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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND (DEVCOM) ARMAMENTS CENTER (AC) CLOSED BOMB REDUCTION ANALYSIS (CIoBRA) – USER'S MANUAL

Christopher Houthuysen
Carlton Adam
Oscar De Leon

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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMAMENTS CENTER

Munitions Engineering Technology Center

Picatinny Arsenal, New Jersey

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14. ABSTRACT
        The U.S. Combat Capabilities Development Command Armaments Center Closed Bomb Reduction Analysis (CloBRA) program, Picatinny Arsenal, NJ, has been developed to reduce closed bomb test data using a refined, user-friendly, and interactive approach. The program has been shown to produce consistent results with legacy closed bomb codes and includes new features to support future closed bomb testing efforts. These features include a burn table feature, which allows users to analyze geometries that don't adhere to analytical form functions, and a pressure-time curve generator, which allows users to construct a closed bomb pressure-time curve based on governing parameters. The documentation herein discusses the governing equations and theory utilized in the code and also provides a detailed walkthrough of the CloBRA program such that it can be readily used upon installation.

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FOREWORD

This report was written to support the use of the U.S. Army Combat Capabilities Development Command Armaments Center Closed Bomb Reduction Analysis Program. Any comments or questions should be directed to Christopher Houthuysen at christopher.a.houthuysen.civ@mail.mil or 973-724-4551.

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BACKGROUND

Solid propellants can be defined as energetic materials that are typically used in gun and rocket propulsion systems. During combustion, these propellants produce high pressure/temperature gases that are used to accelerate the projectile of a weapon system or provide thrust for a rocket system. For both applications, it is very important for engineers to understand how propellants deflagrate when subjected to an ignition stimuli as over-pressurization or complex pressure wave phenomena can reap serious consequences on propulsion system designs. In order to ensure that propellants burn evenly and reliably, engineers test the burn rate characteristics of propellants through a wide array of methods, one of which is closed bomb testing.

Closed bombs are rigid structures that contain piezoelectric sensors to capture the pressure-time data of propellants during combustion. The pressure-time trace of solid propellants is of significant importance as experiments have shown that the burn rate of solid propellants is directly related to the pressure at which combustion takes place. From thermodynamic theory, the experimentally collected pressure-time curve and the time derivative of pressure can be used to determine the burn rate of solid propellant and the gas generation rate, respectively. Due to the extensive number of data points collected during closed bomb testing, determining the aforementioned parameters via hand calculations is an unfeasible task, and thus closed bomb data reduction codes have been written to perform this feat.

PURPOSE

This paper documents the U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC) Closed Bomb Reduction Analysis (CloBRA) program at Picatinny Arsenal, NJ, which is a comprehensive computer program used to reduce and analyze collected closed bomb test data. The program offers three distinct features, which are essential for closed bomb related analyses. The first feature is a traditional burn rate analysis, which determines the linear burn rate of a propellant based on the collected experimental pressure-time trace and the propellant's thermochemistry. The second feature is a relative measurements analysis, which is used to compare the relative force (RF), relative quickness (RQ), and relative vivacity (RV) of a test propellant to a given reference propellant. The third feature is a pressure-time curve generator that can be used to predict the pressure-time curve of a given formulation or also to compare predicted pressure-time trace results against experimental data.

While several closed bomb data reduction analysis programs have been developed in the past, such as the legacy Armament Research Development and Engineering Center (ARDEC) Closed Bomb Analysis (CBA) program (ref. 1), Closed Bomb Data Reduction Program (CBRED) (ref. 2), Ballistic Research Laboratory Closed Bomb (BRLCB) (ref. 3), and Excel Closed Bomb (XLCB) (ref. 4), the DEVCOM AC CloBRA program offers a refined, user-friendly, and interactive approach to reducing closed bomb test data. Some of these refined features are discussed in the following:

1) <u>Graphical User Interface (GUI) Display Window:</u> In lieu of interacting with complex lines of coding, the user is prompted to enter all of their data parameters into a detailed GUI window. Additionally, the user is provided with an option to import an input deck to populate the appropriate fields of the GUI vice manually entering data into each field. Sample template input decks are provided in this report in appendix A.

2) <u>Iterative Savitzky-Golay Filter Type:</u> Various closed bomb data reduction codes utilize differing filtering methodologies to smooth the experimental pressure-time data traces. Smoothing of the data is vital to the functionality of these closed bomb data reduction codes as it ensures that the time derivative of pressure is continuous in the calculation domain, which in turn allows the governing equations of the system to be solved accordingly at each time step of the analysis. Consistent with XLCB, a Savitzky-Golay filter type is used to smooth the pressure-time trace and also remove anomalous noise from it. However, CloBRA is programmed such that the filter can be iteratively adjusted throughout the analysis to ensure that the characteristic profile of the pressure-time curve is preserved. To elaborate, CloBRA produces a plot that demonstrates how the filtered pressure-time data compares to the raw data set. If the filter attenuates any of the characteristic features of the raw pressure-time trace, the user can iteratively adjust the filtering parameters accordingly.

3) <u>Interactive Vivacity versus Normalized Pressure Trace:</u> Prior to discussing this feature, it is important to first provide some relevant background information. Dynamic vivacity is an expression for the rate of gas generation. When vivacity is plotted against the normalized pressure trace of the data set, it provides insight as to how the burning surface is regressing with respect to pressure (e.g., burning in accordance with the form function of the solid propellant geometry). A sample vivacity versus normalized pressure plot for multiple propellant geometries is provided in figure 1, which was obtained from reference 5.
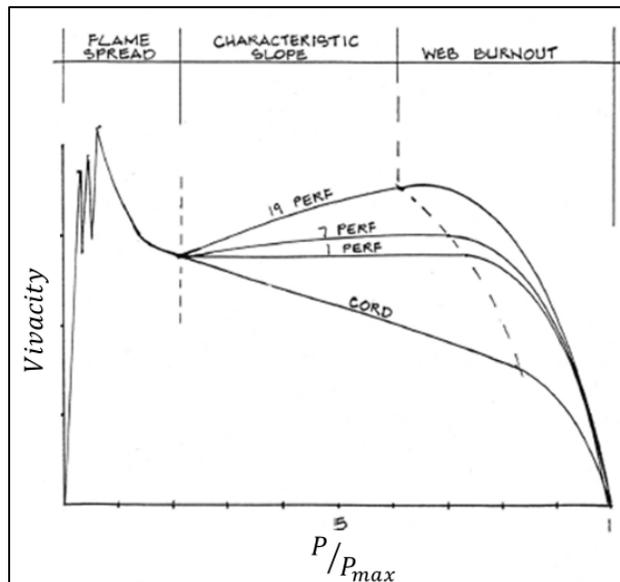
Figure 1
Sample vivacity versus normalized pressure plot for multiple propellant geometries

As shown in the figure, the vivacity versus normalized pressure plot can generally be broken up into three distinct regions: the flame spread, characteristic slope, and web burnout regions (i.e., where solid propellant slivering occurs). Of particular importance is the characteristic slope region since this is generally where all the propellant surface area is inflamed and burns according to Piobert's law (i.e., burning surface regresses layer-by-layer, in the direction normal to the

solid surface). In the characteristic slope region of the data trace, solid propellants are assumed to follow Vielle's law, which linearly relates the burn rate of a solid propellant to pressure on a log-log plot. The CloBRA program enables the user to visually inspect the vivacity versus normalized pressure plot and select the location of the characteristic slope region via their data cursor. The code then fits a best fit tangent line to the end points of the user's selection to further adjust this selection within some defined tolerance. Then, CloBRA uses this selected region to fit a trend line to the log(burn rate) versus log(pressure) plot to obtain the burn rate parameters defined in Vielle's law. This region can be further refined by the user later in the job-stream.

4) <u>Iterative Burn Rate Computations:</u> As alluded to previously, CloBRA enables the user to iteratively update the window region in which Vielle's law is implemented on the log(burn rate) versus log(pressure) plot. The GUI displays a coefficient of determination (R-squared) value associated with the linear fit in this window region. If the corresponding coefficient of determination is not sufficient, the user can iteratively update the window space to further improve the wellness of their regression fit.

