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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND (DEVCOM) ARMAMENTS CENTER (AC) PHOTONIC DOPPLER VELOCIMETRY CYLINDER EXPANSION TESTING

David Rydzewski
Erik Wrobel
Rodger Cornell

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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT
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Munitions Engineering and Technology Center

Picatinny Arsenal, New Jersey

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14. ABSTRACT

The cylinder expansion (CYLEX) test is used to characterize the work output of explosive formulations for use in modeling and simulation efforts as well as to provide calculated Gurney constant estimates at specific volume expansions. As there is currently no overarching standardization agreement or other reference dictating the methodology of this experiment, there is some flexibility in how CYLEX testing can be conducted. As a result, differences in methodologies often influence experimental observables and can significantly increase overall uncertainty if not documented properly. Documenting the procedures, data reduction methodologies, and testing parameters will allow for simplified experiment replication. This technical report details the methodology currently employed at the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ. The procedures necessary to accommodate specific material callouts are discussed and the details regarding how the dimensional data was captured are explained. The photonic Doppler velocimetry (PDV) probe setup and general procedure are also conveyed.

15. SUBJECT TERMS
Cylinder expansion CYLEX CYLEX testing Photonic Doppler velocimetry PDV PDV probe

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INTRODUCTION

The characterization of secondary explosives can be a time-consuming and detailed process, as many tests are often required to adequately understand the sensitivity and performance of new formulations. One of the more impactful performance tests for secondary explosive formulations is commonly known as the cylinder expansion (CYLEX) test. The CYLEX test involves detonating an explosive sample loaded within an oxygen-free copper cylinder and then measuring the resultant copper wall velocity as it is accelerated by both shock propagation and gaseous product expansion. The measured wall velocity can then be used to calculate the detonation energy density of the sample as a function of volume expansion, providing a quantitative description of how well the sample is expected to push metal in munition applications.

While the analytical expression for detonation energy density has significantly improved in recent years to correct for wall-thinning, shock attenuation, air gap losses, etc., many still find value in using the 1943 Gurney equations to calculate Gurney constants for new explosive formulations (ref. 1). While this equation is known to be inaccurate (~10% error) due to its many simplifying assumptions, calculating Gurney constants requires no computational support and provides rapid evaluation criteria for new formulations through comparative assessments with legacy explosives.

The Gurney constant (reported in units of velocity) was introduced as part of a model to describe the expansion of confining inert material (typically metal) when driven by detonation and has been an important U.S. Department of Defense (DoD) explosive performance metric for many decades (ref. 2). The Gurney constant is typically calculated at multiple volume expansions (2, 3, 5, 7 for DoD customers) to provide defined points of reference when comparing different explosive materials. Some laboratories, particularly those associated with the U.S. Department of Energy (DoE), may also report the results in the form of a detonation energy, which can be shown to be mathematically equivalent (ref. 3).

The Gurney constant is of particular interest to the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ, and its customers as the direct comparison to other energetic materials provides a useful evaluation of an explosive’s performance. The CYLEX data also provides needed information for determining various parameters of both the Jones-Wilkens-Lee (JWL) (ref. 4) and Jones-Wilkens-Lee-Baker (JWLB) equations of state (EOS). These EOSs are utilized in many modeling and simulation efforts such as warhead performance and shape charge liner design (ref. 5).

The testing process has evolved significantly over time at DEVCOM AC as initial experiments viewed the expansion of a 1-in. cylinder using a streak camera coupled with an argon bomb light source (ref. 5). Early modifications to the experiment allowed for numerous cylinder diameters, which has helped many research efforts, as new formulations can often be difficult to manufacture in significant quantities (ref. 6). Photonic Doppler velocimetry (PDV) was introduced in the late 2000s to replace streak camera observation for improved spatial and temporal resolution (refs. 7 and 8).

While the introduction of PDV has simplified the overall complexity of the experiment, DEVCOM AC CYLEX testing utilizes multiple diagnostic techniques to capture all the necessary data. Currently, there is no standard for CYLEX testing dictating methodology for data collection, as opposed to many other tests that are standardized via allied ordnance publications (AOP, technical bulletins (TB), and standardization agreements (STANAG). This freedom thus requires some documentation to ensure that reported results have less room for interpretation and may be easily translated across groups with different methodologies.

METHODS, ASSUMPTIONS, AND PROCEDURES

The characterization of explosive formulations intended for warhead integration is a priority in developing new materials that push the boundaries of performance in traditional and insensitive munitions. However, this process requires standard operating procedures (SOP) to ensure small differences in methodologies do not lead to measurable differences in results or large experimental uncertainties. One such procedure has been implemented for cylinder material selection. As the material callout is for annealed C101 copper, it does require some special handling procedures to ensure that the tube is free from dents and has no noticeable oxidation prior to testing. Annealed C101 copper is selected as its high conductivity allows for large-volume expansions (typically ≥15) before catastrophic material failure is observed. In order to prevent unwanted oxidation, the SOP at DEVCOM AC aims to minimize the time the tube is exposed to air prior to an experiment.

Copper Cylinder

As the physical dimensions of the cylinder are needed to use the Gurney constant, the beginning of every test consists of accurately measuring all cylinder dimensions. The physical dimensions of each cylinder are straightforward to measure, as they require only simple equipment. Depending on cylinder sizes, a large set of calipers can measure the outer diameter (OD), inner diameter (ID), and length of each cylinder. The cylinders, shown in figures 1 and 2, are 1 in. in diameter and 12 in. in length, although this will increase as sample diameter increases. The weight of each tube should be measured using an appropriate scale that can handle the weight of the cylinder and still provide an acceptable level of fidelity (minimum accuracy of ±0.1 g). Ideally, diameter measurements would occur at the PDV beam location (where particle velocities are being captured), but this is typically not feasible and could potentially scratch the surface of the tube if calipers or pin gauges are used. Such measurements would require the use of specialized equipment, such as a coordinate measurement machine (CMM), which may not be practical for many test facilities. As a result, diameter measurements are typically taken at the cylinder ends so that any resulting physical damage to the cylinder will have minimal influence on test results.

Figure 1
Packaged and unpackaged 1-in. diameter copper cylinders

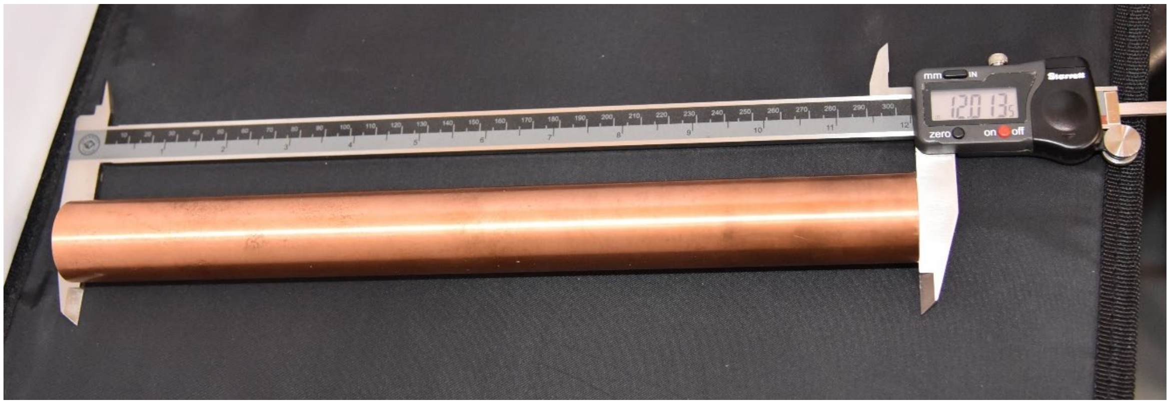
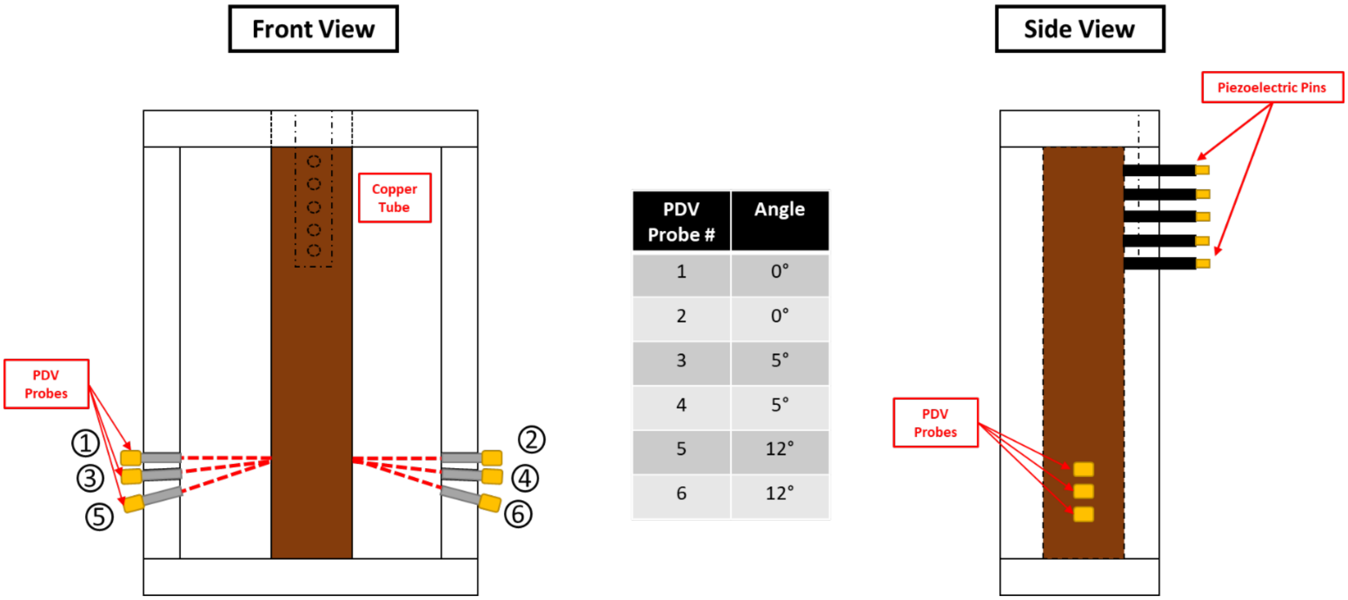


Figure 2
Example of measuring the length of a 1-in. diameter copper cylinder with calipers

Acrylic Fixture

Typically, DEVCOM AC uses machined acrylic fixtures to provide a stable and dimensionally accurate platform for the various diagnostics required for the test. The engineering drawings are detailed in appendix A. The top and bottom of the acrylic fixture centers the copper cylinder, while the side plates provide mounting locations for PDV probes on both sides of the cylinder. There are three available angles of 0, 5, and 12 deg, which are all directed at the same initial location on each respective side of the cylinder, as shown in figure 3. Typically, DEVCOM AC uses the 0 and 5-deg probe angles as they provide strong return signals and are easy to align. It is worth commenting that by placing probes on both sides of the cylinder, the chances of a manufacturing defect in the cylinder affecting the results of the test would be minimized. For example, if only one side of the tube was measured for wall velocity, a nonconcentric cylinder could produce an artificially higher or lower velocity due to differing amounts of wall material at each circumferential location. The fixturing also allows for piezoelectric pins to be accurately spaced and mounted onto the top of the cylinder via a small cutout in the acrylic top plate.



