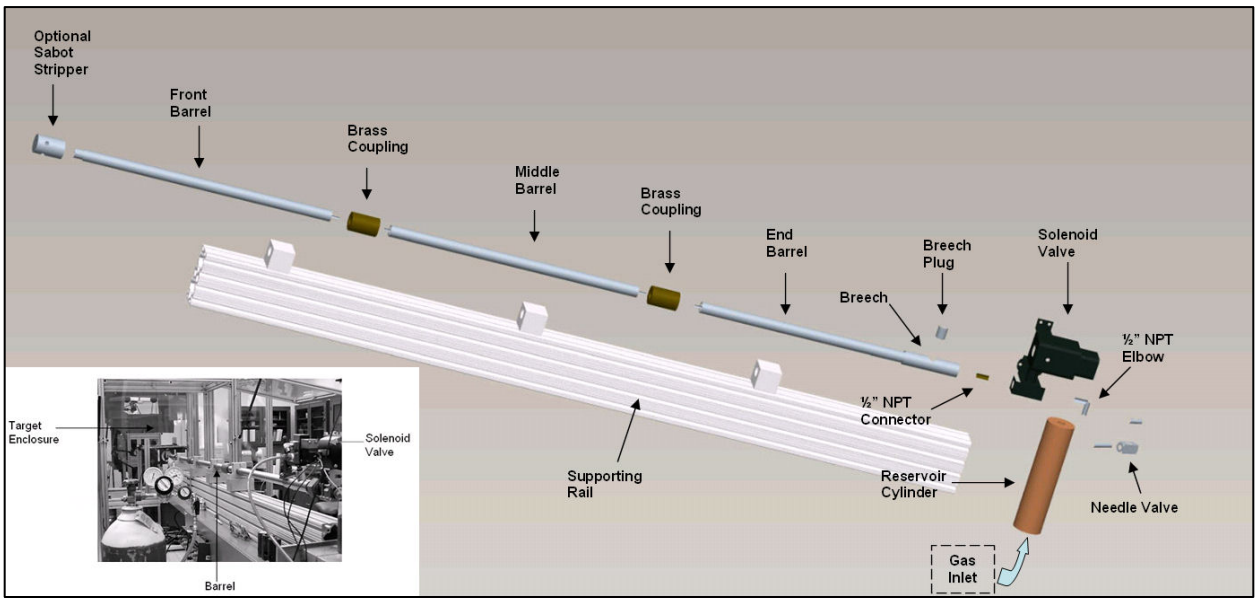

Figure 1. An exploded view of the 0.22 CAL barrel. The insert is the assembled barrel and the target enclosure.

A normally closed ball valve is connected to the breech end of the barrel by a 1/2 in. National Pipe Thread Taper (NPT) fitting. The ball valve has a pneumatically driven pilot valve that actuates the ball valve and rapidly releases the compressed gas from the reservoir into the barrel. The pilot valve is activated by a momentary switch. The gas reservoir is a steel cylindrical vessel with a volume capacity of 0.332 $(cm)^3$. A needle valve is connected to the side of the gas reservoir to relieve excess pressure, and serves to dial in the pressure for launching the FSP at the desired speed. Flexible 1/2 in. braided stainless steel hoses are used to deliver gas from the main gas tank to the reservoir gas inlet. Figure 2 illustrates the gas line connections between the main gas tank and the reservoir.

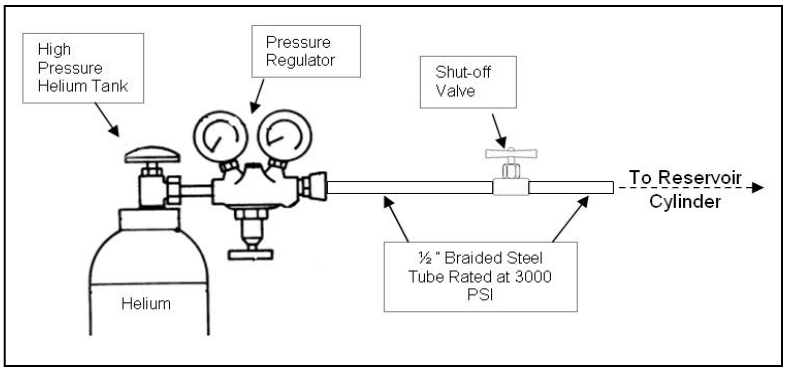

Figure 2. The supply line from the main gas tank to the reservoir.

The breech of the barrel is located 7.62 cm (3 in.) in front of the ball valve. A steel cylindrical plug is used to close the breech. A Teflon® (registered trademark of DuPont Company) gasket is placed between the plug and the breech to prevent gas leakage, and a C-clamp is used to hold the plug in place during pressurization and launch.

A large transparent enclosure surrounds the targeting area to contain debris during impact. The enclosure frame is constructed of 80/20® (registered trademark of 80/20, Inc.) aluminum modular components. The walls of the enclosure are 0.95 cm (3/8 in.) polycarbonate panels. The enclosure is divided into three sections. The forward chamber houses the timing and lighting equipment; the middle chamber houses the target stand; and the aft chamber servers as a catch box for spall and projectiles. Doors are positioned on the chambers to allow for access inside the enclosure.

2.1.2 Assembly for the 0.15 CAL Barrel

The 0.15 CAL barrel uses the same enclosure and gas reservoir as the 0.22 CAL barrel. Figure 3 shows the exploded view of the 0.15 CAL barrel. The 0.15 CAL barrel assembly differs from the 0.22 CAL barrel; it has two barrel sections instead of three and it uses a quick-disconnect 3/8 in. NPT adaptor at the breech end of the barrel for ease loading. To load the projectile, the barrel is first separated from the ball valve at the quick-disconnect, then the projectile is inserted into the barrel. After the projectile is inserted, the barrel is reconnected to the solenoid ball-valve at the quick-disconnect.

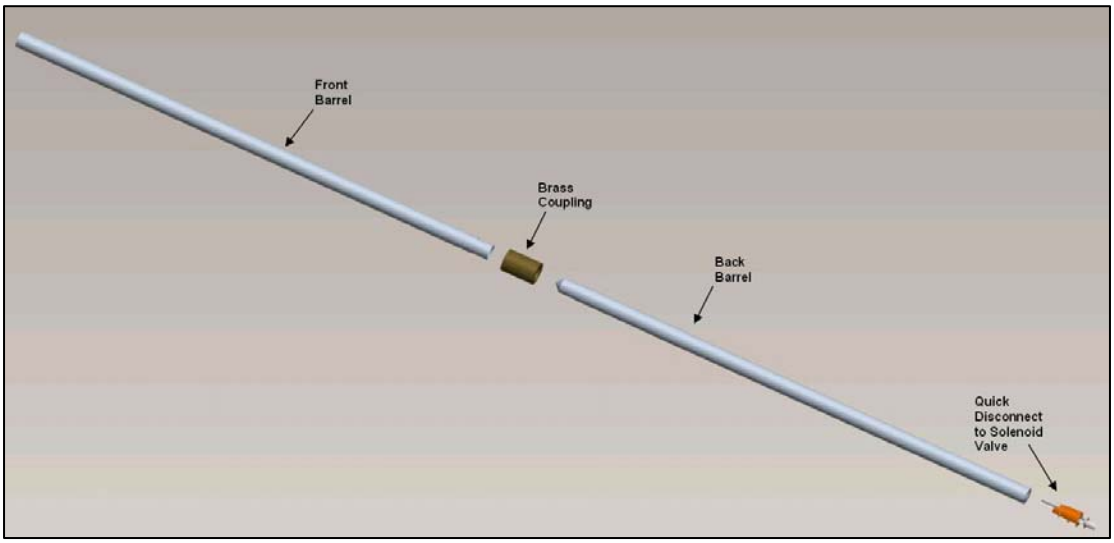

Figure 3. An exploded view of the 0.15 CAL barrel.

2.2 FSP

The FSP is used to test the ballistic resistance of a material and simulates the effects of high speed fragment strike on a target. The 0.22 CAL and 0.15 CAL FSPs are shown in figure 4. Both projectiles have a cylindrical body and a chiseled nose (see CAD diagrams in appendix). The 0.22 CAL FSP has a tail skirt, while the 0.15 CAL FSP does not. The FSP is manufactured from cold rolled annealed steel (4337H or 4340H). The weights of the 0.22 and the 0.15 CAL FSP are 1.1 and 0.4 g, respectively. The 0.22 CAL FSP skirt has a slightly larger diameter than the inner diameter of the barrel and must be sized through a die twice before it can be inserted into the barrel. The 0.15 CAL FSP does not need to be sized.

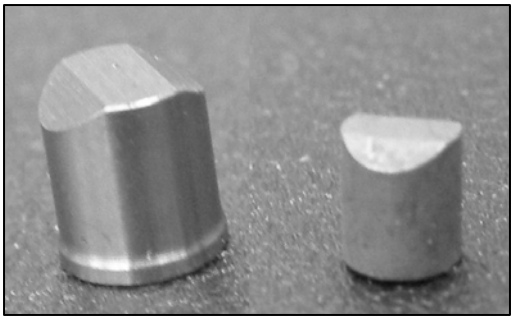

Figure 4. Left to right: 0.22 CAL and 0.15 CAL FSPs. Material: cold rolled annealed steel (4337H or 4340H).