5) <u>Dynamic Propellant Geometry Form Functions:</u> Due to the iterative nature of the CloBRA program, the burn rate of the propellant is determined at every data point analyzed. As a direct result of this, dynamic propellant geometry form functions were coded to determine the available solid propellant volume at each time step, even when slivering occurs and up to solid propellant burn out. With this feature, users can determine the burn rate of the propellant past the characteristic region discussed earlier. Note that since the derivations used in the CloBRA program assume that all of the solid ignitor is instantly converted to gas and the propellants instantaneously burn according to Piobert's law, the burn rate computed in the flame spread region of the vivacity versus normalized pressure plot may not be representative of the experimental results, since ignition of the propellant takes a finite amount of time. Thus, users are cautioned to only use burn rate computations from the start of the characteristic slope region and onward. The dynamic form functions are further discussed in appendix B.

6) <u>Data Transcription to Various Files:</u> The CloBRA program also provides the user with the option to print their computational results to Excel and print generated figures to PDF files. This feature is beneficial for the user as this gives them the ability to interact with the data. The computational results in the Excel file include the inputs provided to the GUI and also the pressure, time derivative of pressure, burn rate, distance burned, solid volume remaining, vivacity, percent burned for each data point in the fitted window space discussed previously, as well as other outputs. The plots saved to a given shot's PDF file include pressure versus time, vivacity versus normalized pressure, time derivative of pressure versus pressure, and log(burn rate) versus log(pressure). When multiple shots are analyzed, each subsequent shot data set is added to a new worksheet in the same Excel file. The average of these results is then provided on the last worksheet of the Excel file. Additionally, if multiple shots are analyzed, the same PDF files mentioned earlier are generated for each shot, and composite (showing all the shots on each plot) and average valued (average results of shots) PDF files are generated as well. Note that the user can either print these outputs in Metric or English units. Additionally, raw text files are generated to provide the time, pressure, time derivative of pressure, vivacity, and normalized pressure outputs from the initial data point until peak pressure.

7) <u>Burn Table Grain Regression Analysis:</u> In order to support future efforts for propellant grain production via additive manufacturing, the CloBRA program has been equipped with a burn table feature. This table enables users to specify the volume of a given grain geometry as a function of distance burned. The CloBRA program then uses the burn table as an effective form function when performing burn rate analyses. More information on this is provided in appendix C.

8) <u>Pressure-Time Curve Generator:</u> The CloBRA program is also equipped with a pressure-time curve generator feature. This feature allows the user to predict the pressure-time curve for a given propellant formulation and geometry within the rise action region (i.e., from 10 to 90% maximum pressure). Additionally, this feature can be used to compare predicted pressure-time curves with experimental results. The CloBRA program also has an optimization routine in which the burn rate parameters can be further adjusted to improve how the predicted pressure-time trace aligns with the experimental pressure-time trace. This is done by minimizing the sum of square error between the two curves. Use of this optimization routine is not recommended for propellants that are characterized by two or more burning rates on the pressure interval tested as the optimization routine assumes one set of Alpha and Beta parameters.

OVERVIEW OF METHODOLOGY

Governing Assumptions

Prior to defining the governing equations describing the thermodynamic theory of closed bomb testing, it is important to discuss the underlying assumptions that are incorporated in the constituent equations. Consistent with most closed bomb data reduction codes, CloBRA uses the following modeling assumptions per reference 6:

- The ignitor (also referred to as the primer) is entirely consumed at the first time step of the analysis
- The deflagration process follows the well-stirred reactor assumption (gas and solid phases are treated as a uniform mixture)
- There are no gradients in temperature, concentration, velocity, or pressure
- The solid propellant grain kinetic energy is zero (i.e., no grain motion)
- The air, primer, and propellant gases follow the Noble-Abel equation of state and Dalton's law of partial pressure
- The air, primer, and propellant gases have a constant heat capacity over the range of interest
- The propellant follows Piobert's law with an instantaneous flame spread (the speed of the primer flame spread is assumed to be much greater than the initial propellant burning rate)
- No work is done on the bomb (i.e., assumed to be a rigid vessel)
- The solid propellant has a constant density
- The solid propellant is homogenous with no large voids
- No solid propellant remains at the maximum pressure (i.e., all propellant has been converted to gas)
- There is no cracking or mechanical degradation of the propellant grains during the ignition and combustion processes
- The air in the closed bomb vessel is initially at standard room conditions

While the CloBRA program does share consistent assumptions with many legacy closed bomb reduction programs, it is important to note that CloBRA deviates from some legacy codes in regard to the two following capabilities:

1. <u>Propellants must be uniform (i.e., cannot be layered or deterred):</u> While programs such as BRLCB may have the capability to model layered or deterred propellants, the accuracy of the results are entirely contingent on the user correctly specifying the depth of each propellant grain layer (where each layer has differing thermochemical properties). Although this can be done, determining the depth of each propellant grain layer is an arduous process that involves intricate experimental testing techniques such as Fourier Transform Infrared (FTIR) Spectroscopy. However, even with advanced techniques like FTIR, the results are typically error prone, which in turn adversely influences burn rate predictions in closed bomb reduction programs.

   As an example of how sensitive burn rate predictions are to spatial variations in propellant thermochemistry, reference 7 documents a study performed to evaluate how the ballistic performance of small caliber weapons is impacted due to dibutyl phthalate (DBP) migration in propellant grains. In this paper, FTIR was used to determine the spatially varying DBP concentration profile in propellant grains after an allotted amount of exposure to a controlled storage environment. An interior ballistics (IB) model was then set up to account for the corresponding spatial variation in propellant thermochemistry, and when this model was compared against ballistic test data, the percent error was significant. Furthermore, while a layered/deterred propellant modeling feature could have been implemented in the CloBRA program, it is not warranted at this point in time as the aforementioned uncertainty introduces significant error to downstream IB analyses. When processes can be improved to accurately determine the depth of each propellant grain layer, this feature will be incorporated in a later release of the program.

2. <u>Accounting for Heat Loss:</u> During the combustion process, some amount of thermal energy from the hot convective gases deposits into the colder walls of the closed bomb vessel. As discussed in reference 6, many legacy closed bomb programs are not aligned with their treatment of heat loss from the closed bomb control volume. Some programs, such as the legacy ARDEC CBA program, even assume the combustion process is adiabatic. Other codes, such as CBRED and XLCB, assume that the heat loss term is proportional to the pressure in the vessel–although, even these codes differ in their heat loss quantification.

   Per reference 8, an empirical study was conducted to examine the heat loss of closed bomb vessels. In this study, two tests were conducted. For the first test, four different propellant types, in terms of geometry, dimensions, and formulation, were tested in three different closed bomb vessels of differing surface area-to-volume ratios with a constant loading density of 0.2 g/cm^3. For the second test, different loading densities ranging from 0.1 to 0.3 g/cm^3 of the same propellant types were tested in a 200-cm^3 bomb. The study then compared burning rate calculations of the tests with and without the inclusion of heat loss effects. Based on the results, the study demonstrated that omission of heat loss in the burn rate calculations resulted in an underestimation of the deduced burn rate and the error was much more pronounced for bombs of higher surface area-to-volume ratios since the rate of heat loss was increased dramatically. Additionally, the study demonstrated that the simple pressure averaging heat loss model employed by

XLCB was capable of accounting for the heat loss across a wide range of closed bomb and propellant combinations. Due to this result, the CloBRA program always accounts for heat loss and uses the same pressure averaging model employed by XLCB per reference 4.