PDV Probe #	Angle
1	0°
2	0°
3	5°
4	5°
5	12°
6	12°

Figure 3
Representative setup of a PDV CYLEX test

Piezoelectric Pins

The detonation velocity of the energetic material is measured via five piezoelectric pins that are placed in contact with the copper cylinder, as shown in figure 4. The piezoelectric pins have a rise time of 10 nsec and are evenly spaced, with the distance between each pin being dependent on the OD of the test being performed (ref. 9). For example, a 1-in. CYLEX test will have 0.5 in. between each pin, while a 0.5-in. test will have 0.25-in. spacing. The detonation velocity can then be measured by finding the time difference between each peak and then calculating the average of the dataset. When placing the piezoelectric pins against the cylinder, typically a small amount of vacuum grease is added to the tip of the pin to maintain contact between the pin and cylinder wall. While this technique can provide a reasonable estimate of detonation velocity, it should be noted that it is an imperfect solution, as detonation velocity may be transient at the top of the cylinder. In addition, the pins can cause premature cylinder rupture. A more ideal solution is to use evenly spaced PDV probes that provide shock arrival information without direct cylinder contact, although this has not yet been implemented at DEVCOM AC.

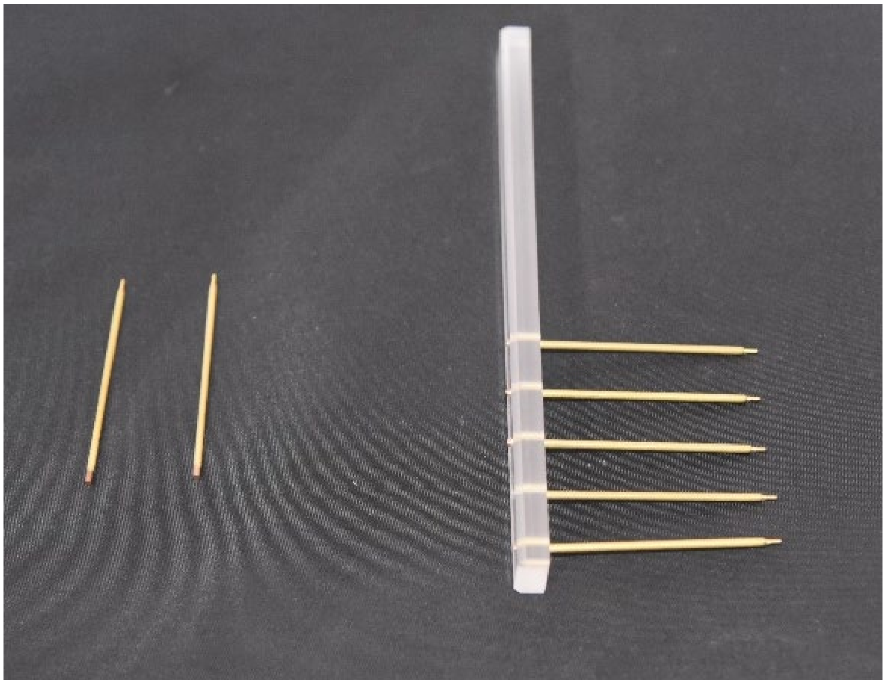


Figure 4
Piezoelectric pins in sample configuration

Photonic Doppler Velocimetry Probes

The specific details to implementing PDV can be of considerable importance, as there is potential to introduce additional sources of error if careful considerations are not made. All PDV probe beams are initially focused 4 in. from the bottom of the tube. It is important that the initial beam location is well known, as it is advantageous to avoid observing cylinder locations near explosive pellet interfaces when testing pressed samples. Locating a PDV beam on a pellet interface may introduce additional measurement error, as the ratio of cylinder mass to explosive charge mass (M/C) at that location may be different due to the presence of air gaps or inert pellet bonding material.

As PDV relies on Doppler-shifted light reflected off the cylinder's surface to determine its velocity, the initial angle of the probe relative to the cylinder must be carefully controlled and measured to accurately apply geometric corrections. While probes normal to the cylinder provide stronger initial backreflections (for initial alignment), steeper angles can better capture signal returns when the cylinder begins to expand. However, the alignment process will generally become more difficult with increasing probe angle. The alignment process is a necessary step during preparation, as it ensures any potential problems with the PDV probes are detected before testing and the instance of shock arrival is precisely captured. While measuring shock arrival is more critical when using the PDV probes as time-of-arrival (TOA) sensors, it is still best practice to attempt to optimize the initial backreflection. The alignment process involves connecting the PDV probe to a backreflection meter (DEVCOM AC uses an OZ Optics BM-100, 1550-nm wavelength, backreflection meter with -3 dBm output power) and then adjusting the probe until a satisfactory value is achieved. For DEVCOM AC, the PDV probes are rotated while a small amount of epoxy is used to secure the probes into place. The final setup after all PDV probes and piezoelectric pins are installed is shown in figure 3.

Energetic Pellets

The CYLEX pellets typically come in two variants depending on the desired testing diameter. The 1-in. diameter test pellets will be pressed to a 1.000 in. - 0.001-in. OD and a 1.14-in. length, while the 0.5-in. diameter test pellets will be pressed to a 0.5-in. OD and a 0.8-in. length. These pellet heights will locate the center of a pellet on the PDV observation plane given the aforementioned acrylic fixture. In the case of melt-casted materials, these are typically cast into split molds of 1.25 or 0.75 in. for the 1-in. and 0.5-in. tests, respectively. The billets are then machined to the same diameter as the pressed pellets before being loaded into the cylinder. Cast cures are loaded directly into the copper cylinders regardless of which testing diameter is being performed. In all cases, radiographic inspection is recommended to inspect porosity, void content, and potential density gradients within the material.

Specific to pressed pellets, pressing studies have been performed on granular materials prior to conducting the CYLEX test so that characteristics such as spring back have been quantified and are accounted for. However, growth over longer durations, particularly for melt-cast materials, is far less understood. As there is motivation to reduce the air gap between the pellet OD and tube ID, pellets are manufactured to tight tolerances and do result in rejected assets if the fit is unacceptable.

Process

While it is useful to specify all of the aforementioned details, outlining the general process is also important. First, a cylinder is selected and evaluated for geometric conformance to the specifications provided by the engineering drawings. All cylinder dimensions are then measured, and the sample explosive pellets are placed into the tube (if possible) to verify proper fit. The test fixture is then assembled, and the tube is properly secured to the fixture. Individual pellets are then added to the tube in a predetermined order to account for density fluctuations between pellets. Lower density pellets are prioritized toward the top of the cylinder to increase sensitivity and subsequently promote a rapid transition to detonation. The PDV probes are then secured to the acrylic fixture and aligned to the outer surface of the copper cylinder. In order to ensure the PDV probes are firmly set, a rest period of at least 30 min is required prior to moving the test sample. Additional run-up sample pellets, booster pellets, and an RP-80 exploding bridgewire (EBW) detonator are then added to the top of the sample and secured to both the acrylic fixture and each other. Run-up lengths are specified so that a steady detonation front is sustained in the sample before entering the copper cylinder. The standard 1-in. test typically requires 4 in. of run-up to ensure the detonation front is stable upon reaching the first piezoelectric pin. The booster material may vary, but it is typically a

90%+ nitramine formulation such as PBXN-5 or Composition (Comp) A-3 Type II. Test equipment parameters and other information are provided in appendix B.

The test sample is then moved into the testing chambers where it is placed within a firing pot to protect the wall of the chambers from the copper tube and simultaneously raise the test sample off the floor of the chamber. The PDV cables are then run to the instrumentation room and the piezoelectric pins are placed into contact with the cylinder. When all test setup is complete, the detonator is wired and the chamber doors are shut. An example test setup is pictured in figure 5. Prior to firing, all active diagnostic techniques are verified to be functioning via a series of pretest checks to minimize the potential for lost data due to equipment failure.