2.3 Speed Measurement Device

The speed of the projectile is determined by measuring the flight time between two break screens that are perpendicular to the flight path of the projectile (figure 5). The break screens are separated at a distance of 0.5 m and their aperture diameter is 9.5 cm. Figure 5 shows one of the break screens with a silver conductive screen in its aperture. The circuit screen is a rectangular (15 × 9.5 cm) printed-circuit paper with 1 mm fine silver grid lines. Once the projectile pierces the conductive screen, the circuit is tripped and the time-of-flight between the two screens is recorded in a time counter.

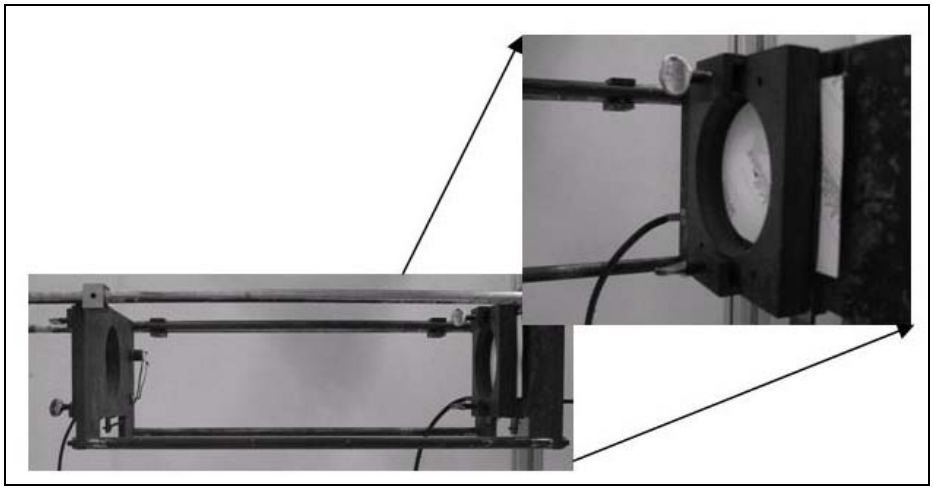

Figure 5. Break Screens Timer. Large insert: a silver conductive screen in the aperture.

2.4 List of Components and Manufacturer for the Launching Apparatus

- Smooth-bore barrels, 0.22 CAL and 0.15 CAL
  Lilja Precision Rifle Barrels, Inc., Plains, MT.
- Solenoid Valve
  Model 133SR, Whitey Company (Swagelok®), Solon, OH.

- FSP, 022 CAL and 0.15 CAL
  Best Machine Company, Inc., Edgewood, MD.
- Time Counter
  Model 5304A, Hewlett-Packard, Palo Alto, CA.
- Silver break screen
  PT #025025350500V, Whithner Corporation, Baltimore, MD.

3. Photographic Capability

3.1 High-Speed Photography

The flight history of the projectile and the impact event can be captured with a high-speed digital camera. To capture the projectile in flight, the exposure time must be set to a minimum. The minimum required exposure time, t_{min}, can be estimated by the following formula:

$$t_{min} \approx \frac{\text{smallest feature size to be captured}}{\text{speed of the object}} \quad (1)$$

For example, the skirt on the 0.22 CAL FSP is about 0.64 mm (0.025 in). In order to capture the fine details of a FSP traveling at the speed of sound (approximately 335 m/s or 1100 ft/s), a minimum exposure time of 2 μs is required. Short time exposure needs a high intensity light source. Currently, continuous high intensity halogen lamps are used to illuminate the field of view.

3.2 Camera Hardware

Currently, there are three Phantom high speed cameras (Model v7) available to record the impact event at three different locations. The camera operation is controlled by computers; however, the triggering of the cameras is controlled manually using a momentary switch. The Phantom camera consists of a CMOS sensor and an integrated control system. The cameras can be fitted with any Nikon AF-mount lens. The minimum exposure time is 2 μs. The maximum resolution can be set at 800 × 600 pixels with a frame rate of 5000 frames per second (fps). Usually, a frame rate of 10,000 fps is required to record the impact event; however, the resolution has to be lowered in order to increase the frame rate. For 0.22 CAL FSP impact events, the optimal resolution is set between 512 × 512 pixels and 256 × 256 pixels with maximum frame rates of 8,200 and 26,000 fps, respectively. The cameras record continuously in a loop until they are triggered. The captured images are stored in the cameras' memory, and then the images are downloaded to a computer.

4. Standard Operating Procedure for Launching and Imaging

4.1 Launching FSP

- Fix the target firmly in the targeting stand.
- Align the target to the intended point of impact using laser levels.
- Place break screens in the timing circuit, then hit the “reset” button on the timer.
- Close all doors on enclosure.
- Size and load FSP into the barrel.
- For 0.22 CAL, close breech with the breech plug and clamp it down with a C-clamp.
- For 0.15 CAL, close quick-disconnect.
- Connect 120V power to the solenoid ball-valve.
- Open the gas valve at the gas tank and pressurize the gas reservoir slowly.
- Use the pressure gauge to monitor the pressure.
- Close the gas valve to prevent re-pressurization of the gas reservoir after launching.
- Use the needle valve to adjust the pressure in the reservoir if necessary.
- Wait for the pressure to stabilize for one minute.
- Launch the FSP by clicking the momentary switch that opens the solenoid valve.

4.2 Phantom Camera Setup

- Connect camera Ethernet cable to the computer.
- Power on the camera before booting the computer.
- Run Phantom control software and open camera setup (Phantom v7 Control).
- Select appropriate resolution and frame rate.
- Set post-trigger to one-half of the available frames (the number of frames is defaulted by the camera).
- With the camera lens covered, calibrate the camera by clicking “current camera reference,” click “yes” or “ok” to continue the calibration process.

- Remove lens cover and adjust zoom and focus (use long exposure time setting during focusing).
- Select the correct exposure time (see aforementioned equation), adjust light intensity accordingly.
- Click “pre-trigger” and test the camera by triggering it.
- If the images are good, click “pre-trigger” again to erase the old images and ready for triggering.
- When ready, click the momentary switch to trigger the camera.
- Download images from camera to computer.

5. Barrel Performance

The performance of the 0.22 CAL barrel is evaluated at various helium gas pressures. The muzzle speed of the FSP is determined by the break-screens. Figure 6 is a plot of 0.22 CAL FSP muzzle speed as a function of compressed helium pressure in the reservoir. The minimum required launching pressure is 0.138 megapascal (MPa) (20 pounds per square inch (psi)). The maximum allowable pressure is 20.68 MPa (3000 psi). Several data points were collected at three different pressures: 0.586, 3.162, and 17.24 MPa (85, 525, and 2500 psi) to test the reproducibility of the muzzle speed. The error bars represents the spread of the speeds from average. The widest spread occurs at 17.24 MPa (2500 psi). At this pressure, the compressed gas begins to leak out at the ball-valve. Frequently, the gasket at the ball-valve does not seal properly, which causes the launching speeds to vary significantly. At the low pressure limit, the sensitivity of the pressure gauge is near its lower boundary and the accuracy of the pressure reading is reduced. As a result, the launching speeds fluctuate at the low pressure range, but not as erratically as in the high pressure range. The optimal operating range for the 0.22 CAL barrel is at the intermediate pressures between 1.38 and 5.52 MPa (200 and 800 psi). The launching speeds are very reproducible, usually within +/- 10 m/s.

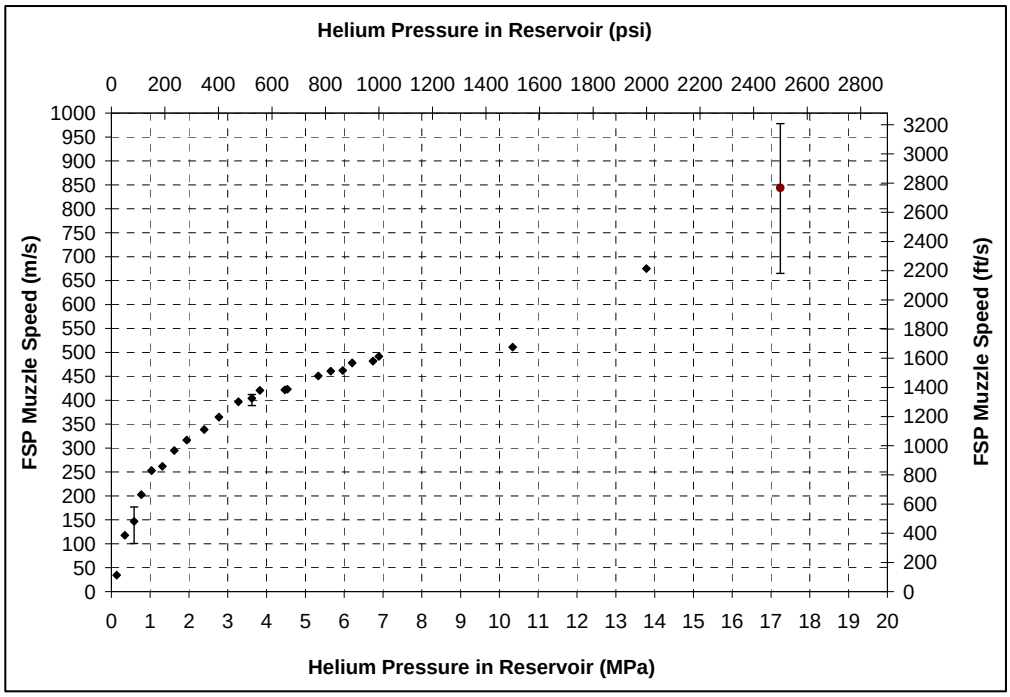

Figure 6. FSP speed as a function of helium pressure.