Governing Equations for Burn Rate Analysis

With respect to the assumptions provided previously, the energy balance in the closed bomb chamber at a given time, t, is expressed via equation 1. Note that the mass of air is computed via the ideal gas law by assuming standard room conditions (i.e., 21 °C and 101.3 kPa) and using the free volume in the bomb as input.

$$m_p(t)c_{v,p}T_{f,p} + M_s c_{v,s}T_{f,s} + M_a c_{v,a}T_{in} = \left(m_p(t)c_{v,p} + M_s c_{v,s} + M_a c_{v,a}\right)T(t) + Q(t) \tag{1}$$

Where,

$m_p(t)$ = Time dependent mass function of the propellant gas (kg)

$c_{v,p}$ = Specific heat capacity of the propellant gas at fixed volume [J/(kg-K)]

$T_{f,p}$ = Adiabatic flame temperature of the propellant gas (K)

M_s = Mass of the primer gas (kg)

$c_{v,s}$ = Specific heat capacity of the primer gas at fixed volume [J/(kg-K)]

$T_{f,s}$ = Adiabatic flame temperature of the primer gas (K)

M_a = Mass of air in closed bomb vessel (kg)

$c_{v,a}$ = Specific heat capacity of air at fixed volume [J/(kg-K)]

T_{in} = Initial temperature of the closed bomb vessel (K)

$T(t)$ = Time dependent temperature of the combustion gas in the closed bomb (K)

$Q(t)$ = Time dependent heat loss term (J)

Additionally, in order to relate the measured pressure of the combustion gas to its corresponding temperature, the Noble-Abel equation of state is used as shown in equation 2. The Noble-Abel equation of state is used in lieu of the ideal gas law in order to compensate for the finite volume occupied by the gas molecules at high pressures.

$$P(t)\left(\forall_b - \frac{M_p}{\rho} + m_p(t)\left(\frac{1}{\rho} - \eta_p\right) - M_s\eta_s - M_a\eta_a\right) = \left(R_p m_p(t) + R_s M_s + R_a M_a\right)T(t) \tag{2}$$

Where,

$P(t)$ = Pressure of the combustion gas as a function of time (Pa)

$\forall_b$ = Bomb volume (m³)

M_p =   Initial mass of the solid propellant (kg)

η_p =   Covolume of the propellant gas (m³/kg)

η_s =   Covolume of the primer gas (m³/kg)

η_a =   Covolume of air (m³/kg)

ρ =   Density of the solid propellant (kg/m³)

R_p =   Specific gas constant of the propellant gas [J/(kg-K)]

R_s =   Specific gas constant of the primer gas [J/(kg-K)]

R_a =   Specific gas constant of air [J/(kg-K)]

As discussed earlier, it is assumed that the heat loss term of equation 1 varies proportionally with respect to the normalized pressure within the closed bomb. The expression for this relationship is documented in reference 4 and is provided in equation 3:

$$Q(t) = Q_{max}\left(\frac{P(t)}{P_{max}}\right) \tag{3}$$

Where,

P_{max} =   Maximum pressure of the combustion gas in the closed bomb vessel (Pa)

Q_{max} =   Maximum heat loss in the closed bomb vessel (J)

Prior to proceeding, it is important to note that the maximum heat loss shown in equation 3 occurs when all the solid propellant has been consumed and the gas is at its maximum pressure. In order to determine the maximum heat loss, the maximum temperature within the closed bomb must first be determined. From the Noble-Abel equation of state, the maximum temperature can be computed per equation 4 by noting that the mass of the propellant gas is now numerically equivalent to the initial mass of the solid propellant.

$$T_{max} = \frac{P_{max}\left(\forall_b - M_p\eta_p - M_s\eta_s - M_a\eta_a\right)}{\left(R_p M_p + R_s M_s + R_a M_a\right)} \tag{4}$$

Where,

T_{max} =   Maximum temperature of the combustion gas in the closed bomb vessel (K)

The maximum temperature and known mass of the propellant gas can then be inserted into equation 1 to determine the maximum heat loss as shown in equation 5:

$$Q_{max} = M_p c_{v,p} T_{f,p} + M_s c_{v,s} T_{f,s} + M_a c_{v,a} T_{in} - \left(M_p c_{v,p} + M_s c_{v,s} + M_a c_{v,a}\right)T_{max} \tag{5}$$

With the maximum heat loss determined, this value can be inserted into equation 1 to solve for the time varying temperature within the closed bomb as a function of the mass of the propellant gas. This relationship is shown in equation 6:

$$T(t) = \frac{m_p(t)c_{v,p}T_{f,p} + M_s c_{v,s}T_{f,s} + M_a c_{v,a}T_{in} - Q_{max}\left(\frac{P(t)}{P_{max}}\right)}{(m_p(t)c_{v,p} + M_s c_{v,s} + M_a c_{v,a})} \tag{6}$$

Equation 6 can then be inserted into equation 2 and rearranged to solve for the mass function of the propellant gas. Upon doing so, this equation takes the form of equation 7:

$$A(t)m_p(t)^2 + B(t)m_p(t) + C(t) = 0 \tag{7}$$

Where,

$$A(t) \quad = \quad P(t)c_{v,p}\left(\frac{1}{\rho} - \eta_p\right) - R_p c_{v,p}T_{f,p}$$

$$B(t) \quad = \quad P(t)\forall_b c_{v,p} - P(t)\frac{M_p}{\rho}c_{v,p} - P(t)M_s\eta_s c_{v,p} - P(t)M_a\eta_a c_{v,p} + P(t)\left(\frac{1}{\rho} - \eta_p\right)M_s c_{v,s} +$$

$$\quad P(t)\left(\frac{1}{\rho} - \eta_p\right)M_a c_{v,a} - R_p M_s c_{v,s}T_{f,s} - R_p M_a c_{v,a}T_{in} + R_p Q_{max}\left(\frac{P(t)}{P_{max}}\right) - R_a M_a c_{v,p}T_{f,p} -$$

$$\quad R_s M_s c_{v,p}T_{f,p}$$

$$C(t) \quad = \quad P(t)\forall_b M_s c_{v,s} - P(t)\frac{M_p}{\rho}M_s c_{v,s} - P(t)M_s{}^2\eta_s c_{v,s} - P(t)M_a\eta_a M_s c_{v,s} + P(t)\forall_b M_a c_{v,a} -$$

$$\quad P(t)\frac{M_p}{\rho}M_a c_{v,a} - P(t)M_s\eta_s M_a c_{v,a} - P(t)M_a{}^2\eta_a c_{v,a} - R_a M_a M_s c_{v,s}T_{f,s} - R_a M_a{}^2 c_{v,a}T_{in} +$$

$$\quad R_a M_a Q_{max}\left(\frac{P(t)}{P_{max}}\right) - R_s M_s{}^2 c_{v,s}T_{f,s} - R_s M_s M_a c_{v,a}T_{in} + R_s M_s Q_{max}\left(\frac{P(t)}{P_{max}}\right)$$

The quadratic formula can then be invoked to determine the mass function of the propellant gas as shown in equation 8. Note that the other root of the quadratic formula is disregarded since it is just an artifact of the mathematics.

$$m_p(t) = \frac{-B(t) - \sqrt{B(t)^2 - 4A(t)C(t)}}{2A(t)} \tag{8}$$

Once the mass of the propellant gas is determined via the methodology defined in equation 8, the volume of solid propellant remaining at each time step can be determined via equation 9. Note that the volume terms below are in terms of total volume instead of the single grain volume.

$$\forall_{solid}(t) = \forall_{initial} - \frac{m_p(t)}{\rho} \tag{9}$$

Where,

$\forall_{solid}(t)$ = Total solid propellant volume remaining at each time step (m³)

$\forall_{initial}$ = Total initial volume of the solid propellant (m³)

The form functions governing the geometry of the solid propellant can then be used to determine the distance burned via root-solving the expression shown in equation 10. These form

functions are geometry specific and assume that the distance burned normal to each layer is uniform.

$$\forall_{solid}(t) - \forall_{FF}(x) = 0 \qquad (10)$$

Where,

$\forall_{FF}(x)$ =   Total solid propellant volume determined by the form function, which is a function of the distance burned, x, as well as initial geometric parameters (e.g., initial grain diameter) (m^3)