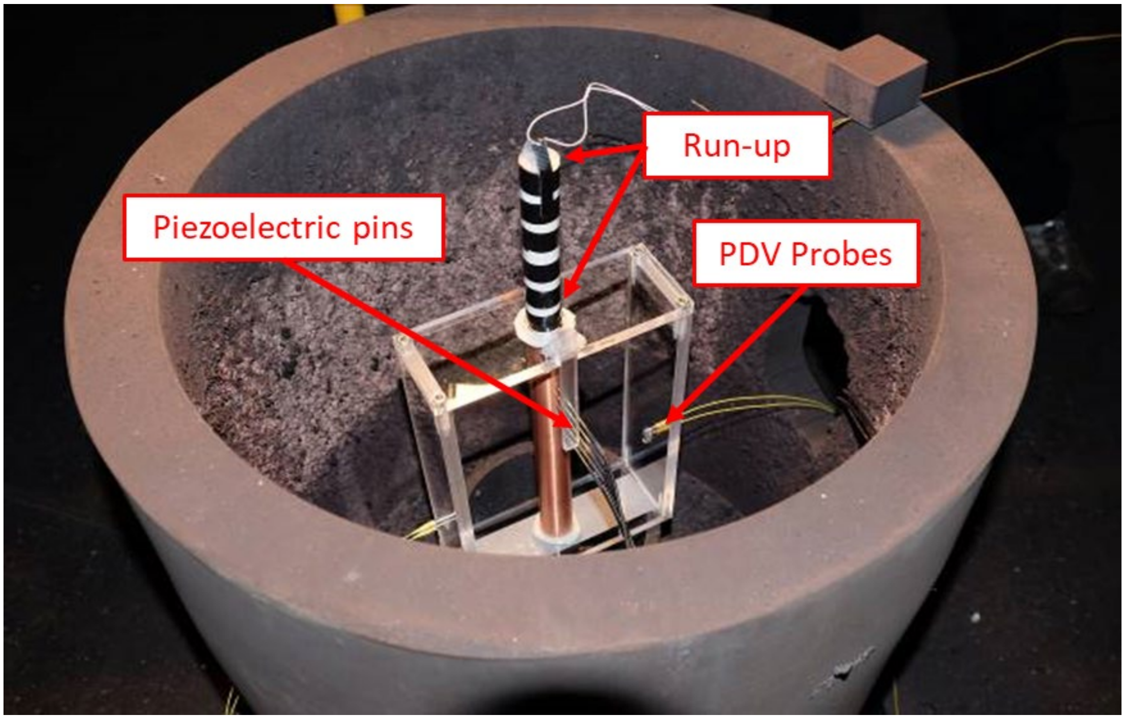


Figure 5
Example 1-in. CYLEX test setup

RESULTS AND DISCUSSION

Each test of the CYLEX experiment will capture four to eight channels of PDV data, which directly corresponds to the number of PDV probes in use for the test. The captured PDV data is simply a voltage response from the system’s optical receiver that will need to be properly transformed into frequency space to reveal the cylinder velocity measurements. An example of the raw oscilloscope output is displayed in figure 6. Due to the large file sizes inherent to a high sampling rate oscilloscope, the data is typically clipped so that only the active part of the experiment is saved, as much of the captured window is not directly relevant to the experiment. This greatly reduces the data storage requirements, though if something odd is noticed, a larger file size may be recorded. As a standard practice, the data will also be stored in the native format of the oscilloscope in case further review is necessary at a later data.

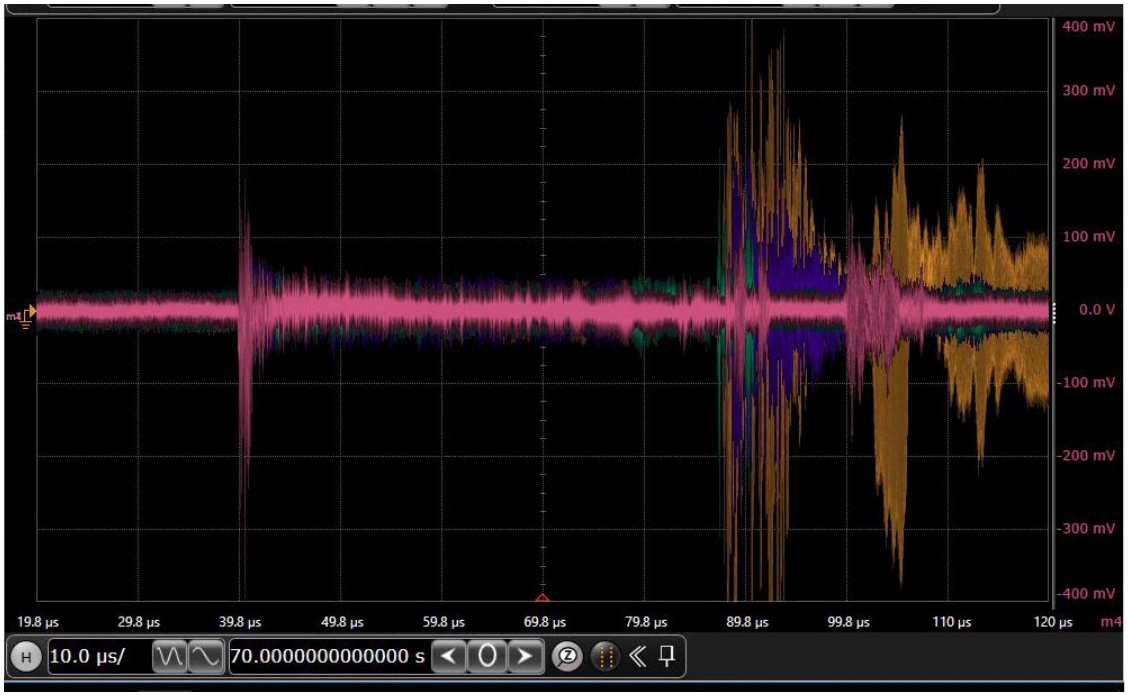


Figure 6
Raw oscilloscope data (clipped)

All raw voltage output signals are then transferred to AnalyzeData, a signal processing program developed at Los Alamos National Laboratory, Los Alamos, NM (ref. 10). This program is a useful tool that visualizes the reduction process by running a fast Fourier transform (FFT) to create a spectrograph, which can then be used to graphically isolate the cylinder velocity curve. Figure 7 shows the spectrograph of a CYLEX test. After the velocity curve is isolated and recorded, the velocity data is then transferred to an in-house MATLAB script to perform final calculations. The details of the analytical portion of the script are provided in appendix C.

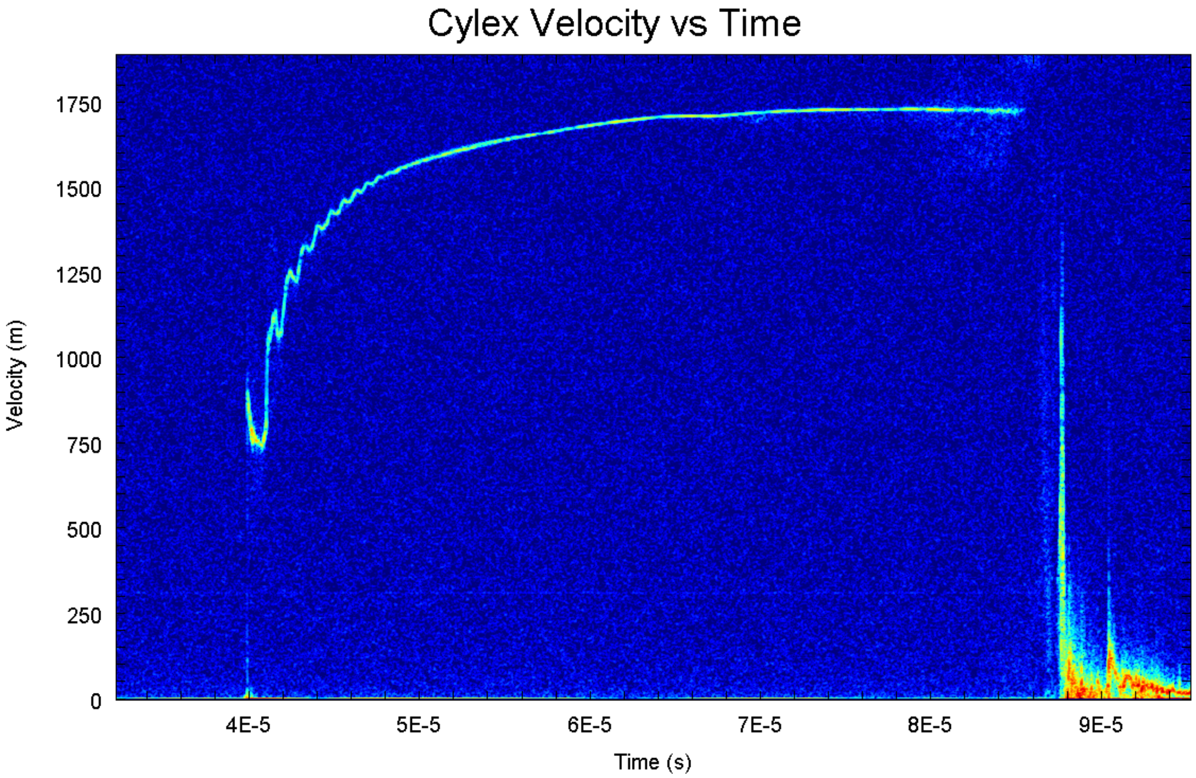


Figure 7
Example spectrograph of a CYLEX test showing velocity versus time

As there is still a significant amount of data from each channel, the data is condensed and subsequently summarized depending on the needs of the specific program. Generally, energetic formulation programs prefer to have the Gurney constants of a specific formulation reported at volume expansions of 2, 3, 5, 7, and 10 (some DoD customers instead prefer data at 2.4, 4.4, and 7 volume expansions). These points are averaged across all channels for each test, as well as across all tests (since more than one is typically performed on each material) before being reported to the customer. A typical output graph is shown in figure 8.