6. Examples of Impact Analysis

6.1 V_{50} Ballistic Test for Polycarbonate (PC) and Poly(methyl methacrylate) (PMMA)

The ballistic resistance of PMMA and PC were tested against the 0.22 CAL FSP impact. The testing method followed the procedure outlined in the Department of Defense (DoD) Test Method Standard for armor Military Standard 662F (MIL-STD-662F)[2]. All shots were fired on the target's planar surface at 0° of obliquity. The area of the target is 15.24 × 15.24 cm (6 × 6 in.). The target was mounted onto a frame with four C-clamps, one at each of the corners. The witness plate (0.05 mm thick aluminum foil) was placed 5.08 cm (2 in.) behind the back surface of the target and checked for penetration after each shot. The V_{50} value for these tests is an average of at least six pairs of penetrating and non-penetrating impact speeds. The acceptable standard deviation is less than 10 m/s. The V_{50} ballistic performances of PC and PMMA at various thicknesses are presented in figure 7.

[2] MIL-P-46593A (ORD). *Military Specification for Projectile Calibers .22, .30, .50, and 20 mm Fragment-Simulating.* October, 1962.

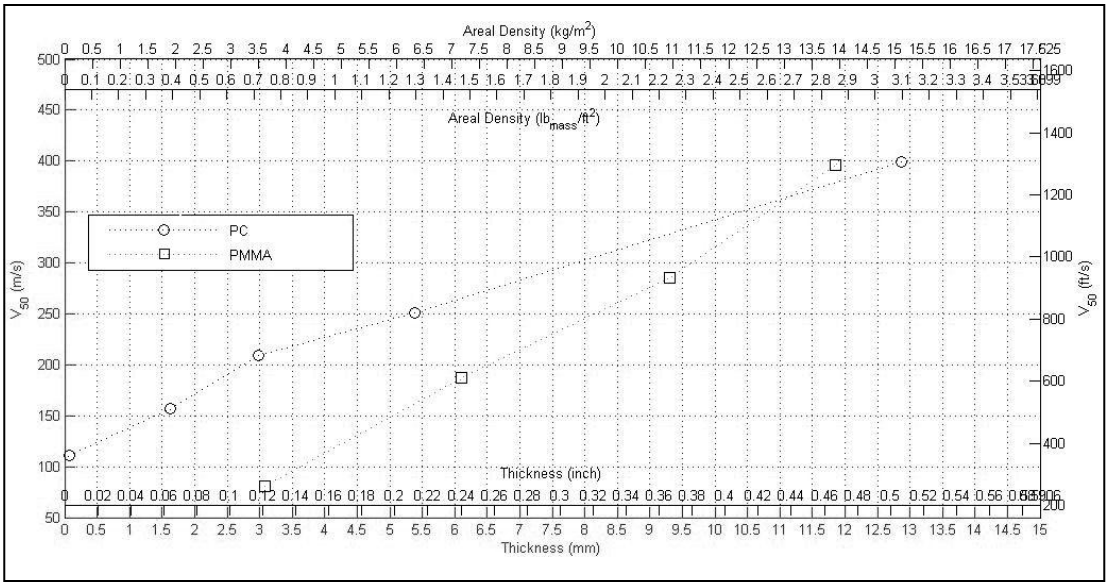

Figure 7. V_{50} ballistic performance of PMMA and PC against 0.22 CAL FSP.

6.2 Typical Residual Speed and Spall Pattern Analysis

A high-speed camera was used to capture impact events on a PMMA plate that was sandwiched in a transparent frame. Figure 8 illustrates the setup of the camera and the lighting equipment. The camera was aimed at 90° to the path of the FSP. The targeting area was illuminated by backlighting using a high intensity halogen lamp. A light diffuser was used to spread out the light intensity. The focal length of the lens was 70 mm. The f-stop was set to f/8 to increase the depth of field. The exposure time was 2 μs, and the resolution was 512 × 256 pixels. The frame rate was defaulted by the camera to 25,000 fps at this resolution. The Phantom camera comes with its own photo analysis software and can calculate speed as well as displacement of an object in 2-dimensional space. Figure 9 shows three selected frames from a video file capturing a 0.22 CAL FSP impact on a 1.143 cm (0.45 in.) thick PMMA plate. The impact speed was 351 m/s. The residual speed of the FSP after the impact was zero; the projectile was wedged onto the target.

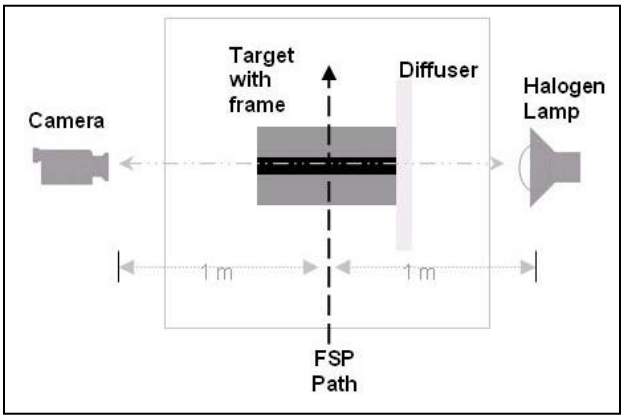

Figure 8. Setup diagram for residual speed analysis.

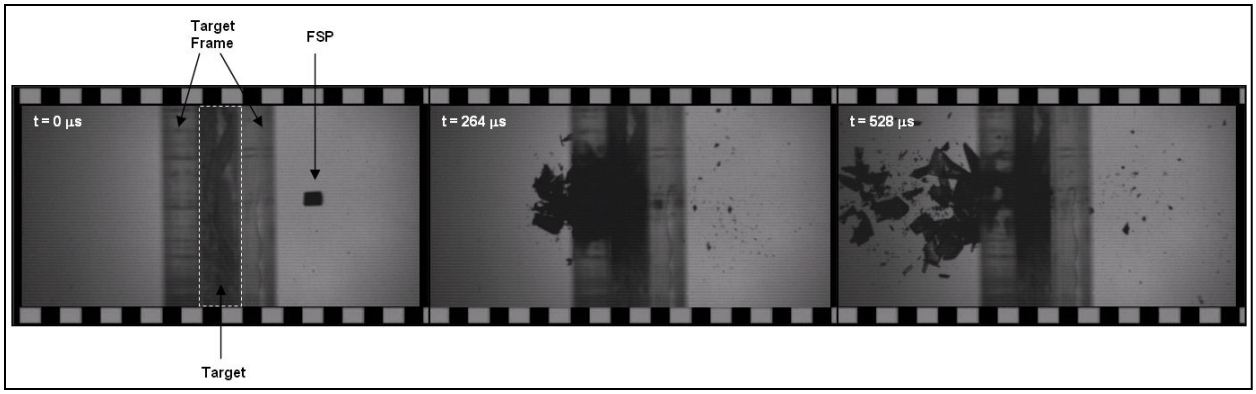

Figure 9. Selected still photos of 0.22 CAL FSP impacting on 1.143 cm (0.45 in.) thick PMMA.

6.3 Deformation Analysis

ARAMIS is a non-contact measurement system that calculates the strain history of a deformation event. The detailed operation of the ARAMIS system will be described in a separate report, only a brief description will be presented in this report. The ARAMIS system takes a series of synchronized stereo images generated from two cameras and renders these images into three-dimensional displacement vectors and strain vectors as functions of time. The ARAMIS system requires the target to be painted with dots for displacement tracking, which is one limitation of the system. If any object, such as spall or projectile obscures the dots, displacement tracking would be lost. If the target undergoes fracture failure, the displacement tracking would be lost at the cracks. Figure 10 shows an example of an impact event of a 0.22 CAL FSP on a 0.635 cm (1/4 in.) PC target that was rendered by ARAMIS. The contour plot shows the displacement of the back-surface of the plate at a specific time after the impact. The displacement accuracy is within 0.6 millimeter.

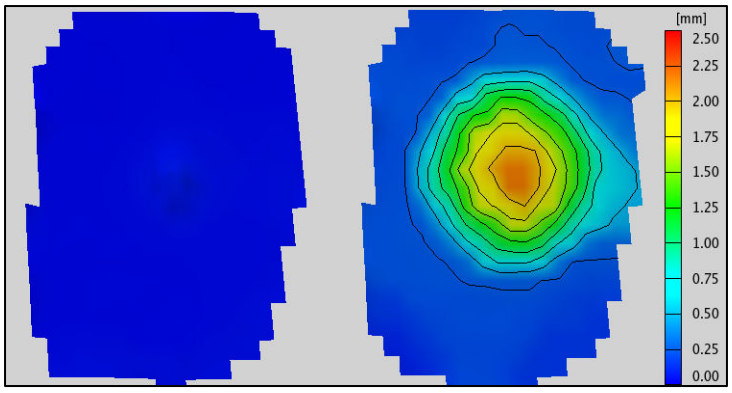

Figure 10. An ARAMIS rendering of the back surface displacement of a polycarbonate plate impacted by a 0.22 CAL FSP.

7. Future Equipment Upgrades

7.1 Speed Measurement Device Upgrade

There are two potential speed measurement devices to be integrated in the impact tester. The first is a Doppler radar, which not only measures the pre-impact velocity of the projectile, but also the post impact velocity. The accuracy is about 0.1%. The second velocity measurement device is a magnetic intervalometer system that is similar to the break screens. The circuit is tripped by a passing projectile through a set of magnetic coils. Unlike the break screens that can interfere with the flight characteristic of the projectile, the magnetic coils measure the speed with out making physical contact with the projectile.

7.2 High-Speed Camera Upgrade

The current high-speed cameras lack high pixel resolution at fast frame rate settings. The upgrades would double the frame rate from 10,000 to 20,000 fps at 512 × 512 pixels. The minimum exposure time is reduced from 2 to 1 μs.