      Once the distance burned is determined via equation 10, the burn rate is computed as simply the time derivative of this quantity. By plotting burn rate versus pressure (units of MPa) on a log-log plot, the burn rate parameters of Vielle's law can be determined via a linear regression fit within the characteristic slope region. Vielle's law simply states that when all grain surfaces are burning uniformly, the burn rate is linearly proportional to the pressure on a log-log plot. This relationship is provided in equation 11 after the antilogarithm of the equation has been taken.

$$\frac{dx}{dt} = \beta(P(t))^\alpha \qquad (11)$$

Where,

$\dfrac{dx}{dt}$ =   Burn rate (m/s)

$P(t)$ =   Mean pressure of gas (MPa)

α =   Exponent of Vielle's law

β =   Coefficient of Vielle's law (m/(s-MPa$^\alpha$))

Governing Equations for Pressure-Time Curve Generation Analysis

      The pressure-time curve generation analysis employs the same constituent equations used in the burn rate analysis discussed previously. However, the equations are solved differently such that pressure and time can be determined via propellant thermochemistry, burn rate, and geometry. Due to the fact that the derivations assume the propellant is instantaneously ignited, the resulting pressure-time traces are shorter in burn duration than experimental results. Since this discrepancy exists, the pressure-time curve generator is solely intended to predict the profile of the pressure-time curve within the rise action region (i.e., from 10 to 90% of the maximum pressure). For completeness, the solution method used for this analysis feature is explained in this section.

Predicting the Pressure-Time Curve

      The pressure-time curve analysis requires the regression of the propellant grains as input via predefined geometry/form functions or a burn table. To elaborate, for either input, the volume of the grain is evaluated as a function of distance burned from its initial state (i.e., zero burn distance) to propellant burn out. Solving the regression model in this manner establishes an initial condition at time zero where the mass of the propellant gas is zero and a final condition at the last time step of the analysis where the mass of the propellant gas is numerically equivalent to the initial

mass of the solid propellant at peak pressure. At each burn distance, the mass of the propellant gas can be determined via equation 12:

$$m_p(x) = \rho\left(\forall_{initial} - \forall_{FF}(x)\right) \tag{12}$$

Once the mass of the propellant gas is known as a function of distance burned, the corresponding gas temperature can be determined at each analysis point via equation 6. However, it is important to note that for this derivation, the combustion process is assumed to behave adiabatically, and thus the heat loss term of equation 6, $Q(t)$, is set to zero. For further clarity, this relationship is shown in equation 13. While it is recognized that an adiabatic assumption is not truly valid as addressed previously in this report, the heat loss correlation is solely based on empirical results, and thus the time varying heat loss term cannot be approximated without test data. In lieu of using approximation approaches that could ultimately introduce more uncertainty, an adiabatic process was deemed sufficient for prediction purposes since it results in a higher maximum pressure prediction, which is conservative from a modeling/testing standpoint. Sensitivity studies showed that an adiabatic assumption is sufficient for fast burning propellants (i.e., on the order of a few milliseconds); however, it is cautioned that the adiabatic assumption introduces more uncertainty in the predicted pressure-time traces of slow burning propellants (i.e., on the order of tens of milliseconds).

$$T(x) = \frac{m_p(x)c_{v,p}T_{f,p} + M_s c_{v,s}T_{f,s} + M_a c_{v,a}T_{in}}{(m_p(x)c_{v,p} + M_s c_{v,s} + M_a c_{v,a})} \tag{13}$$

The pressure of the propellant gas as a function of distance burned can then be determined via the Noble-Abel equation of state shown in equation 2. After some algebraic manipulation and insertion of equation 13 into equation 2, the pressure function is as shown in equation 14:

$$P(x) = \frac{\left(R_p m_p(x) + R_s M_s + R_a M_a\right)\left(\frac{m_p(x)c_{v,p}T_{f,p} + M_s c_{v,s}T_{f,s} + M_a c_{v,a}T_{in}}{(m_p(x)c_{v,p} + M_s c_{v,s} + M_a c_{v,a})}\right)}{\left(\forall_b - \frac{M_p}{\rho} + m_p(x)\left(\frac{1}{\rho} - \eta_p\right) - M_s\eta_s - M_a\eta_a\right)} \tag{14}$$

The time steps associated with each analysis point can then be determined via manipulation of Vielle's law shown in equation 11 and approximating the burn rate as the fractional change in distance burned divided by the fractional change in time (i.e., $\frac{dx}{dt} \approx \frac{\Delta x}{\Delta t}$). After some manipulation, the time steps are computed as shown in equation 15. The time trace can then be determined by summing the time steps accordingly.

$$\Delta t = \frac{\Delta x}{\beta(P(x))^\alpha} \tag{15}$$

Comparing Pressure-Time Curves

When a predicted pressure-time curve is compared against experimental data, the adiabatic assumption constraint is omitted from the analysis method, and the experimental maximum pressure is used in the heat loss expression shown in equation 3. The same methodology discussed in the earlier section is then employed in the pressure-time curve prediction analysis; however, heat loss is now included in the model. By substituting equations 3 and 6 into the Noble-Abel equation of state, the resulting equation can be further manipulated to solve for pressure as shown in equation 16. Note that the combustion gas temperature is not solved directly in this approach, since it is a

function of pressure. After computing the pressure trace, the time trace is then computed in the same exact manner discussed previously.

$$P(x) = \frac{(\omega_1(x) + \omega_2(x) + \omega_3(x))}{\varphi_1(x)\left(\forall_b - \frac{M_p}{\rho} + m_p(x)\left(\frac{1}{\rho} - \eta_p\right) - M_s\eta_s - M_a\eta_a\right) + \varphi_2(x)\left(\frac{Qmax}{Pmax}\right)} \tag{16}$$

Where,

$$\omega_1(x) \quad = \quad R_s M_s{}^2 c_{v,s} T_{f,s} + R_s M_s m_p(x) c_{v,p} T_{f,p} + R_s M_s M_a c_{v,a} T_{in}$$

$$\omega_2(x) \quad = \quad R_p m_p(x) M_s c_{v,s} T_{f,s} + R_p m_p(x)^2 c_{v,p} T_{f,p} + R_p m_p(x) M_a c_{v,a} T_{in}$$

$$\omega_3(x) \quad = \quad R_a M_a M_s c_{v,s} T_{f,s} + R_a M_a m_p(x) c_{v,p} T_{f,p} + R_a M_a{}^2 c_{v,a} T_{in}$$

$$\varphi_1(x) \quad = \quad M_s c_{v,s} + m_p(x) c_{v,p} + M_a c_{v,a}$$

$$\varphi_2(x) \quad = \quad R_s M_s + R_p m_p(x) + R_a M_a$$

USER MANUAL – SYSTEM REQUIREMENTS

In order to run and successfully utilize the CloBRA program, the user must have the following software installed:

- MATLAB R2020a or a later release
- Microsoft Excel or equivalent spreadsheet program
- Adobe PDF or equivalent PDF reader

The user must also have a screen resolution of 1366 x 768 pixels and at least 4 GB of usable random access memory (RAM). Note that this code has only been validated using MATLAB 2020a, and thus sensitivity studies should be conducted prior to transitioning to a later software release.

USER MANUAL – GETTING STARTED

Once the CloBRA program files are installed on the user's computer, the user must open the MATLAB program and navigate to the "CloBRA" folder as shown in figure 2.

Figure 2
Navigating to the CloBRA program

Once the user has navigated to the CloBRA directory, they will note that it contains four subfolders. **It is very important that the user does not change the names of these folders nor delete them.** The purpose of these subfolders are discussed as follows:

- Code: This subfolder contains the source code for the GUIs. **It is strongly cautioned that the user does not alter any of the source code within this folder.**

- Input Decks: As discussed earlier, the user can populate the fields within the CloBRA GUI via template input decks. This subfolder is where the user would store these premade input decks such that they can be easily loaded into the CloBRA GUI. Alternatively, the user can store their input decks elsewhere on their computer; however, the "Input Decks" subfolder is the default directory for the CloBRA program. More information on the input decks are provided later in this document in appendix A. Additionally, note that premade template decks for the burn rate and pressure-time curve analyses are provided in this subfolder for convenience.