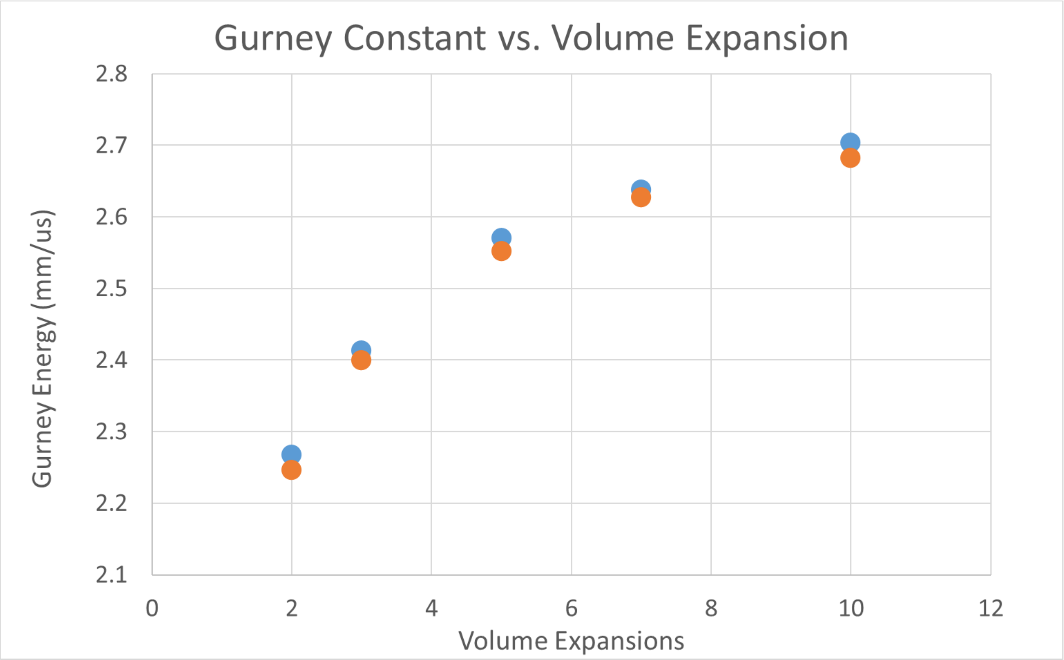


Figure 8
Example Gurney constant versus volume expansion graph

While PDV has replaced streak cameras as the standard for CYLEX testing for DEVCOM AC, it is worth mentioning that the data captured by streak cameras will always result in higher cylinder velocities when compared to PDV. This can be shown via geometric relations regarding what each technique is capable of measuring. Using figure 9 as a reference, various geometric relationships can be built to translate the data from one form to another, though it will assume that various test parameters were measured during experimentation (such as detonation velocity). While a detailed derivation is beyond the scope of this report, four equations are provided (ref. 11).

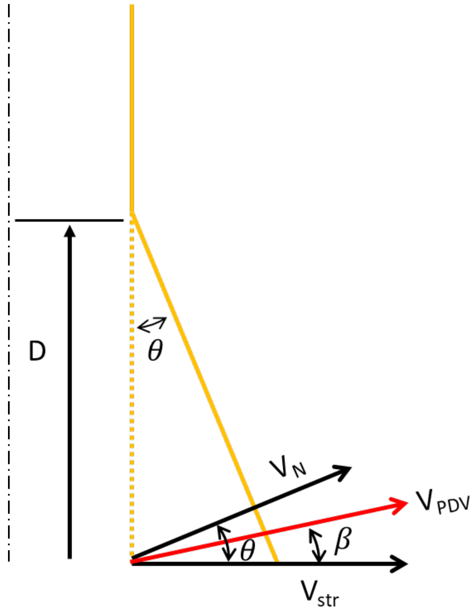


Figure 9
CYLEX test, velocity components

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$$V_{STR} = Dtan\theta \tag{1}$$

$$V_{STR} = \frac{V_N}{cos\theta} \tag{2}$$

$$V_{PDV} = \frac{V_N}{cos(\theta - \beta)} \tag{3}$$

$$\theta = \tan^{-1}\left(\frac{cos\beta}{\frac{D}{V_{PDV}} + sin\beta}\right) \tag{4}$$

D is the measured detonation velocity, V_{STR} is the measured streak camera velocity, V_{PDV} is the measured PDV probe velocity, β is the angle between V_{STR} and V_{PDV}, V_N is the particle velocity component normal to the cylinder wall, and θ is the total wall angle. These relationships can then be used to relate the two different data collection techniques.

CONCLUSIONS

The cylinder expansion (CYLEX) test is an important characterization experiment performed on a regular basis at the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC), Picatinny Arsenal, NJ. While there are multiple ways of running the CYLEX test in regard to diagnostic techniques, the methodology currently employed at the Explosive Development Facility (EDF) at Picatinny Arsenal was detailed herein. The procedures necessary to accommodate specific material callouts were discussed and the details regarding how the dimensional data was captured is also explained. The photonic Doppler velocimetry (PDV) probe setup and general procedure were also conveyed.

Since there is still considerable freedom in analytical choices after PDV data has been collected, the data reduction methodology was reviewed for clarity to improve repeatability across laboratories. The common outputs were reviewed and discussed, which are used as a quantitative measure of relative energetic performance particular to Department of Defense interests.

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APPENDIX A
ENGINEERING DRAWINGS