7.3 Fast-Acting Solenoid Valve

The current solenoid valve is only able to operate at a maximum pressure of 20.68 MPa (3000 psi). Significant gas leakage occurs near this pressure. The upgraded valve will able to withstand 10,000 psi.

7.4 High Intensity Xenon Flash

The current halogen lamp lacks the intensity to illuminate fast-moving object from the front; only back illumination is possible for high-speed photography. The solution is to use a high intensity flash Xenon lamp. The flash lamp is able to deliver over 1000 joules of light energy in less than a ms, far exceeding that of the current 250 W, 2 amps halogen lamp.

8. Conclusion

The current dynamic impact testing equipment is able to provide a way to evaluate ballistic impact and deformation phenomena of armor materials. The imaging system can reveal the transient details, such as displacement and strain during the impact event.

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Appendix. CAD Drawings

The CAD drawings in this appendix are included for fabricating spare parts and providing a reference for designing new barrels. The dimensions are in inches.

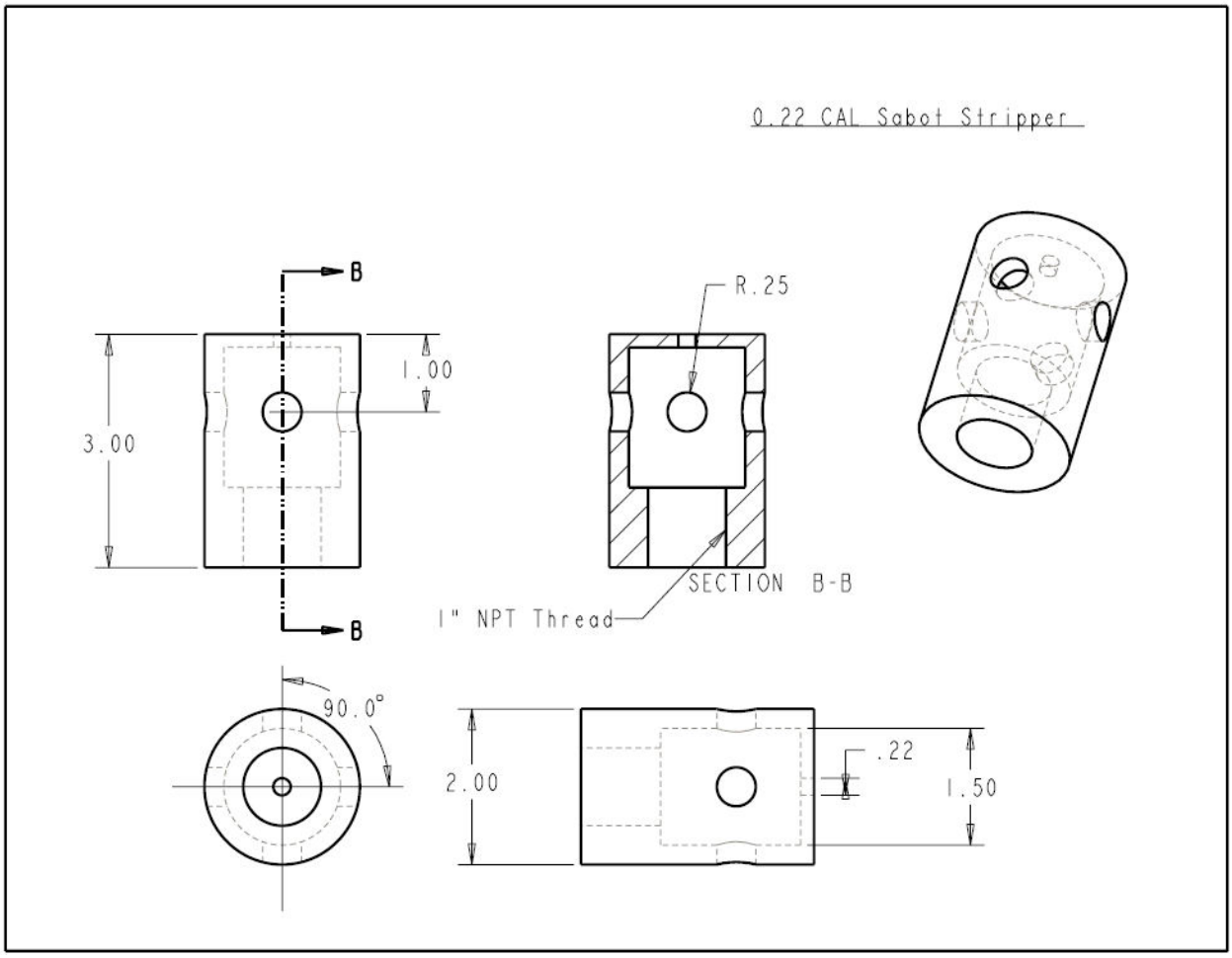

Figure A-1. Sabot Stripper for the 0.22 CAL barrel.

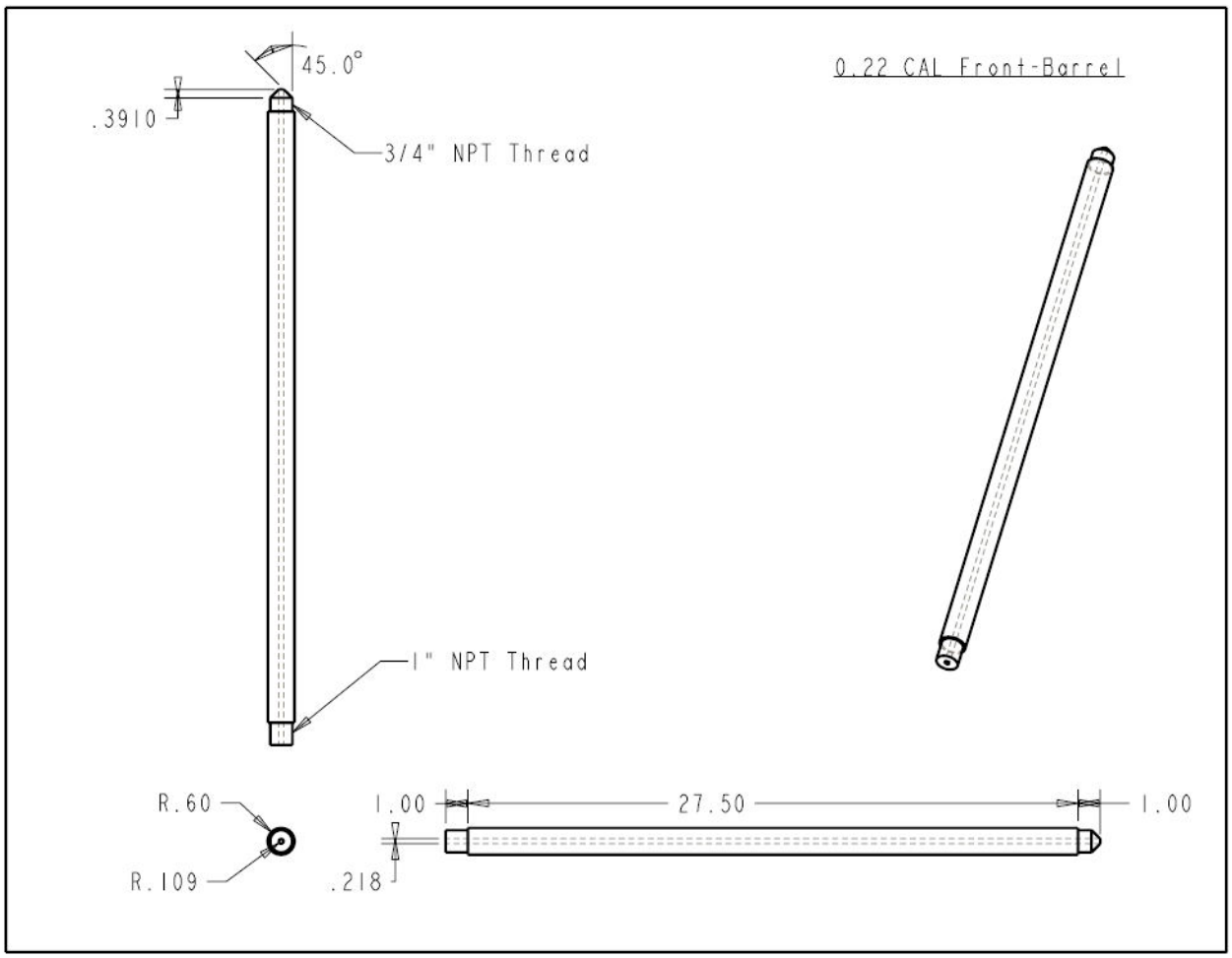

Figure A-2. The 0.22 CAL front barrel.