- Output: This subfolder is the default directory for which the output files from the CloBRA program are stored. Alternatively, the user can store their output files elsewhere on their computer as prompted by the CloBRA program.

- Raw Data: This subfolder is where the raw closed bomb testing data is stored. Alternatively, the user can store their data files elsewhere; however, this subfolder was established for convenience.

Running the CloBRA Program

Once in the CloBRA directory, the user can run the program by typing "CloBRA" into the MATLAB command window. Upon running the CloBRA program, the display window shown in figure 3 will appear onscreen, and the user will be prompted to enter information/data into the appropriate fields. Note that this information/data is only required for closed bomb burn rate analyses.

Figure 3
CloBRA program display prompt

As shown in figure 3, the user must enter the following information if conducting a burn rate analysis:

- The name of the tester
- The propellant formulation name and corresponding lot number (maximum of 35 characters)
- The loading density of the propellant (in units of g/cm^3)
- The conditioning temperature of the propellant prior to testing (default: 21 °C)
- The date in which the test was conducted (in MM/DD/YYYY format)
- Specify the shot type (i.e., reference or test shot)
- Any additional comments captured during testing (optional)

After entering this information, the user is then prompted to select which type of analysis they would like conduct from the drop-down menu. The burn rate analysis can be conducted for three different raw data type formats as follows: direct transducer data (i.e., voltage-time data), pressure-time data (in either units of psi or MPa), and Radford Ballistics relative force/relative quickness analysis formats. The user is required to select the appropriate option based on the format of their data. The user can also choose to perform a relative measurements analysis; however, this can only be done if a burn rate analysis has been conducted on the propellant data set in question. This is because the output Excel and text files of the burn rate analysis are input to the relative measurements analysis of the CloBRA program. More information on this is provided later in the

document. Lastly, the user can perform a pressure-time curve generation analysis as mentioned earlier. The five options in the drop-down menu are listed as follows:

1) Burn Rate Analysis: Voltage vs. Time (seconds) Format
2) Burn Rate Analysis: Pressure vs. Time (seconds) Format
3) Burn Rate Analysis: BAE Systems – Radford Ballistics Excel Format
4) Relative Measurements Analysis
5) Pressure-Time Curve Generator

Once the run is set up appropriately, the user would click the "Generate GUI" button in order to generate the corresponding GUI for the analysis type selected.

USER MANUAL – BURN RATE ANALYSIS

Walkthrough of Voltage versus Time GUI Format

Upon selecting the voltage versus time burn rate analysis format, the GUI shown in figure 4 will be displayed onscreen.
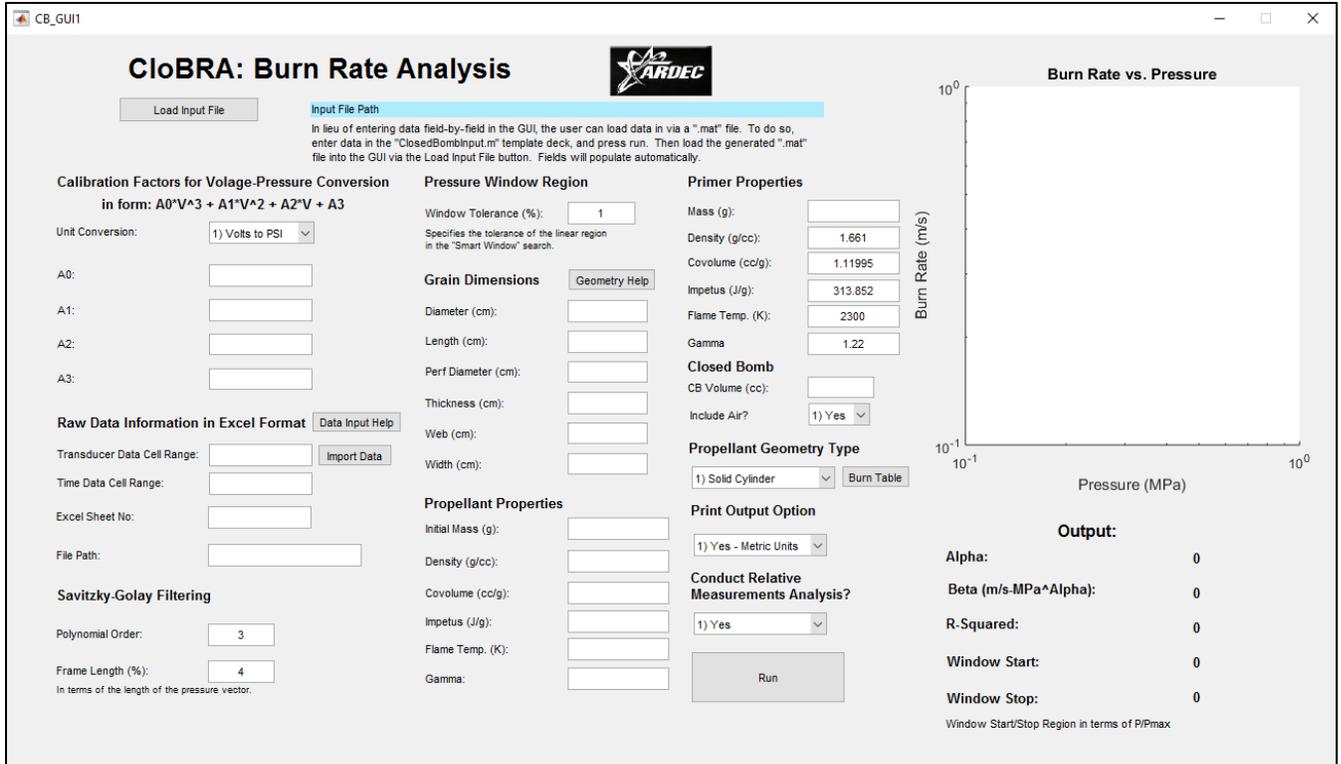
Figure 4
CloBRA: Burn rate analysis GUI for voltage versus time format

Based upon inspection of figure 4, it can be noted that input parameters are congregated into differing subcategories. The remaining portion of this section will walkthrough each subcategory and will define how the user should enter data/information accordingly.

Calibration Factor Input Deck

For the voltage versus time raw data format, it is assumed that the voltage reading from the transducer can be converted to pressure via a third order polynomial fit. If a higher order polynomial is used or the raw data is converted in a different manner, the user can convert the raw data appropriately and then use the pressure-time data format. CloBRA assumes that the voltage is converted to pressure in units of either psi or MPa. The appropriate conversion type is to be selected by the user via the "Unit Conversion" drop-down menu. Additionally, it is worth noting that if a linear or second order polynomial fit were used instead of the prescribed third order polynomial, the user would just set the approriate coefficients of the polynomial to zero. The conversion relationship between voltage and pressure is shown via equation 17 and is also displayed on the GUI for convenience.

$$P(t) = A_0(V(t))^3 + A_1(V(t))^2 + A_2V(t) + A_3 \tag{17}$$

Where,

$P(t)$ =   Mean pressure of gas (psi or MPa, based on user input)

$V(t)$ =   Voltage reading from transducer (Volts)

A_0 = Coefficient for third order term determined via calibration testing (psi/V^3 or MPa/V^3)

A_1 = Coefficient for second order term determined via calibration testing (psi/V^2 or MPa/V^2)

A_2 = Coefficient for first order term determined via calibration testing (psi/V or MPa/V)

A_3 = Coefficient for zero order term determined via calibration testing (psi or MPa)

      The user would then enter the appropriate values for the aforementioned coefficients in the fields provided and select the appropriate unit conversion type from the drop-down menu in this section.

Raw Data in Excel Format Input Deck

      The CloBRA program exclusively reads in raw data provided in an Excel worksheet format. This requires the user to import their raw experimental data into an Excel worksheet prior to using CloBRA; or, if using an HBM GEN5i or equivalent model oscilloscope for the analysis, the raw ".mat" files produced from testing can be automatically converted to an Excel worksheet and loaded into the GUI via the "Import Data" button. Detailed descriptions of the input fields for this section are provided in table 1.