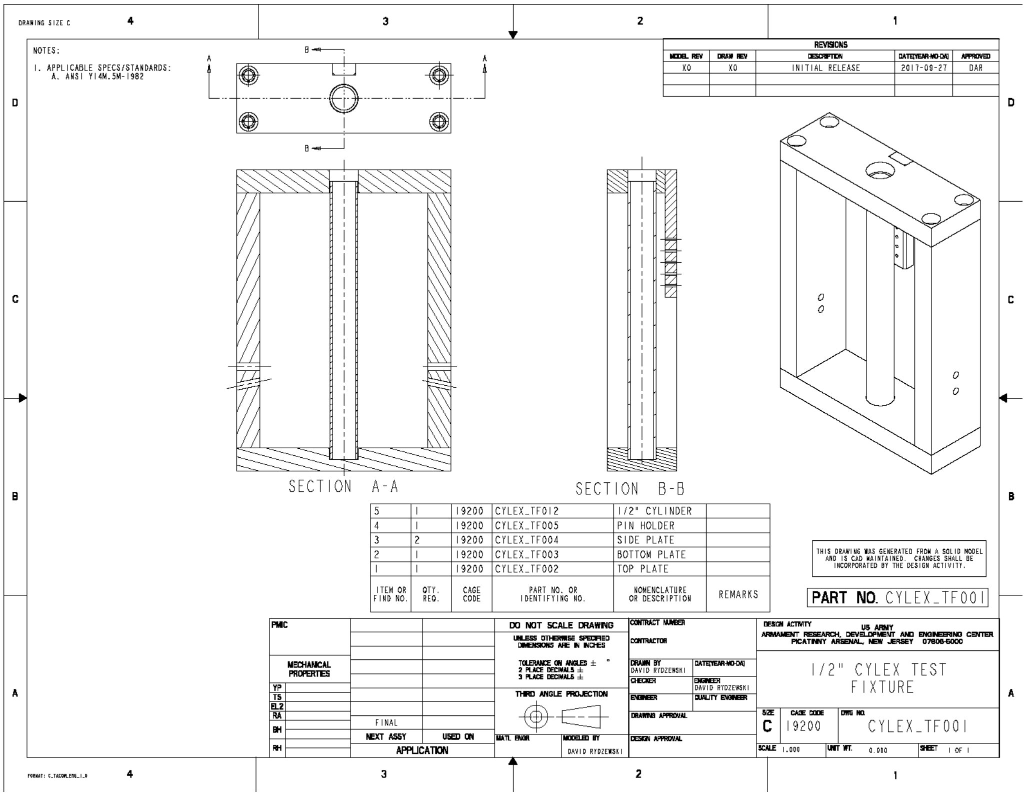


Figure A-1
1/2-in. CYLEX test fixture, assembly

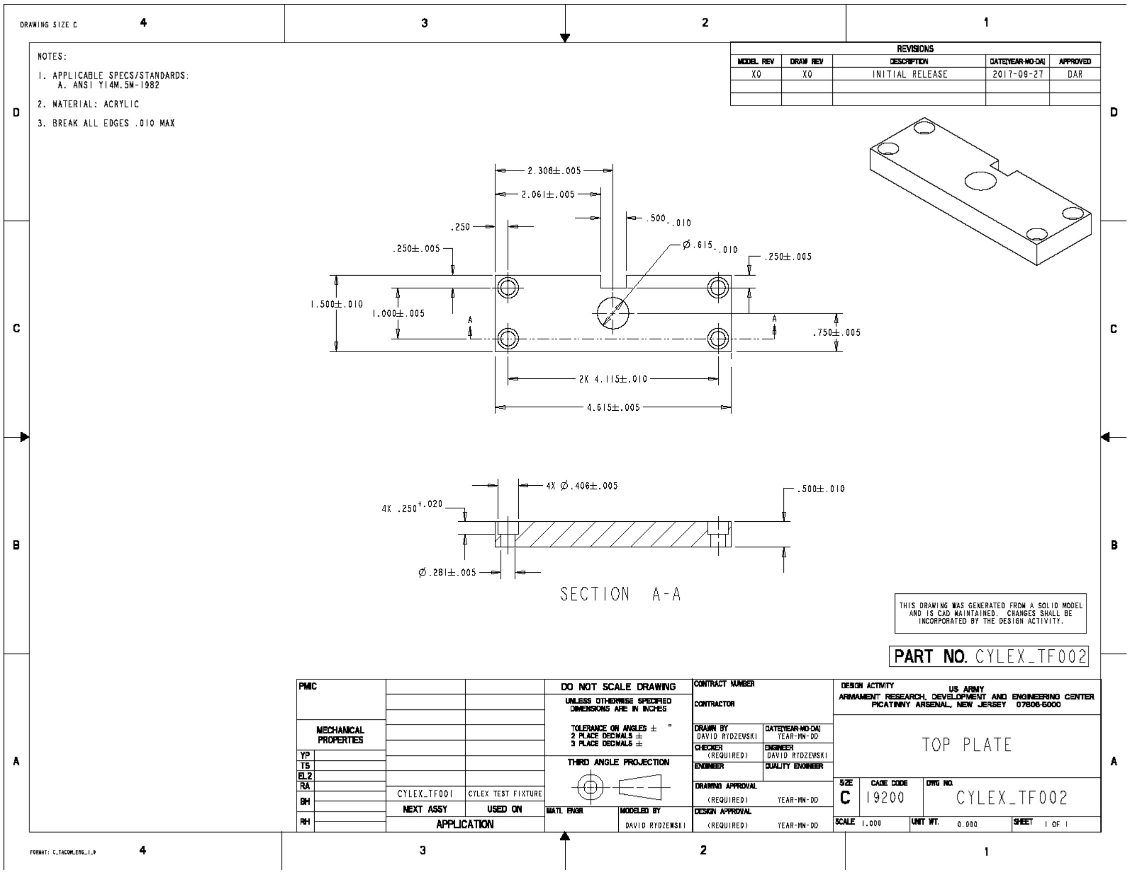


Figure A-2
1/2-in. CYLEX test fixture, top plate

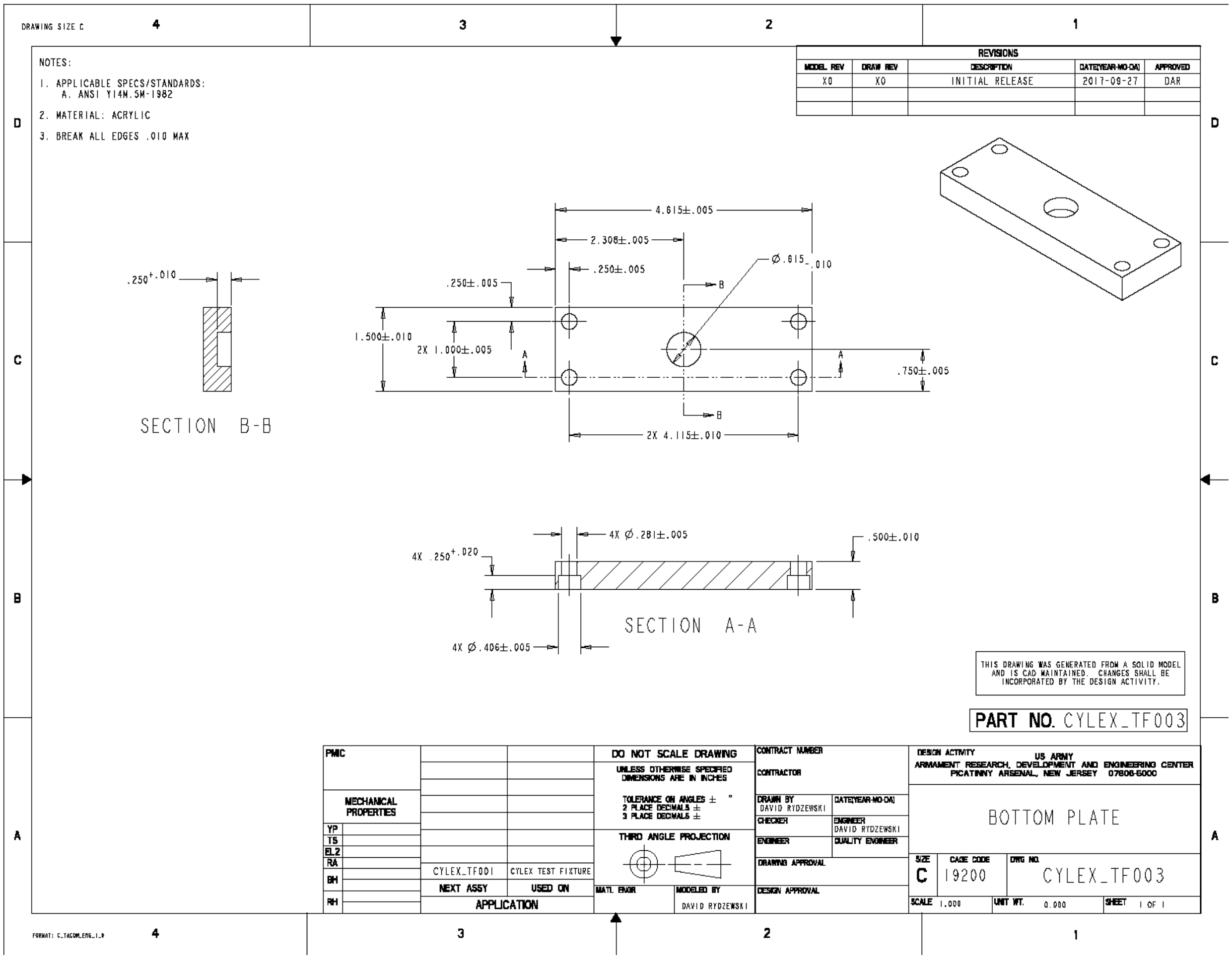


Figure A-3
1/2-in. CYLEX test fixture, bottom plate

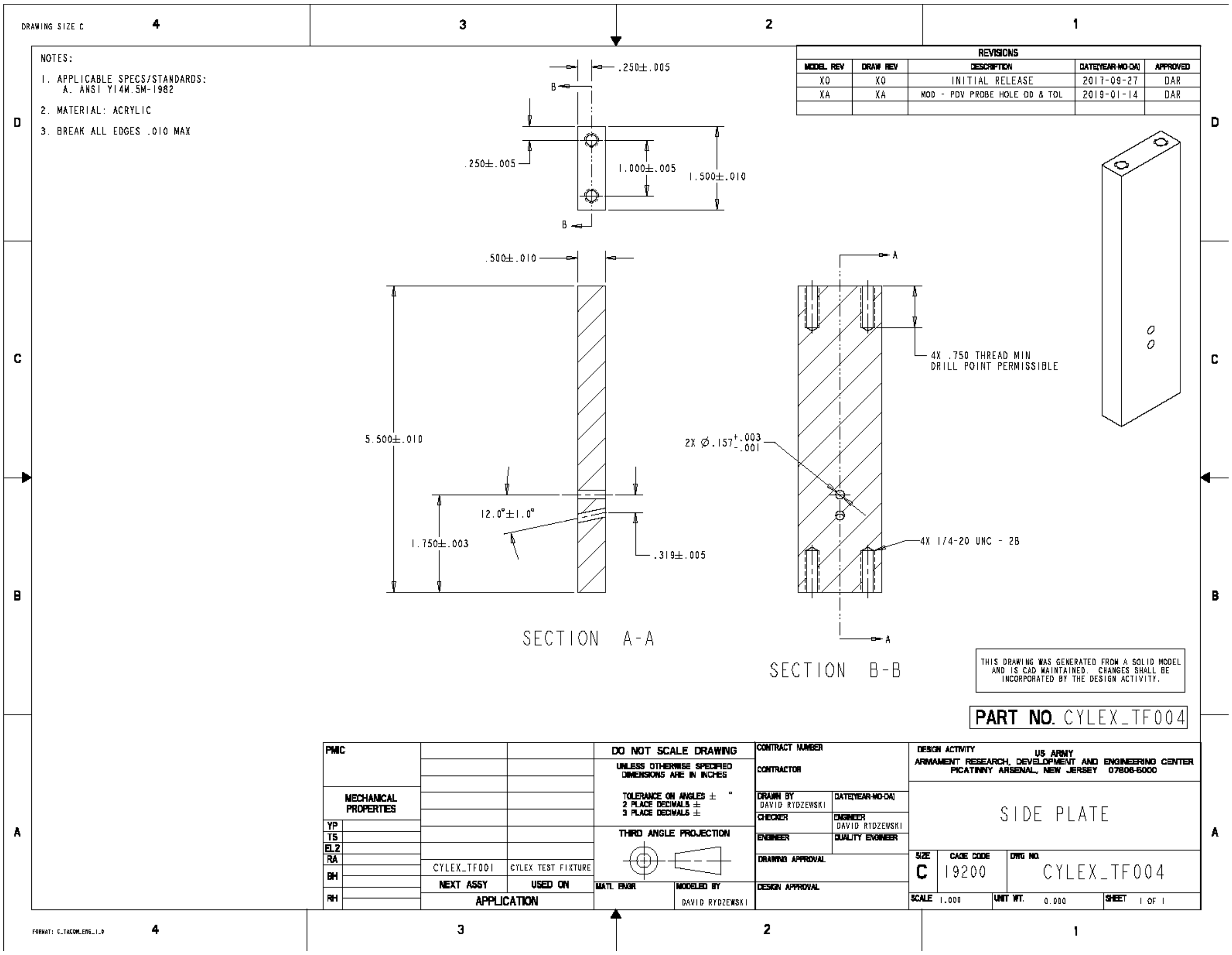


Figure A-4
1/2-in. CYLEX test fixture, side plate

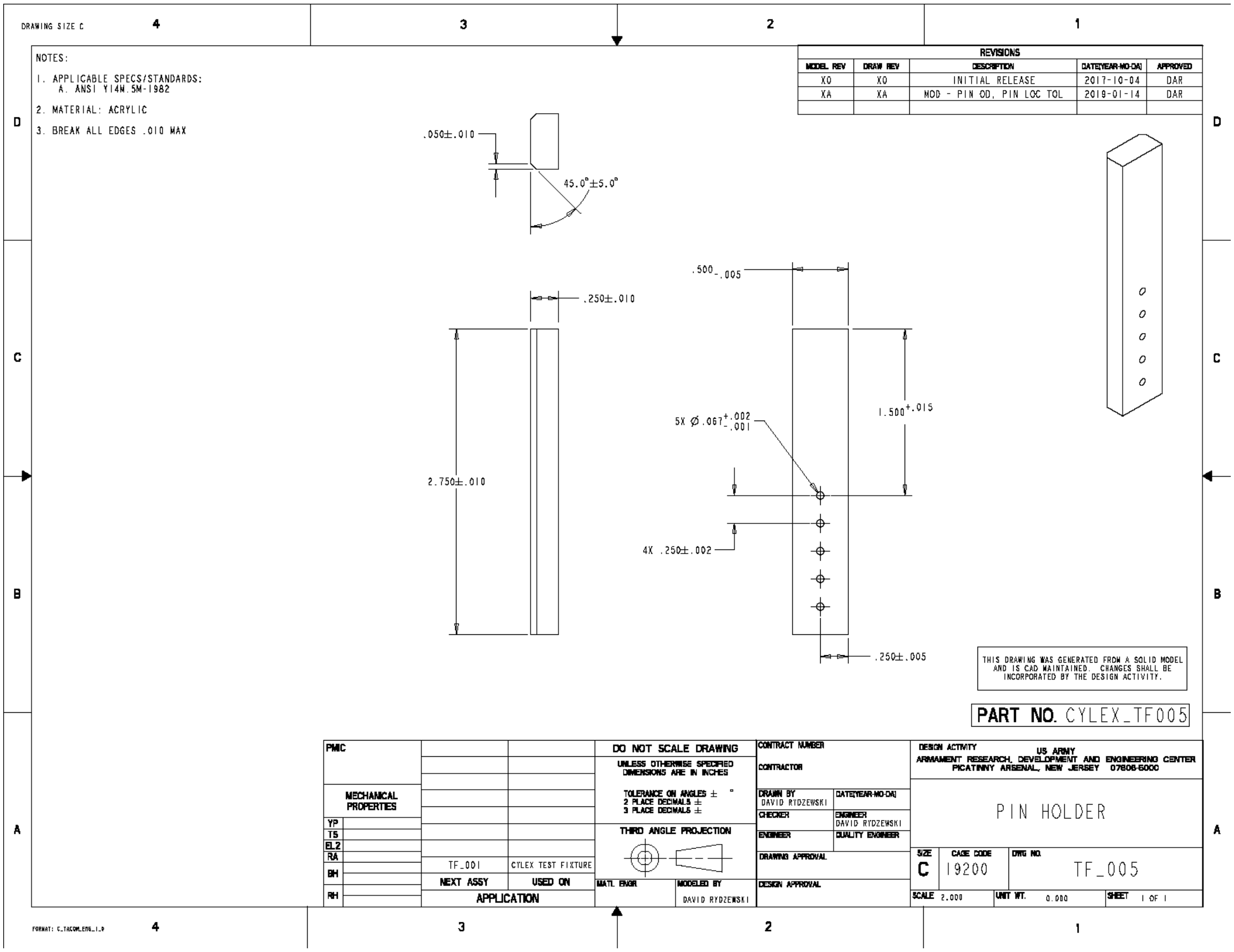
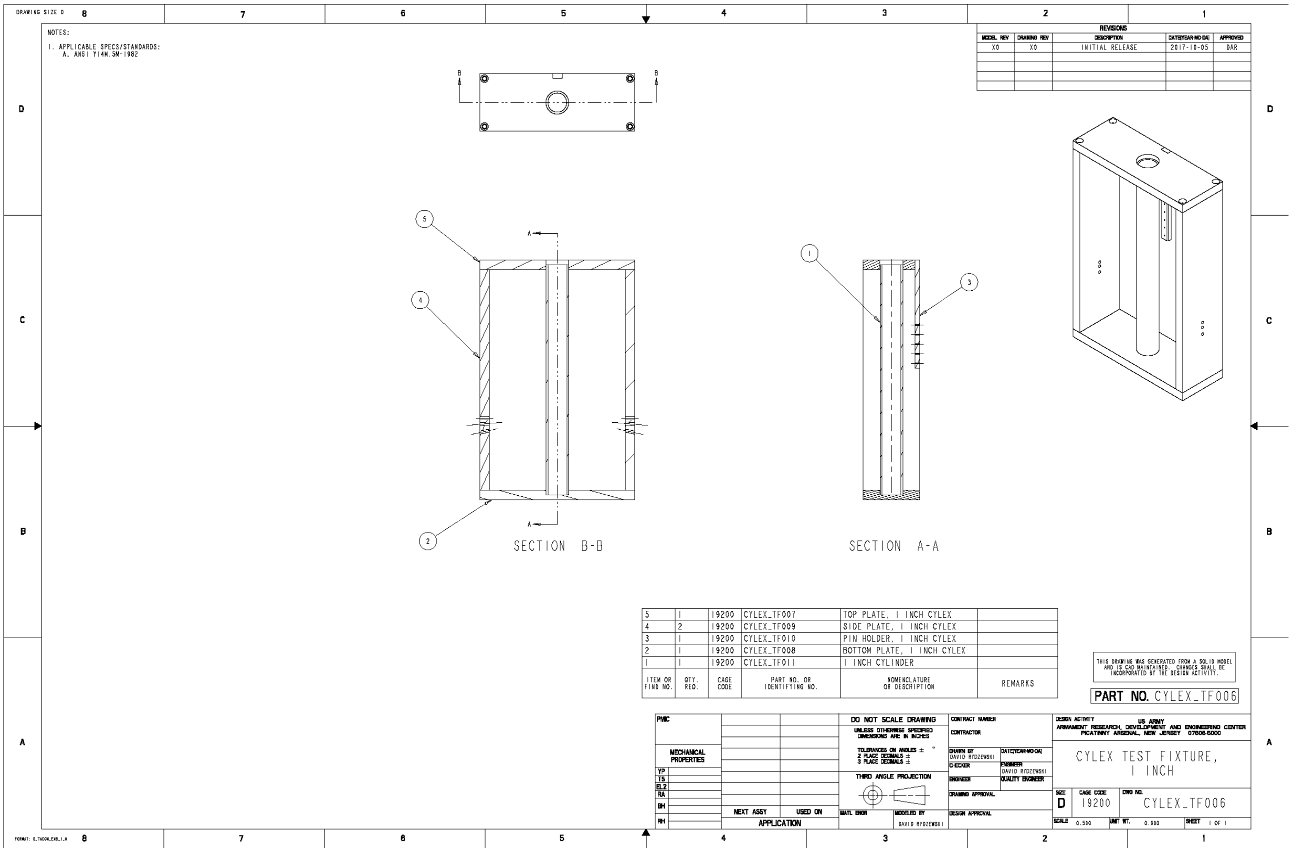


Figure A-5
1/2-in. CYLEX test fixture, pin holder



NOTES:

1. APPLICABLE SPECS/STANDARDS:
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REVISIONS

MODEL REV	DRAWING REV	DESCRIPTION	DATE(YEAR-MO-DA)	APPROVED
X0	X0	INITIAL RELEASE	2017-10-05	DAR

ITEM OR FIND NO.	QTY. REQ.	CAGE CODE	PART NO. OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	REMARKS
5	1	19200	CYLEX_TF007	TOP PLATE, 1 INCH CYLEX	
4	2	19200	CYLEX_TF009	SIDE PLATE, 1 INCH CYLEX	
3	1	19200	CYLEX_TF010	PIN HOLDER, 1 INCH CYLEX	
2	1	19200	CYLEX_TF008	BOTTOM PLATE, 1 INCH CYLEX	
1	1	19200	CYLEX_TF011	1 INCH CYLINDER	

THIS DRAWING WAS GENERATED FROM A SOLID MODEL AND IS CAD MAINTAINED. CHANGES SHALL BE INCORPORATED BY THE DESIGN ACTIVITY.

PART NO. CYLEX_TF006

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MECHANICAL PROPERTIES
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NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON ANGLES ± °
2 PLACE DECIMALS ±
3 PLACE DECIMALS ±
MATL ENGR
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Figure A-6
1-in. CYLEX test fixture, assembly