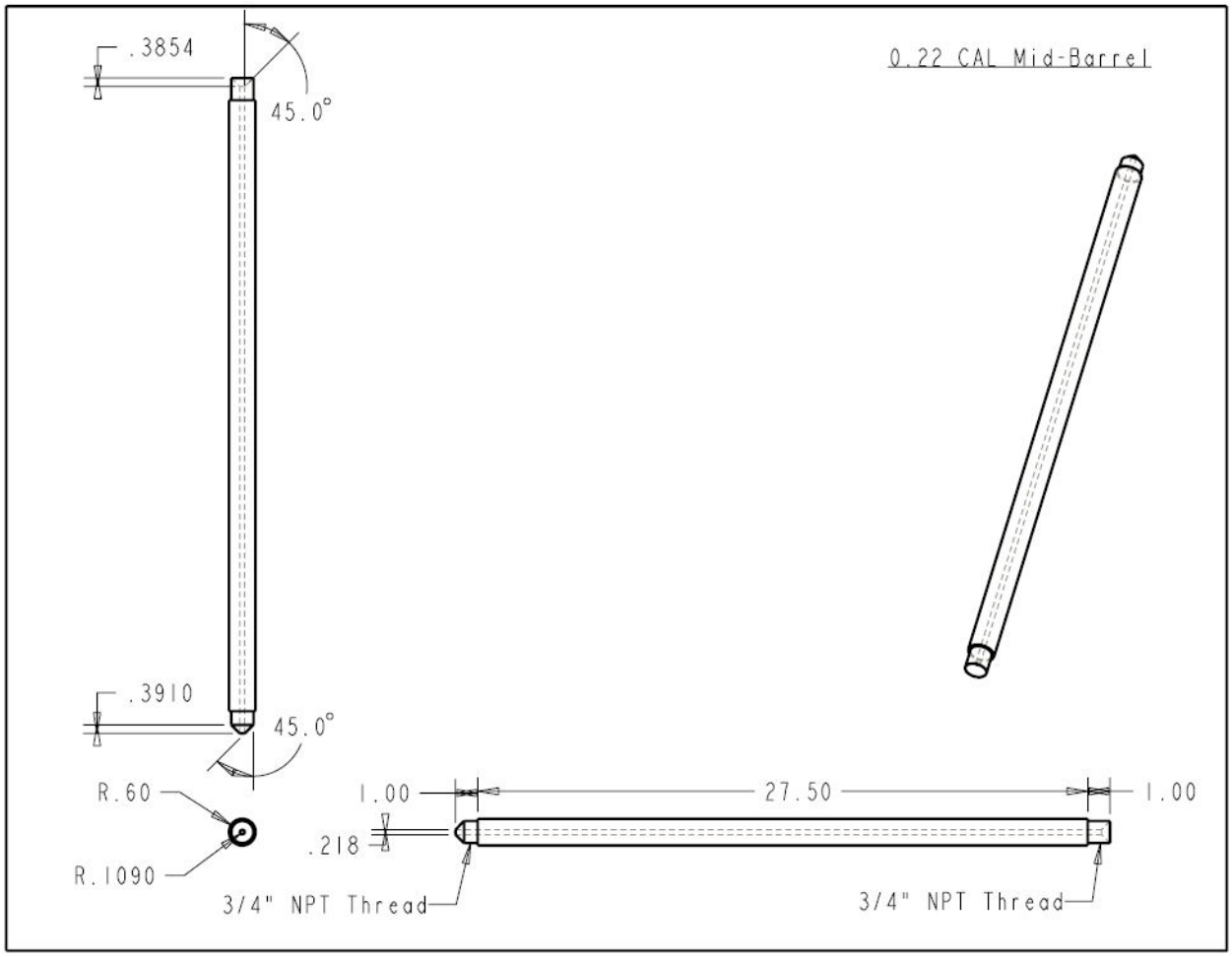

Figure A-3. The 0.22 CAL mid-barrel.

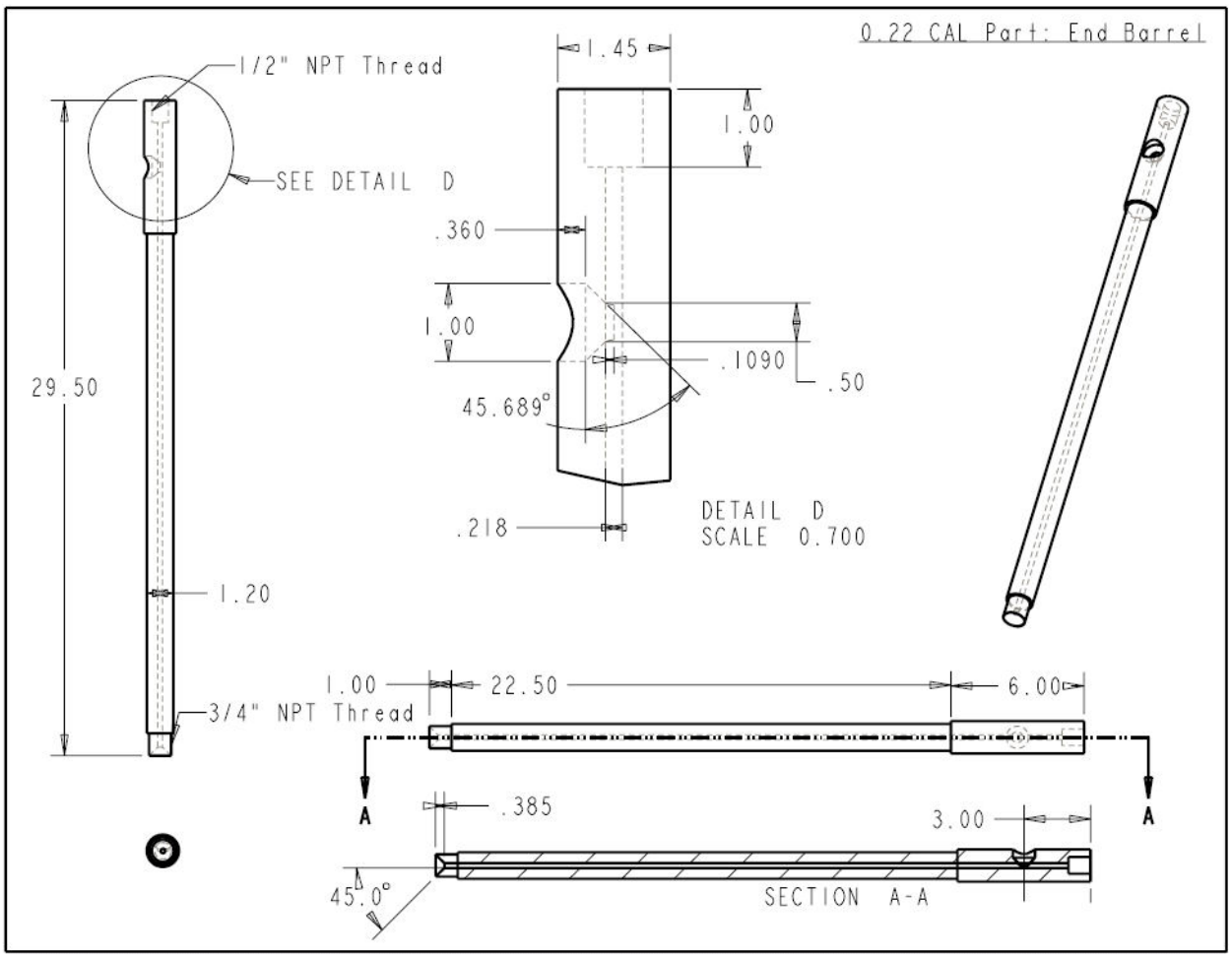

Figure A-4. The 0.22 CAL end-barrel.

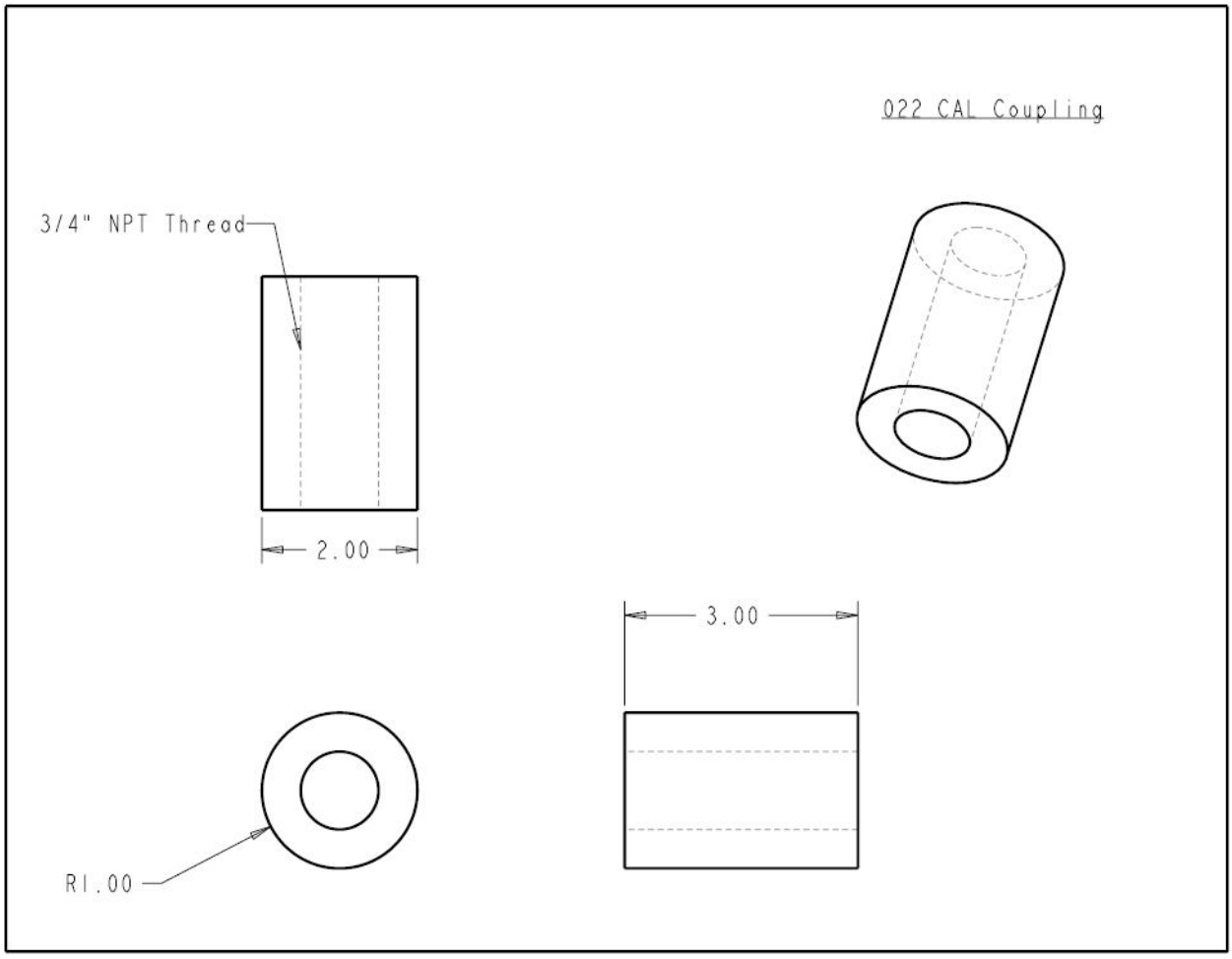

Figure A-5. The 0.22 CAL barrel coupling.