Table 1
Description of fields in raw data information in Excel format input deck

Field name	Description	How to enter information
Transducer Data Cell Range	This field corresponds to the Excel cells that contain the raw experimental transducer data. It is preferred that this data is entered as a column array in Excel (e.g., data for a given shot would span cells B2 through B4097 or higher depending on the number of data points).	* Single Shot Example: **B2:B4097** or **B:B** * Multiple Shot Example: **B2:B4097,D2:D4097,F2:F4097** or **B:B,D:D,F:F** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
Time Data Cell Range	This field corresponds to the Excel cells that contain the time array of the experimental data. It is preferred that this data is entered as a column array in Excel (e.g., data for a given shot would span cells A2 through A4097 or higher depending on the number of data points). Note that when multiple shots are analyzed, the index of the time vector must correspond to the respective index of the transducer data.	* Single Shot Example: **A2:A4097** or **A:A** * Multiple Shot Example: **A2:A4097,C2:C4097,E2:E4097** or **A:A,C:C,E:E** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
Excel Sheet No.	This field corresponds to the sheet in which the transducer and time data are stored (both must be provided on the same worksheet). Note that when multiple shots are analyzed, the length of the sheet array entered must correspond to the number of shots analyzed, even if all data is contained on one sheet.	* Single Shot Example: **1** * Multiple Shot Example: **1,2,3** (if on different worksheets) or **1,1,1** (if all shots are on the same sheet) [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
File Path	This field corresponds to the file name and path in which the Excel sheet with the data is stored. Note that all shots analyzed must be contained within the same Excel file.	Example: **C:\Users\Documents\File**

As emphasized in table 1, multiple shots (no limit) can be analyzed for a given reference shot or test shot iteration. However, it is imperative that the user ensures that the data array inputs are of equivalent length and ensures that all data is provided in the same Excel file. To clarify this further, consider the case in which three shots are being analyzed. For this case, the Transducer Data Cell Range field would have three data cell ranges input, the Time Data Cell Range field would have three data cell ranges input, the Excel Sheet No. field would have three sheet numbers provided (regardless if all data was contained on the same worksheet), and the File Path field would only contain one file. Further guidance on inputting data cell ranges properly can be found by clicking the Data Input Help button on the GUI.

One other quick feature that is worth emphasizing is the Import Data button provided on the GUI. As discussed previously, if an HBM GEN5i or equivalent model oscilloscope is used for the analysis, the raw ".mat" files produced from testing can be mapped to an Excel file, and the appropriate fields of the GUI will populate accordingly via use of this feature. To use the "Import Data" feature, the user must follow the steps provided in the following:

1. Click the Import Data button. By doing so, a "Select File(s) to Open" window will be displayed onscreen prompting the user to select which file(s) they would like to convert to the Excel format.

2. In the "Select File(s) to Open" window, navigate to the appropriate folder where the data is stored, if it is not stored in the "Raw Data" folder.

3. Select the ".mat" file(s) containing the test data. If analyzing multiple files, hold down the "Ctrl" key on the keyboard while selecting the files to ensure that multiple files are selected for the conversion process.

4. Once the appropriate file(s) selection is made, click the "Open" button. In doing so, a new window, titled "Specify the Output Excel Filename", will be displayed.

5. In the "Specify the Output Excel Filename" window, navigate to the desired save location of the output Excel filename if the default folder is not preferred. Note the default folder is the same folder in which the raw data files were stored.

6. Enter a file name for the resulting Excel file in the "File name:" field.

7. Click Save. By doing so, the file will be generated with the data and the fields of the GUI will populate accordingly. Note, do not press the "Run" button until the fields of this section of the GUI are populated.

Savitzky-Golay Filtering Input Deck

As discussed earlier, a Savitzky-Golay filter is used to smooth the raw data and to remove anomalous noise from the data trace. This filter type is included in the MathWorks library for MATLAB as the "sgolayfilt" function. Per reference 9, the Savitzky-Golay filter is based on the least squares polynomial fitting across a moving window within the data in the time domain. It is noted that this filtering method is preferred over a moving average filter since characteristic features (e.g., peak height and width) are usually attenuated with the latter filtering approach. More information on the Savitzky-Golay filter type can be found via reference 9.

In order to use the Savitzky-Golay filter in CloBRA, the user must specify a polynomial order for the filter and the frame length of the moving filter window. These parameters are identified in the GUI as Polynomial Order and Frame Length, respectively. Note that the Frame Length is entered in

terms of the percentage of the length of the pressure vector. By default, the Polynomial Order is set to 3 and the Frame Length is set to 4. However, as discussed earlier, these parameters can be iteratively changed while running the code if the data does not appear to be filtered adequately.

Pressure Window Region Input Deck

As mentioned earlier, the characteristic slope region is determined by the user via data cursor selection of the region's endpoints on the vivacity versus normalized pressure plot. Based on the endpoint selection, a best fit, modular tangent line is fit to this selection in order to further improve the linearity of the selected window space. This best fit, modular tangent line has some defined tolerance to it and is called the Window Tolerance in the GUI. By default, this value is set to 1 and represents a percentage in which the tangent line can vary in terms of linearity. Note that this parameter is not of significant importance as the user can always redefine the window space when conducting the burn rate analysis as discussed later.

It is worth noting that for some erroneous cases the aforementioned tangent line may exhibit some nonlinearity on a peculiar shaped vivacity versus normalized pressure plot (i.e., if the characteristic slope region exhibits nonlinearity, the modular tangent line may exhibit some nonlinearity due to the specified tolerance). This is because the aforementioned tolerance is in terms of the variance between the tangent line and the vivacity curve at a given data point. If the variance is below the tolerance specified, the fitted modular tangent line will include erroneous nonlinear points in the fit and will be depicted graphically in the plot. However, as discussed previously, the window space for the burn rate analysis can always be redefined by the user if the fit is not sufficient. A sample plot of this window fit is included later in this report.

Grain Dimensions Input Deck

Based on the propellant geometry selected from the Propellant Geometry Type drop down menu, the user is then required to provide the appropriate dimensions to properly describe the grain geometry. Table 2 provides all the modeling geometries provided in CloBRA and specifies which dimensions are needed to conduct the burn rate analysis. Note that all dimensions are to be entered in units of centimeters.

Table 2
Description of propellant grain geometries

Propellant grain geometry	Modeling dimensions (cm)
Solid cylinder (Cord grain)	<u>Required:</u> Length and diameter
Single-perforated cylinder (1-perf cylinder)	<u>Required:</u> Length, diameter, and perf diameter
Seven-perforated cylinder (7-perf cylinder)	<u>Required:</u> Length, diameter, and perf diameter <u>Optional:</u> Inner and outer web (if nonuniform)
Nineteen-perforated cylinder (19-perf cylinder)	<u>Required:</u> Length, diameter, and perf diameter <u>Optional:</u> Inner, middle, and outer web (if nonuniform)
Rectangular slab	<u>Required:</u> Length, thickness, and width
Rolled ball	<u>Required:</u> Diameter and thickness
Sphere	<u>Required:</u> Diameter
Seven-perforated hexagonal grain (7-perf hex)	<u>Required:</u> Length, diameter, and perf diameter <u>Optional:</u> Inner and outer web (if non-uniform)
Nineteen-perforated hexagonal grain (19-perf hex)	<u>Required:</u> Length, diameter, and perf diameter <u>Optional:</u> Inner, middle, and outer web (if non-uniform)
Burn table	<u>Required:</u> None

Note that for the multi-perf propellant grain geometries, it is assumed that the web thickness is uniform. However, if web thicknesses are specified, the location of the perforations will update accordingly, and the CloBRA model will explicitly model the regression adhering to the prescribed geometry. For 7-perf geometries, the user can either enter the inner web dimension, or both the inner and outer web dimensions. For 19-perf geometries, the user can enter the inner web dimension, the inner and middle web dimensions, or the inner, middle, and outer web dimensions. Note that when all web dimensions are specified for a multi-perf grain, the resulting diameter from this configuration will supersede the diameter provided in the GUI. However, the user must still enter an outer diameter as it is a required input.