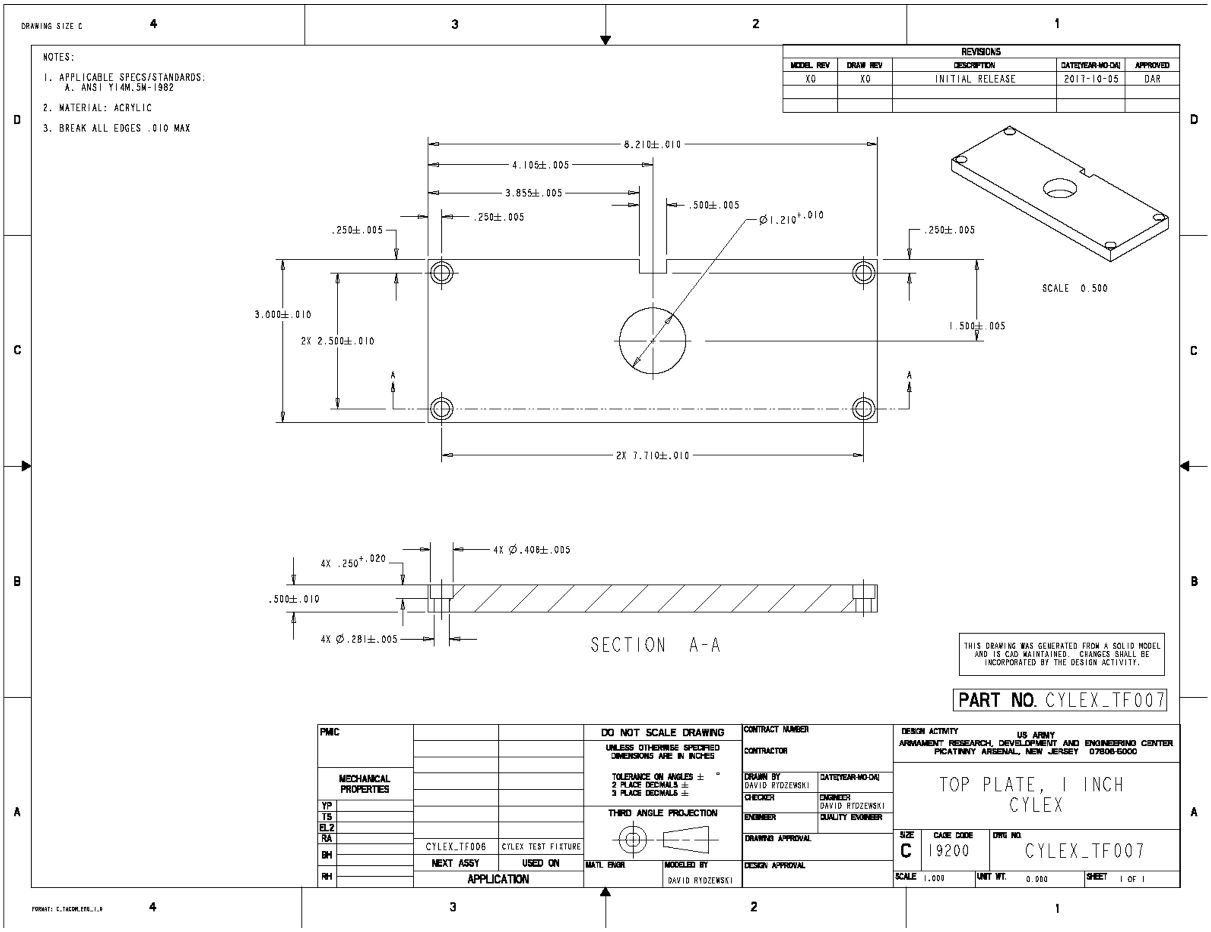

Figure A-7
1-in. CYLEX test fixture, top plate

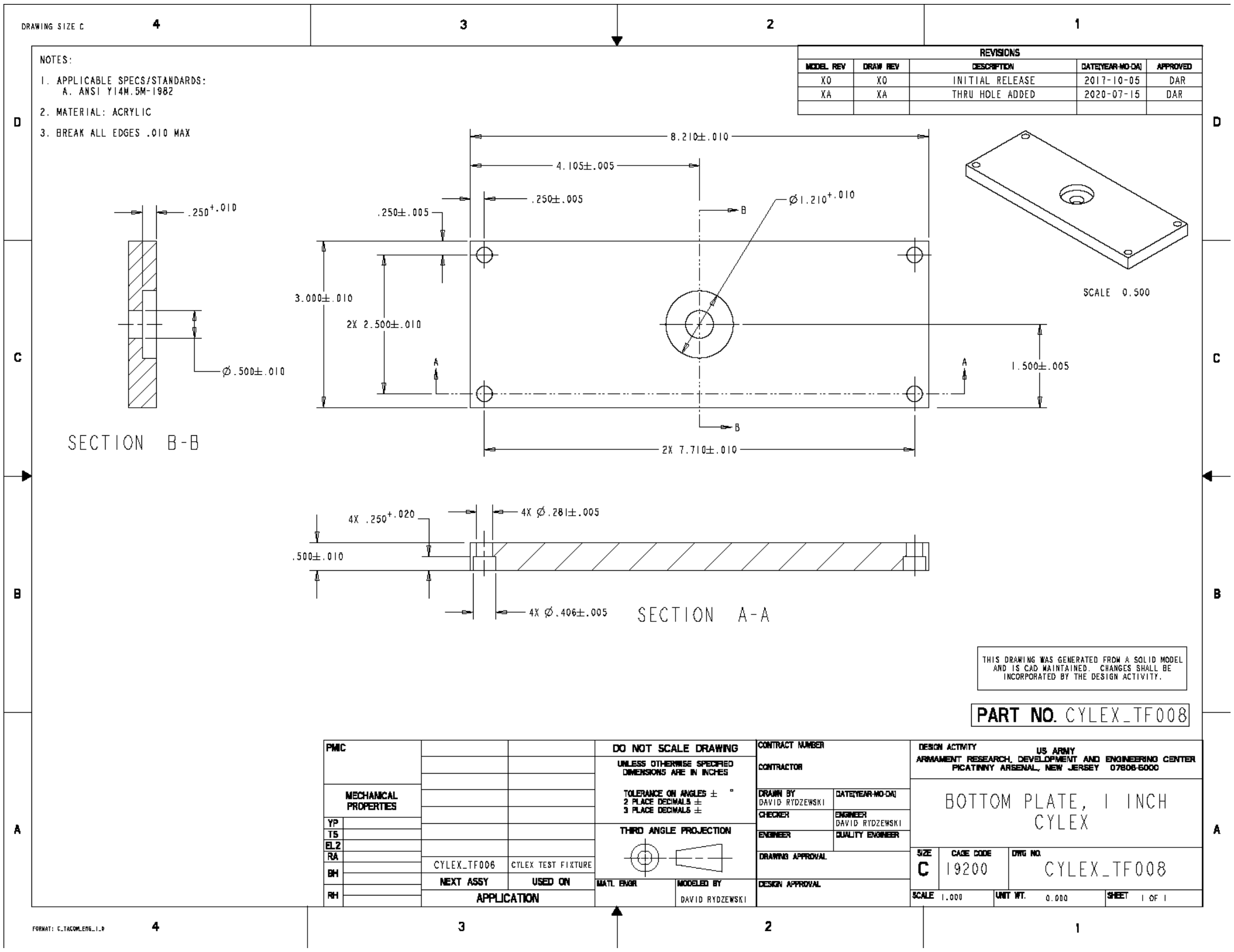

Figure A-8
1-in. CYLEX test fixture, bottom plate

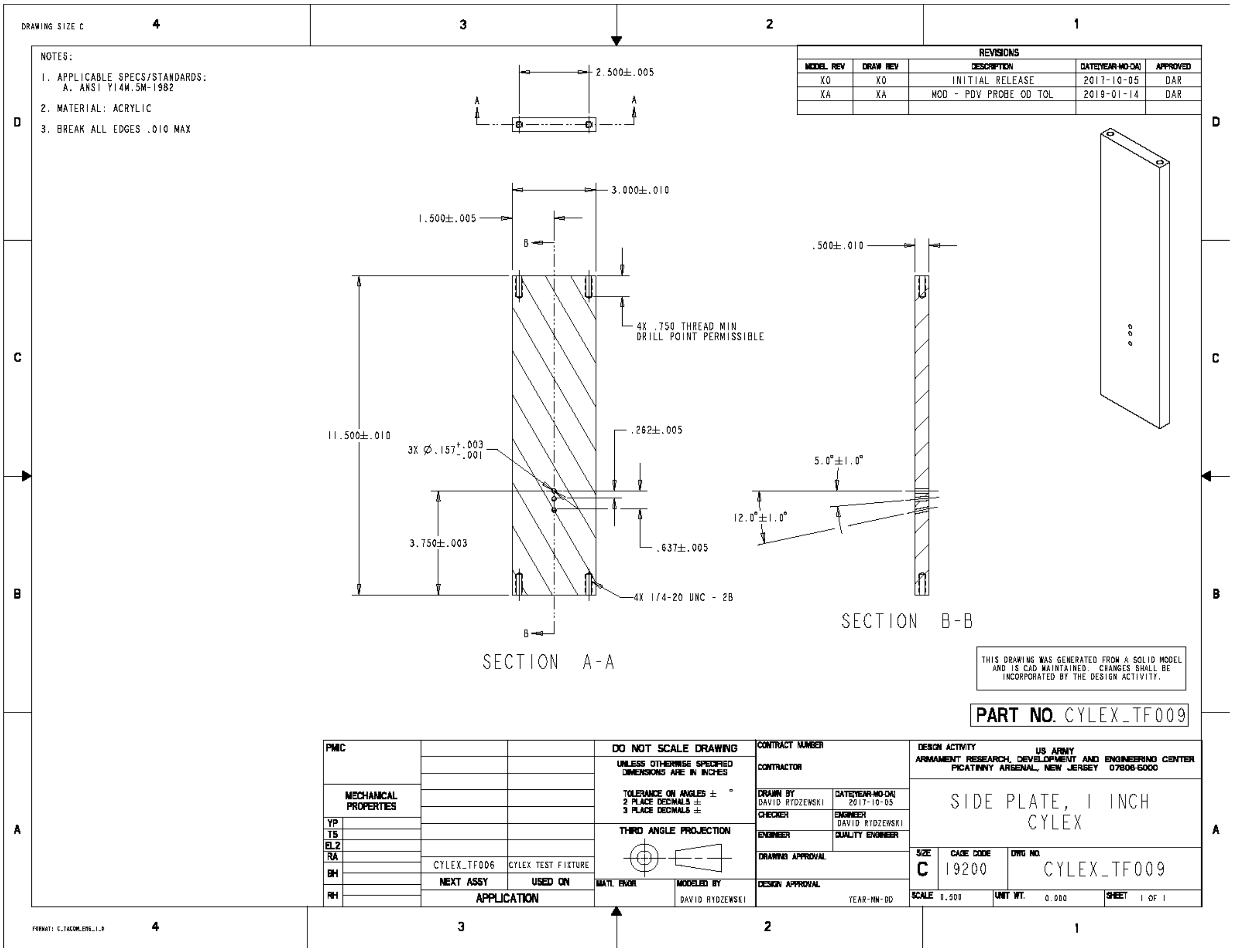

Figure A-9
1-in. CYLEX test fixture, side plate

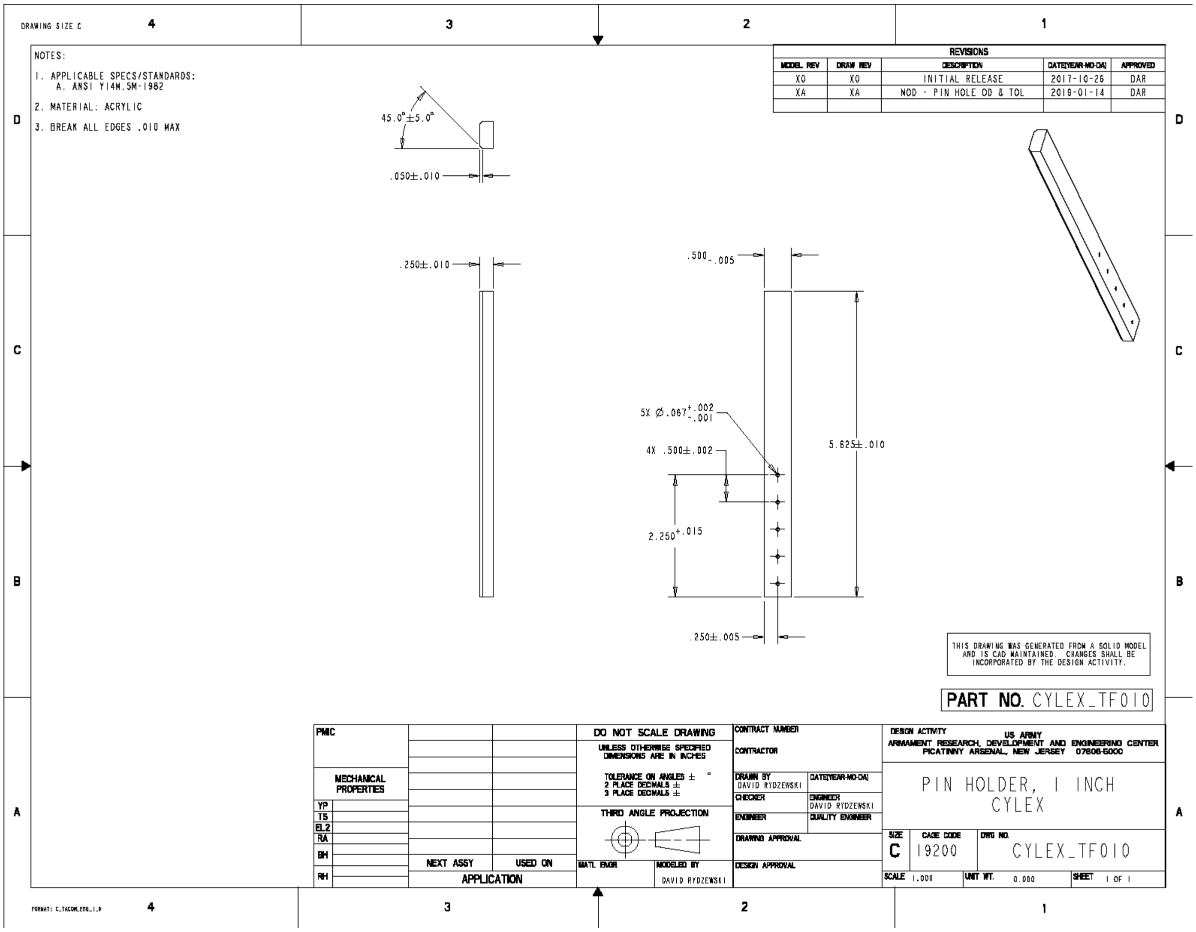

Figure A-10
1-in. CYLEX test fixture, pin holder

APPENDIX B
TEST EQUIPMENT

Table B-1
Test equipment parameters and other information

Oscilloscope	UXR0204A (20Ghz, 128GS/s, 10-bit)	Scope settings (typical): 64 GS/sec sampling rate 50 µs/div (500 µs total) 200 mV/div 1 V trigger aux voltage
Laser(s)	IPG fiber laser (old)	Laser power: 1.5 W output (typically split evenly among eight channels)
	Setup: NKT ADJUSTIK	Wavelength: 1550.12 nm Output: 40 mW
	NKT BOOSTIK (2 W)	Current: 6A ~1.5 W (split evenly among eight channels)
Optical receiver	SCM fiber optic receiver	Manufacturer: Narda-MITEQ
Piezoelectric pins	CA-1135	Manufacturer: Dynasen
Detonator	RP-80	Manufacturer: Teledyne RISI

APPENDIX C
MATLAB SCRIPTS

Note: This script has been edited to reduce the length showing primarily the analytical portions of the script. Some commentary has been left to increase readability.

```
% KNOWNS:
% Probe Angle [PHI]
% Detonation Velocity [D]
% Probe Velocity [PDVdata]

% UNKNOWNS:
% Wall Angle [WA]
% Axial Particle Velocity [U]
% Radial Particle Velocity [V]

syms wa u v

WA = zeros(TotalPoints-1,1);
Time = zeros(TotalPoints-1,1);
U = zeros(TotalPoints-1,1);
V = zeros(TotalPoints-1,1);

count = 1;


% Gwa, Gu and Gv are simply initial guesses for wall velocity, axial
% velocity and radial velocity, respectively. This is just an attempt to
% quicken the computational speed

for i = 2:1:TotalPoints
    Gwa = (0.004*PDVdata(i,1)) + 0.096;
    Gu = (0.01*PDVdata(i,1)) + 0.08;
    Gv = (0.034*PDVdata(i,1)) + 0.8;
    S = vpasolve([PDVdata(i,2) == sqrt((v^2)+(u^2))*cos((wa/2)-PHI),tan((wa/2))
== (u/v),tan(wa) == (v/(D+u))],[wa,u,v],[Gwa,Gu,Gv]);
        WA(count,1) = abs(S.wa)*(180/pi);
        Time(count,1) = PDVdata(i,1);
        U(count,1) = abs(S.u);
        V(count,1) = abs(S.v);
            count = count+1;
            waitbar(count/TotalPoints,h)
end



% Determining Total Particle Velocity of the Wall