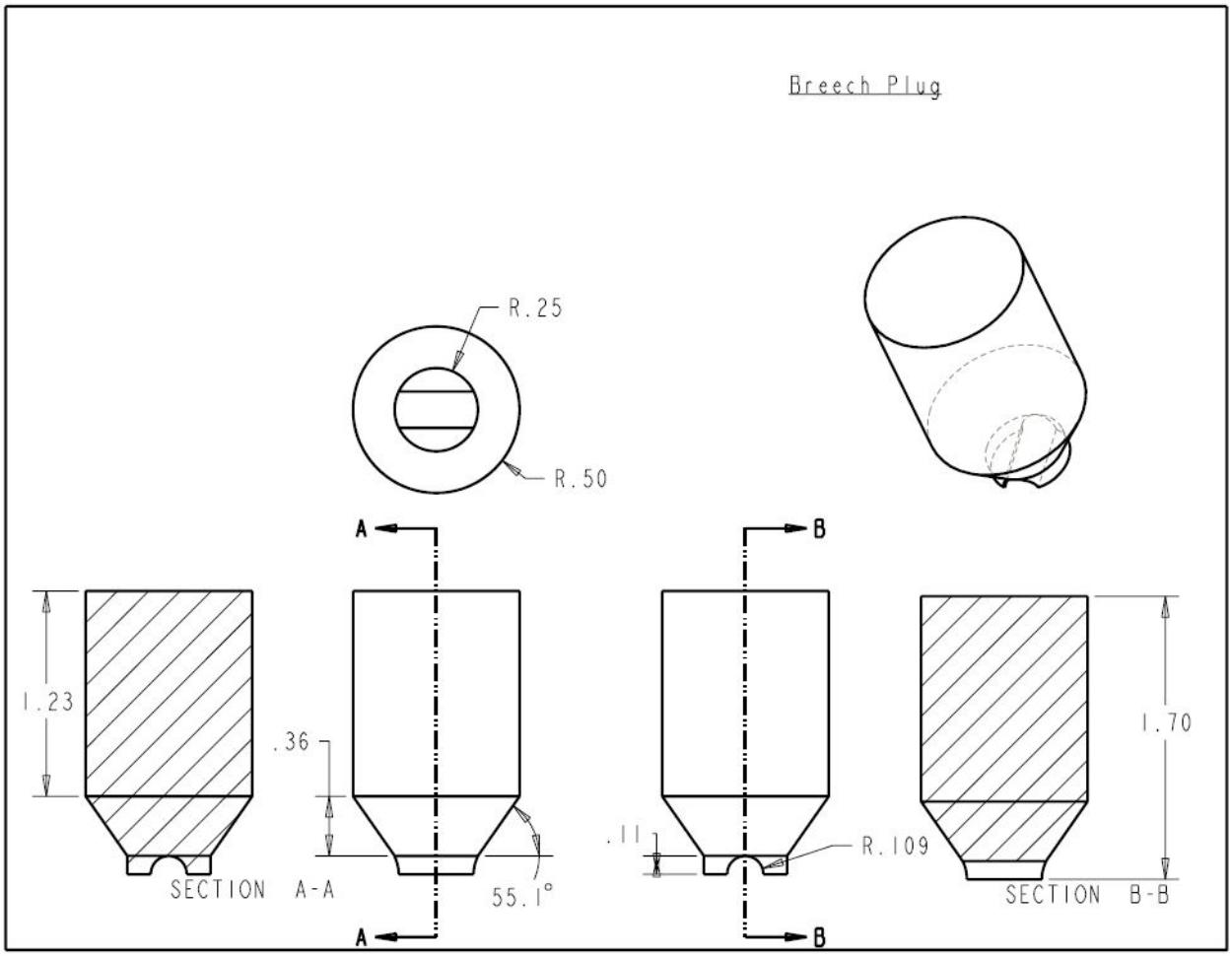

Figure A-6. Breech plug for 0.22 CAL barrel.

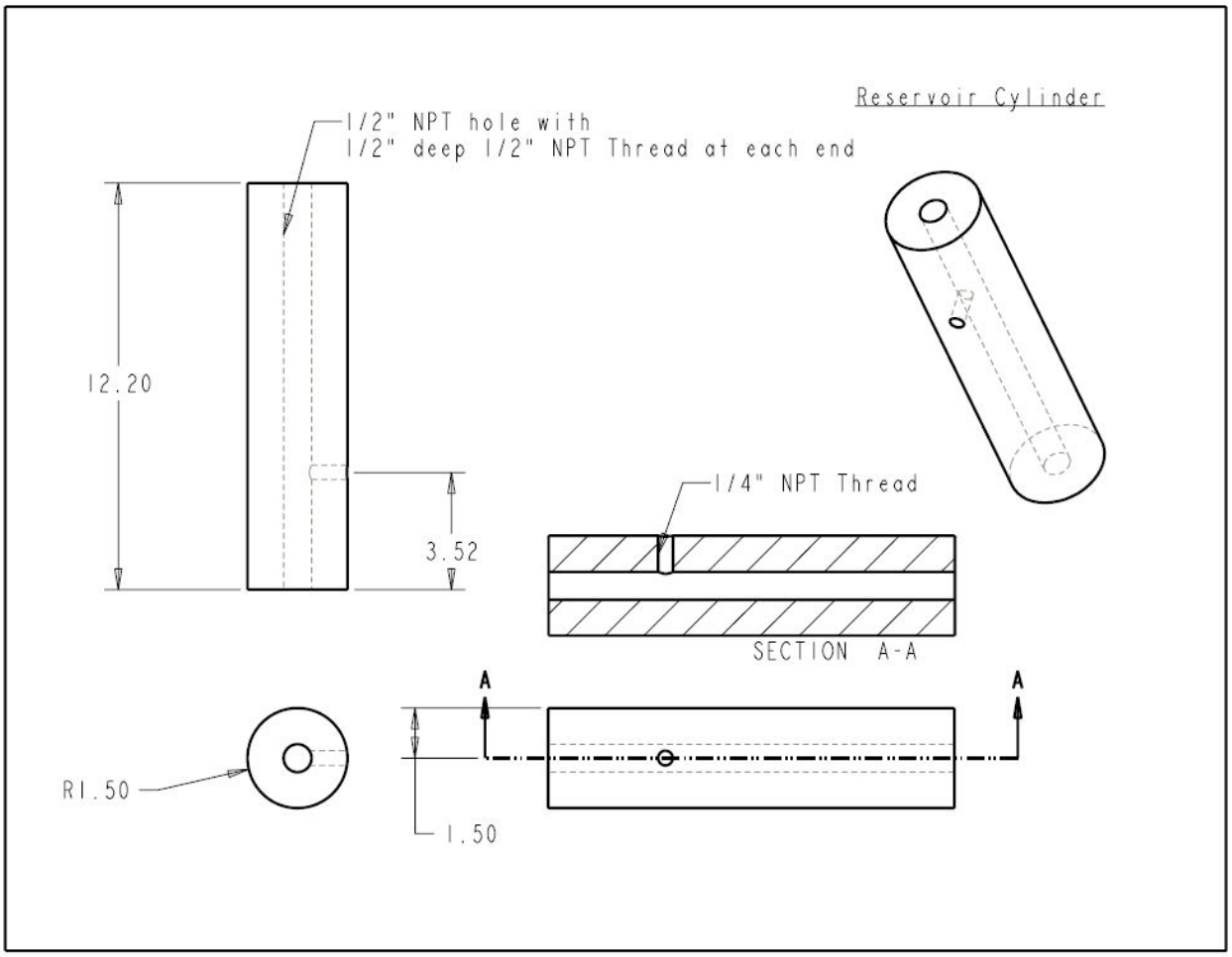

Figure A-7. Steel cylinder gas reservoir.