When entering web dimensions into the GUI, the user is to enter them in an array format starting from the innermost web thickness to the outermost web thickness. If multiple web thicknesses are entered, the user would separate the values via a comma. For example, for a 7-perf grain, if the inner web thickness is 0.1 cm and the outer web thickness is 0.15 cm, the user would enter "0.1,0.15" (without the quotation marks) into the web field. Note that there must not be a space after the comma. More examples of how to enter the web thicknesses into the web field can be viewed via the Geometry Input Help button on the GUI.

Propellant Properties Input Deck

This deck includes input for the initial mass and measured density of the solid propellant, as well as the necessary thermochemical properties that are required to conduct the closed bomb reduction analysis. The thermochemical properties for a given propellant formulation can be determined by the user via the Cheetah thermochemical computer code (ref. 10). The inputs for this section are listed in table 3.

Table 3
Propellant properties input deck description

Parameter	Units
Initial solid propellant mass (initial mass)	Grams (g)
Density [measured via pycnometer or computed by Cheetah as the theoretical maximum density (TMD)]	Grams per cubic centimeter (g/cm³)
Covolume	Cubic centimeters per gram (cm³/g)
Impetus	Joules per gram (J/g)
Adiabatic flame temperature (flame temperature)	Kelvin (K)
Ratio of specific heats (Gamma)	None

As noted in table 3, the density of the propellant is not the same as the loading density specified earlier. The user should enter the measured sample density or the TMD, computed via Cheetah, into this field if the earlier information is not readily available. Note that these values should be relatively close in comparison if the tested propellant formulation was mixed/formulated appropriately. Additionally, it is worth noting that the units specified for the thermochemical input parameters are consistent with the output units provided by the Cheetah thermochemical code. These units were chosen to be consistent for simplicity and to mitigate potential user error.

One other important observation to note is that the thermochemical properties provided in the previous table do not align with the properties provided in the Governing Equations section of this document. Specifically, equation 1 requires the specific heat capacities of the primer and propellant gases at constant volume, and equation 2 requires the specific gas constants of the propellant and primer gases. However, these parameters can be obtained from the thermochemical properties listed in table 3 as demonstrated in equations 18 and 19. Note that these relationships are also applied for the primer gas as discussed in the following section.

$$R = \frac{\lambda}{T_f} \tag{18}$$

Where,

R = Specific gas constant of the primer or propellant gas [J/(kg-K)]

λ = Impetus of the primer or propellant gas (J/kg, converted units in code)

T_f = Adiabatic flame temperature of the primer or propellant gas (K)

$$c_v = \frac{R}{\gamma - 1} \tag{19}$$

Where,

c_v = Specific heat capacity of the primer or propellant gas at constant volume [J/(kg-K)]

γ = Ratio of specific heats of the primer or propellant gas

Primer Properties Input Deck

This deck includes input for the mass of the primer, as well as the necessary thermochemical properties that are required to conduct the closed bomb reduction analysis. The thermochemical properties for a given propellant formulation can be determined by the user via the Cheetah thermochemical computer code (ref. 10). The inputs for this section are listed in table 4. Note that equations 18 and 19 are also used to obtain the appropriate thermochemical parameters for the governing equations discussed earlier in this document.

Table 4
Primer properties input deck description

Parameter	Units
Mass	Grams (g)
Density	Grams per cubic centimeter (g/cm^3)
Covolume	Cubic centimeters per gram (cm^3/g)
Impetus	Joules per gram (J/g)
Adiabatic flame temperature (flame temperature)	Kelvin (K)
Ratio of specific heats (Gamma)	None

Note that by default, the CloBRA GUI has the thermochemical properties for black powder provided in the Primer Properties Input Deck. These values were obtained from reference 11. If a different primer was used, the user can update the thermochemical properties accordingly.

Closed Bomb Input Deck

For this input deck, the user is to provide the volume of the closed bomb in units of cubic centimeters and specify if they would like to include air at atmospheric pressure in the analysis via the drop down menu. If the user elects to include air, the free volume of the bomb (bomb volume minus the volume occupied by the solid propellant and primer prior to deflagration) and standard room temperature and pressure conditions are used to determine how many grams of air are present in the bomb via the ideal gas law. By default, air is included in the burn rate analysis. Note for the governing equations, the thermodynamic properties used pertain to dry air at atmospheric pressure.

Propellant Geometry Type Drop Down Menu

As discussed in the Grain Dimensions Input Deck section, the user selects which propellant grain geometry they are analyzing via the drop down menu. If using a burn table, the user must specify the burn table option via the drop down menu. For more information on the dimensional inputs for the various grain geometries, refer to the aforementioned section.

Burn Table Button

As discussed earlier, CloBRA is equipped with a burn table feature that allows the user to enter a grain regression table in lieu of using form functions. The burn table is to be provided to CloBRA in an Excel file format following the exact structure prescribed in appendix C. In order to use this feature, the user must select the Burn Table option from the Propellant Geometry Type drop down menu and click the Burn Table Button. A "Select Burn Table to Import" window will then load on the screen and will display the contents within the "Input_Decks" folder; however, the user is able

to navigate to other directories if the burn table is stored in an alternate location. Note that by default, the file extension search type for the burn tables is set to ".xlsx"; however, this can be changed to ".xls" or all files via the drop down option of the "Select Burn Table to Import" window.

Print Output Option Drop Down Menu

The user can select if they would like the ouput results printed in metric or English units. Alternatively, the user can elect to not print any output. The default print output option is in Metric units. More discussion on the format of the output files is provided later in this document.

Conduct Relative Measurements Analysis Drop Down Menu

The user can select if they would like to conduct a relative measurements analyis, which computes the relative force, quickness, and vivacity of a test propellant to a reference propellant. In order for this analysis to be performed, burn rate analyses must first be conducted for both the reference and test shots with the Print Output Option set to "yes" (regardless of output units).

Load Input File Button

A Load Input File button has been incorporated into the GUI such that the user can populate the aforementioned fields of the GUI via a template deck vice manually enter all the data. In order to use this feature, the user would first need to set up a template deck in MATLAB (as a ".m" file), which is provided in appendix A, to contain the run specific parameters. The user would then save this file in the "Input_Decks" folder and press the run button at the top of the window as shown in figure 5.
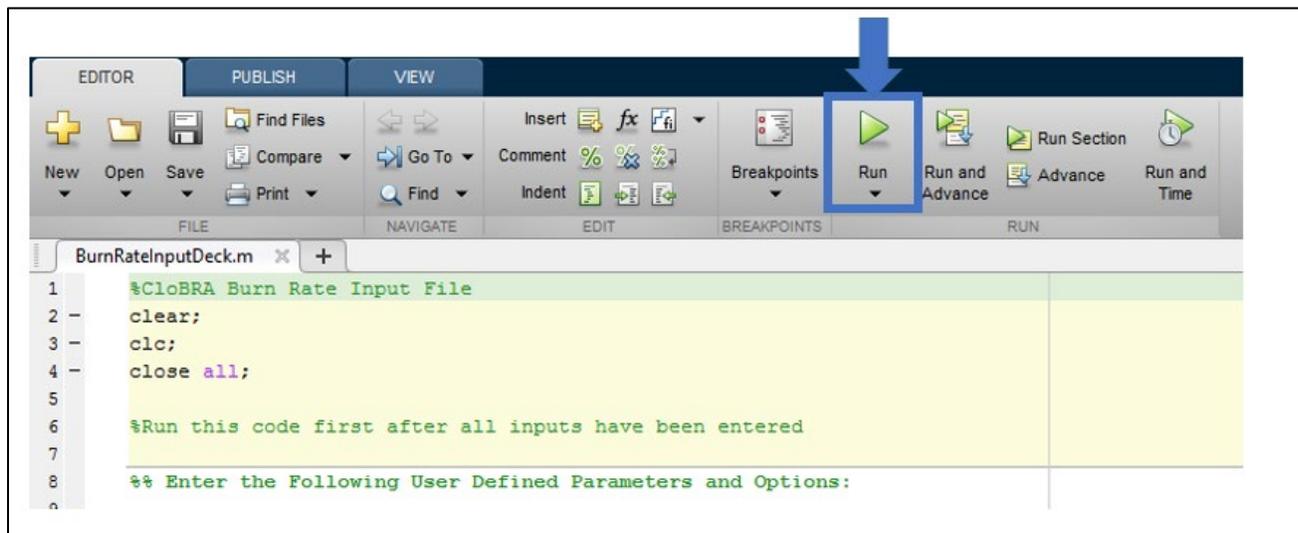
Figure 5
Generating input file in ".mat" format

Upon doing so, a ".mat" file will be generated and saved into the "Input_Decks" folder directory. This ".mat" can then be loaded into the GUI via the Load Input File button, and the corresponding file path will also be displayed in the light blue field next to the button.