Final(:,1) = sqrt((U(:,1).^2) + (V(:,1).^2));


% Calculating Gurney Energy/Constant
% This is simple Gurney Energy. It does not account for wall-thinning,
% axial losses, or any additional losses

count = 1;
Gurney = zeros(length(Time),1);
    for i = 2:1:TotalPoints
        Gurney(count,1) = Final(i-1,1)/sqrt(1/((weightCU/weightHE)+(1/2)));
        count = count+1;
```

```
    end

% Calculating Distance and Area Expansion

% This code should work for any PDV probe angle.

% The Total Particle Velocity data is curve fit with a cubic spline
% function and then integrated to determine Total Particle Motion (axial
% and radial motion) as a function of time. This total distance is then
% geometrically modified to determine the radial and axial position of the
% PDV beam spot for any PDV probe angle.


Vfinal = csapi(Time(:,1),Final(:,1));

Dfinal = zeros(length(Time),1);

for i = 1:1:length(Time)
   Dfinal(i,1) =
integral(@(Time)ppval(Vfinal,Time),min(Time(:,1)),max(Time(i,1)));

end

Dwall = zeros(length(Time),1);
Xwall = zeros(length(Time),1);
Ywall = zeros(length(Time),1);
AreaExp = zeros(TotalPoints-1,1);

PHI = PHI*(180/pi);

for i = 1:1:length(Time)
    if 0 <= PHI < (WA(i,1)/2)
        Dwall(i,1) = (Dfinal(i,1)/sind(90-WA(i,1)+PHI)) * sind(90+(WA(i,1)/2));
        Xwall(i,1) = Dwall(i,1) * sind(90-PHI);
        Ywall(i,1) = Dwall(i,1) * sind(PHI);
        AreaExp(i,1) = ((((Xwall(i,1)/25.4)+(ActualOD/2))^2)-
((ActualOD/2)^2)+((ActualID/2)^2))/((ActualID/2)^2);

    elseif PHI == (WA(i,1)/2)
        Dwall(i,1) = Dfinal(i,1);
        Xwall(i,1) = Dwall(i,1) * sind(90-(WA(i,1)/2));
        Ywall(i,1) = Dwall(i,1) * sind((WA(i,1)/2));
        AreaExp(i,1) = ((((Xwall(i,1)/25.4)+(ActualOD/2))^2)-
((ActualOD/2)^2)+((ActualID/2)^2))/((ActualID/2)^2);

    else
        Dwall(i,1) = (Dfinal(i,1)/sind(90-PHI+WA(i,1))) * sind(90-(WA(i,1)/2));
        Xwall(i,1) = Dwall(i,1) * sind(90-PHI);
        Ywall(i,1) = Dwall(i,1) * sind(PHI);
        AreaExp(i,1) = ((((Xwall(i,1)/25.4)+(ActualOD/2))^2)-
((ActualOD/2)^2)+((ActualID/2)^2))/((ActualID/2)^2);

    end
end
```

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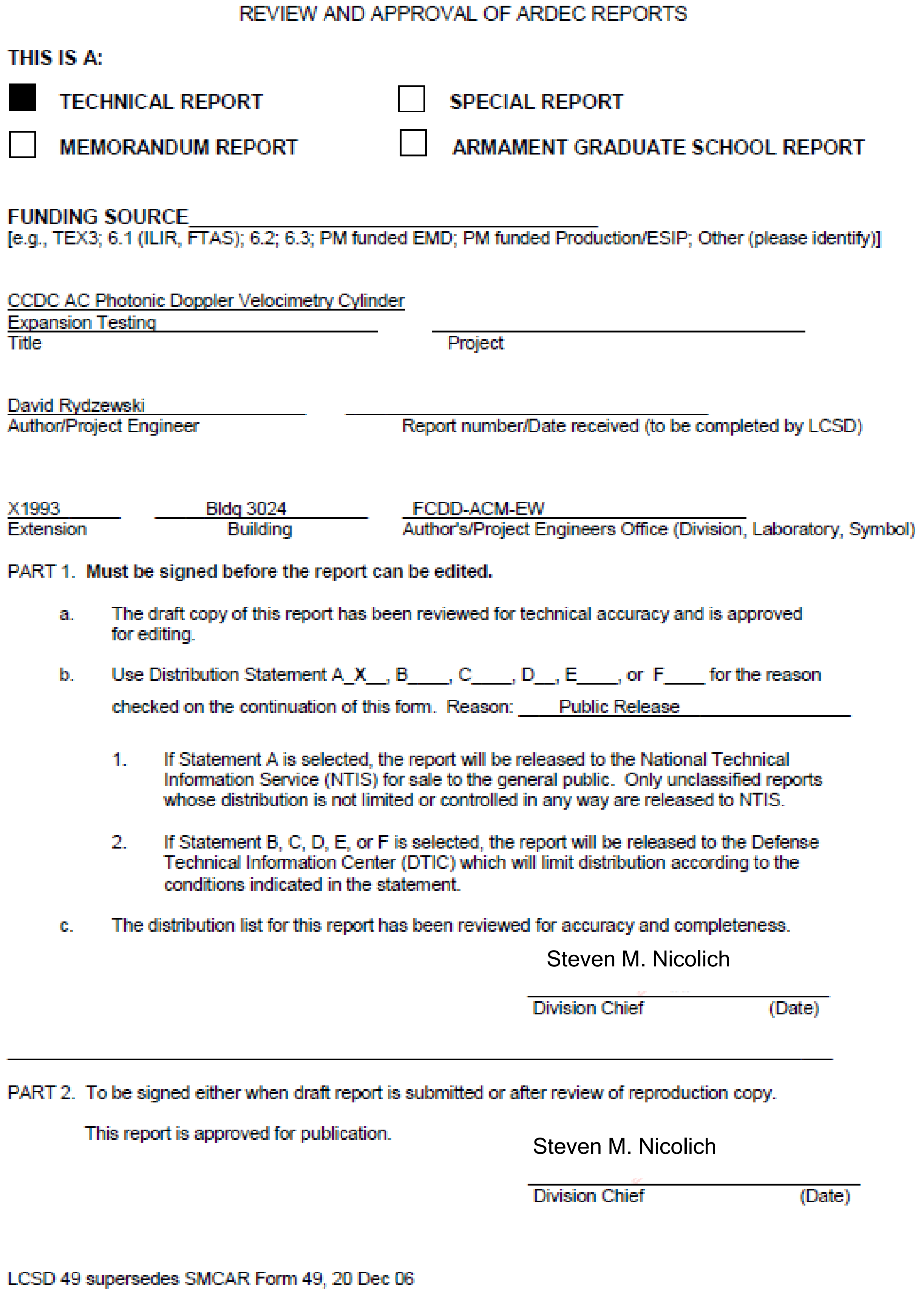

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