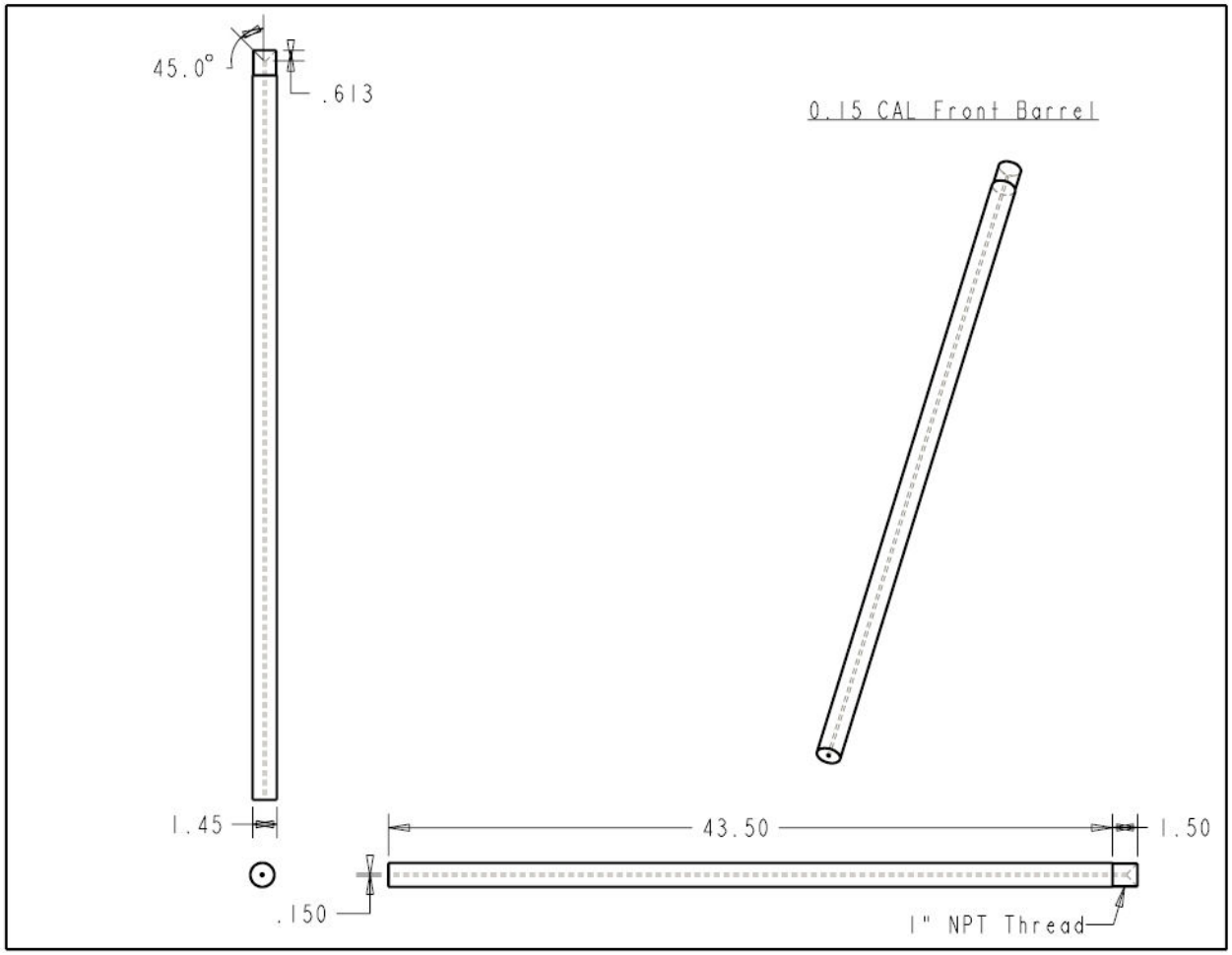

Figure A-8. The 0.15 CAL front barrel.

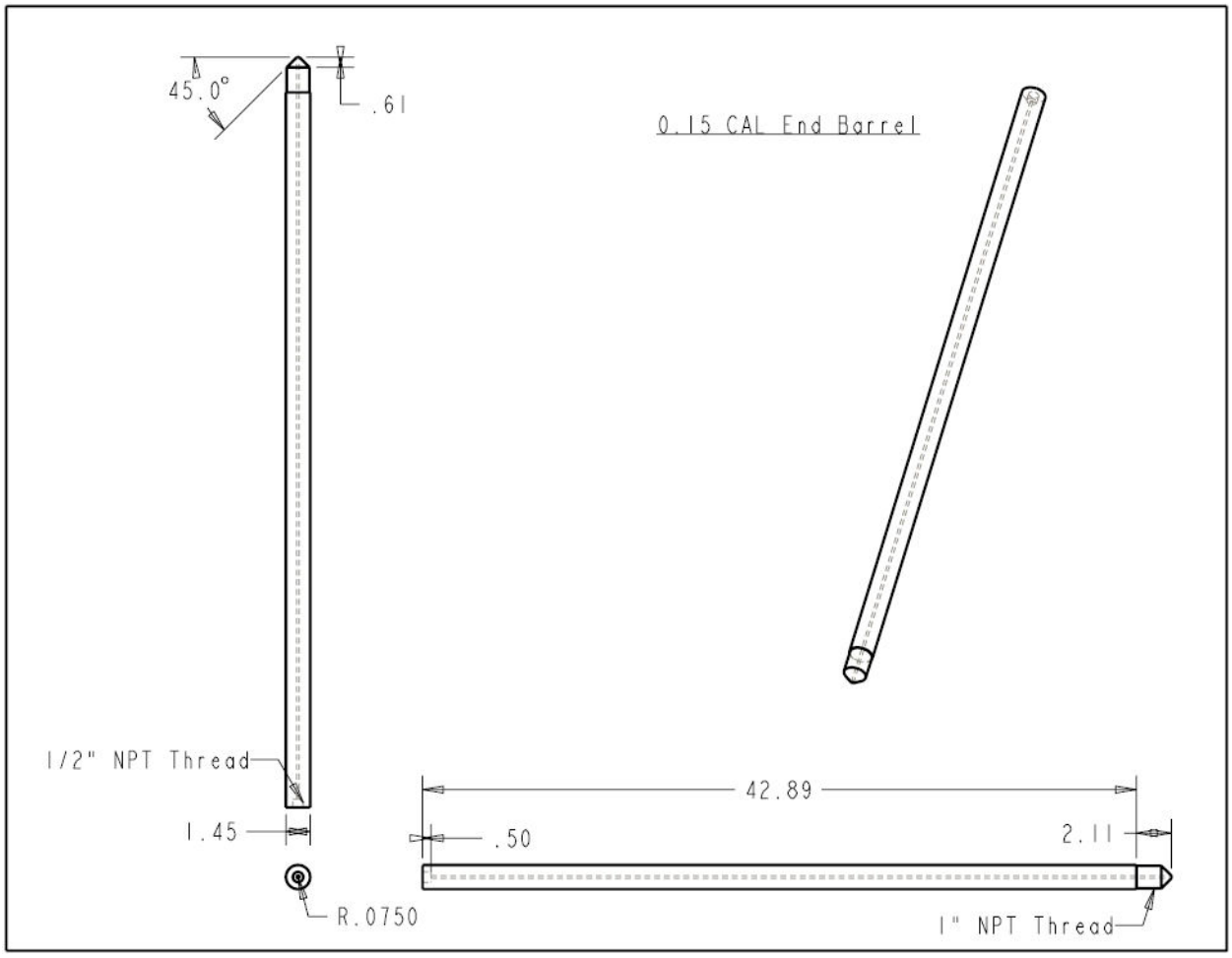

Figure A-9. The 0.15 CAL end-barrel.

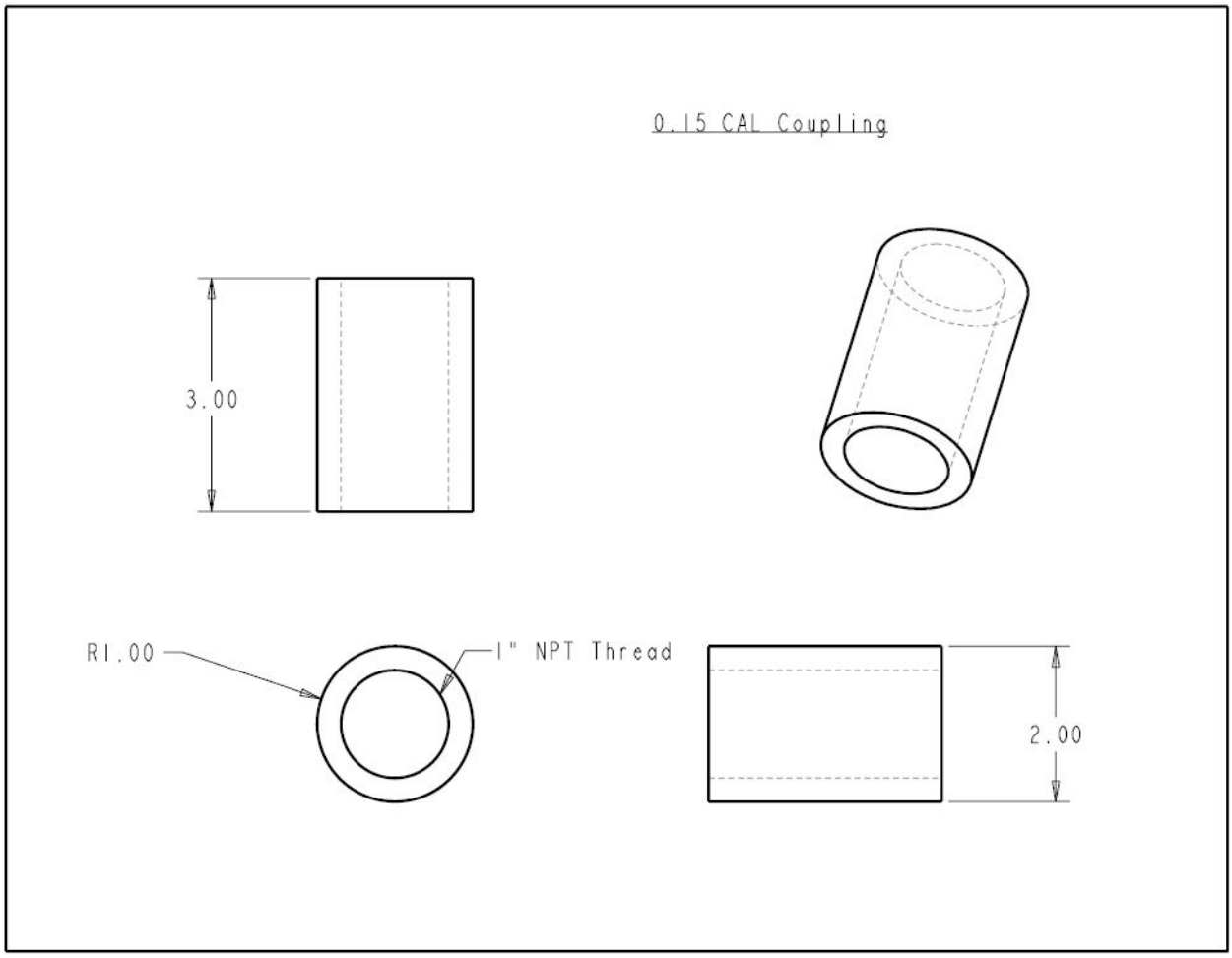

Figure A-10. The 0.15 CAL barrel coupling.

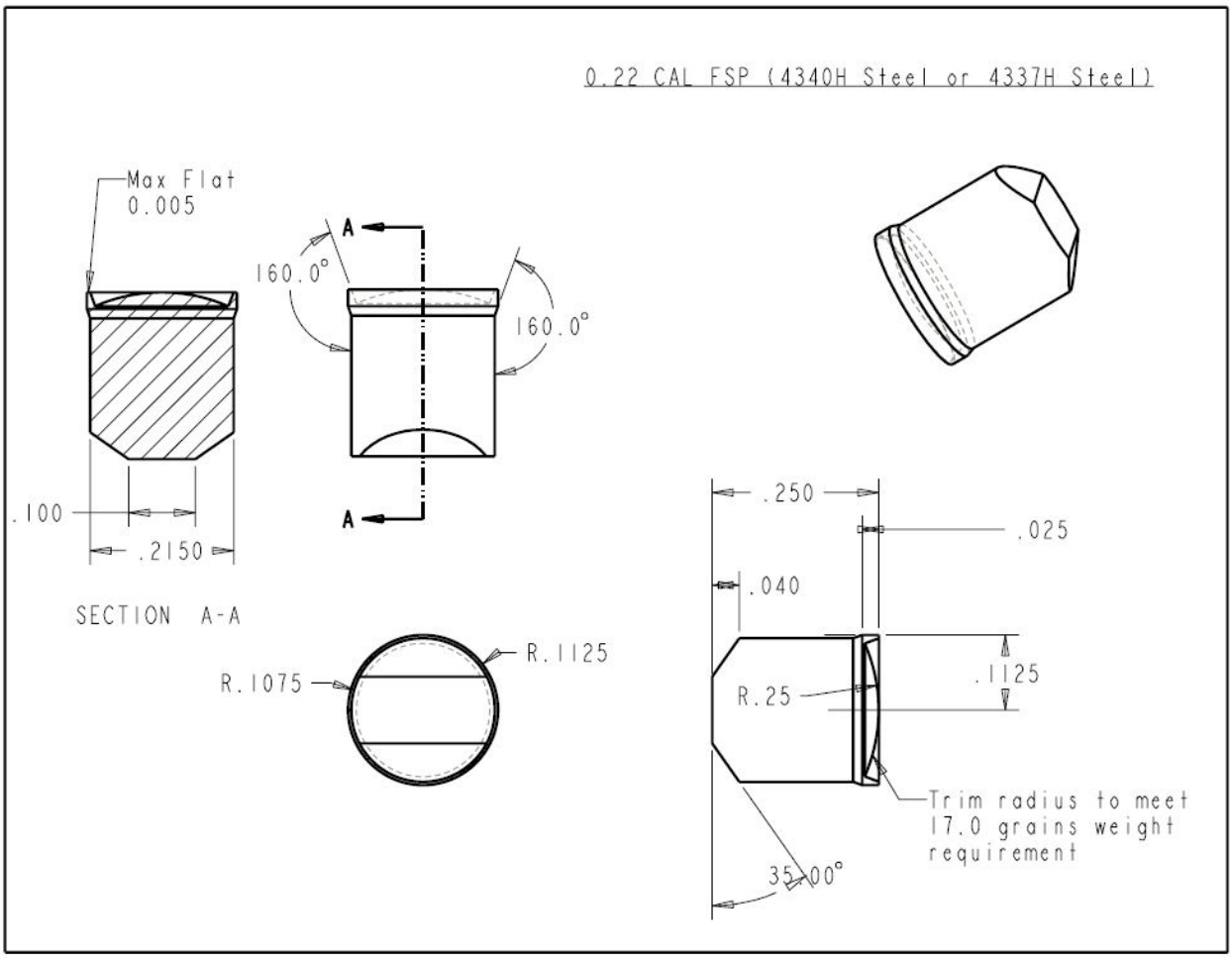

Figure A-11. The 0.22 CAL FSP.

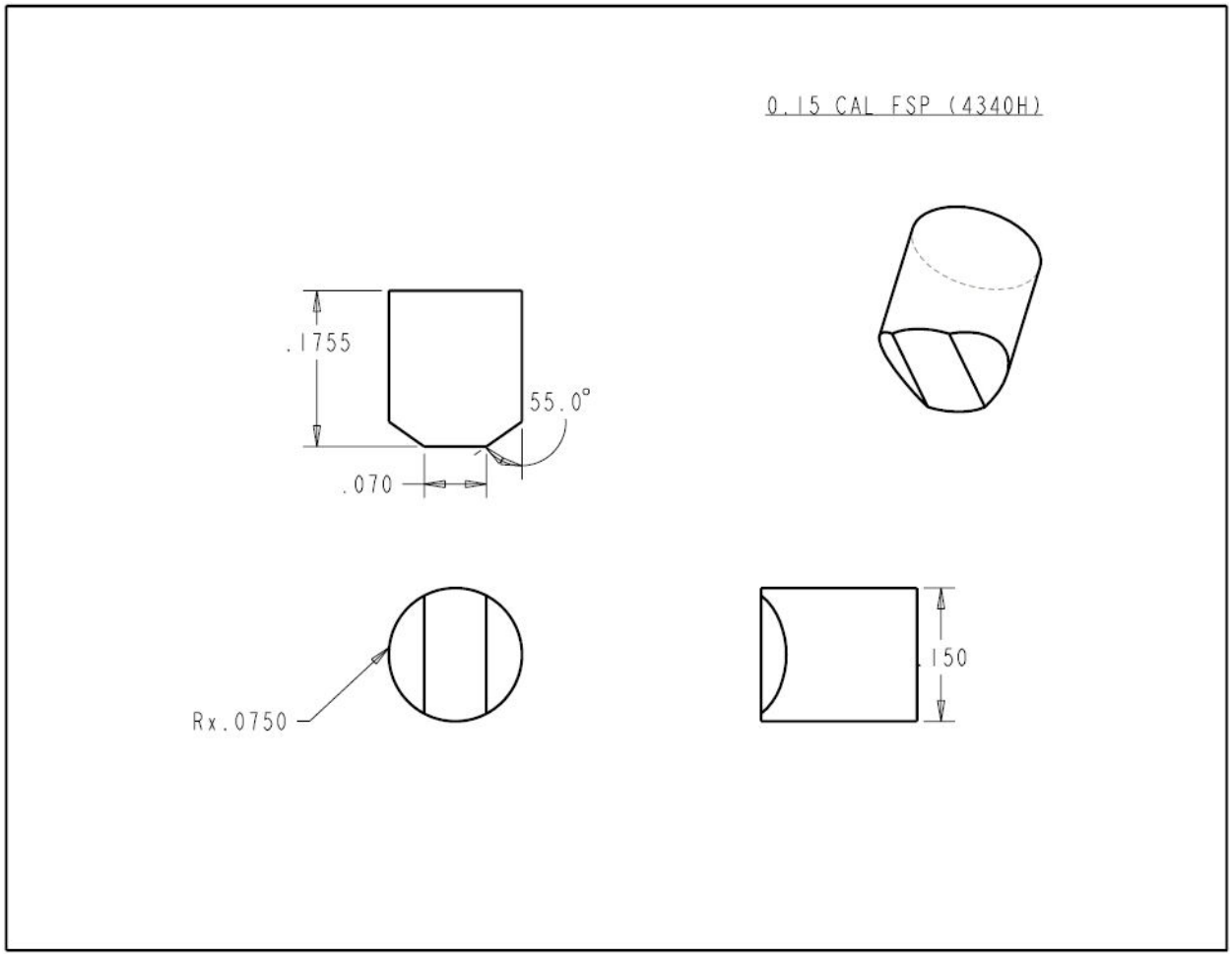

Figure A-12. The 0.15 CAL FSP.

Acronyms

ARL	U.S. Army Research Laboratory
CAD	computer aided design
CAL	caliber
DoD	Department of Defense
fps	frames per second
FSP	fragment simulating projectile
MPa	megapascal
NPT	National Pipe Thread Taper
PC	Polycarbonate
PMMA	Poly(methyl methacrylate)
psi	pounds per square inch

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