Walkthrough of Pressure versus Time GUI Format

Upon selecting the pressure versus time burn rate analysis format, the GUI shown figure 6 will be displayed onscreen.
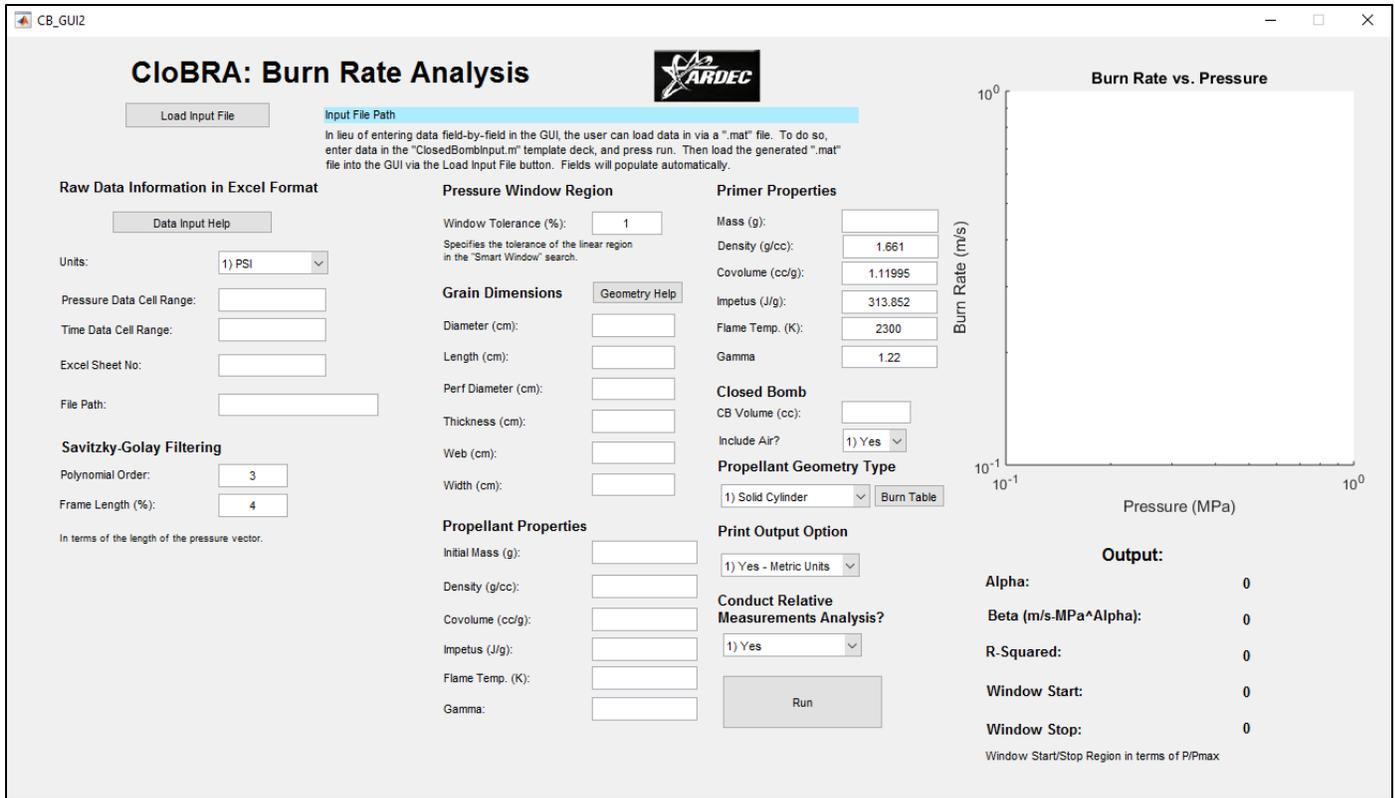
Figure 6
CloBRA: Burn rate analysis GUI for pressure versus time format

Upon observation of figure 6, one will note that the structure of this GUI is almost identical to that of the GUI for the voltage versus time data format. However, the key differences between these two GUIs are as follows: (1) The Calibration Factors Input Deck has been removed (since not needed) and (2) The format of the Raw Data Information in Excel Format input deck has been altered slightly. Since all other input decks are the same, they will not be discussed again in this section to mitigate redundancy. For more information on these fields, the reader is directed to consult the appropriate sections of the Walkthrough of Voltage versus Time GUI Format section provided previously in this document.

Raw Data in Excel Format Input Deck

The CloBRA program exclusively reads in raw data provided in an Excel worksheet format. This requires the user to import their raw experimental data into an Excel worksheet prior to using CloBRA . The pressure data must be provided in units of either psi or MPa. This is selected by the user via the Units drop down menu. Detailed descriptions of the input fields for this section are provided in table 5.

Table 5
Description of fields in Raw Data Information in Excel format input deck

Field name	Description	How to enter information
Pressure Data Cell Range	This field corresponds to the Excel cells that contain the raw experimental pressure data. It is preferred that this data is entered as a column array in Excel (e.g., data for a given shot would span cells B2 through B4097 or higher depending on the number of data points).	* Single Shot Example: **B2:B4097** or **B:B** * Multiple Shot Example: **B2:B4097,D2:D4097,F2:F4097** or **B:B,D:D,F:F** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
Time Data Cell Range	This field corresponds to the Excel cells that contain the time array of the experimental data. It is preferred that this data is entered as a column array in Excel (e.g., data for a given shot would span cells A2 through A4097 or higher depending on the number of data points). Note that when multiple shots are analyzed, the index of the time vector must correspond to the respective index of the transducer data.	* Single Shot Example: **A2:A4097** or **A:A** * Multiple Shot Example: **A2:A4097,C2:C4097,E2:E4097** or **A:A,C:C,E:E** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
Excel Sheet No.	This field corresponds to the sheet in which the transducer and time data are stored (both must be provided on the same worksheet). Note that when multiple shots are analyzed, the length of the sheet array entered must correspond to the number of shots analyzed, even if all data is contained on one sheet.	* Single Shot Example: **1** * Multiple Shot Example: **1,2,3** (if on different worksheets) or **1,1,1** (if all shots are on the same sheet) [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
File Path	This field corresponds to the file name and path in which the Excel sheet with the data is stored. Note that all shots analyzed must be contained within the same Excel file.	Example: **C:\Users\Documents\File**

As discussed in table 5, multiple shots (no limit) can be analyzed for a given reference shot iteration or test shot iteration. However, it is imperative that the user ensures that the data array inputs are of equivalent length and ensures that all data is provided in the same Excel file. To clarify this further, consider the case in which three shots are being analyzed. For this case, the Pressure Data Cell Range field and the Time Data Cell Range field would both have three data cell ranges inputted, the Excel Sheet No. field would have three sheet numbers provided (regardless if all data was contained on the same worksheet), and the File Path field would only contain one file. Further guidance on inputting data cell ranges properly can be found by clicking the Data Input Help button on the GUI.

Walkthrough of Radford Ballistics Relative Force/Relative Quickness Analysis Format

Upon selecting the BAE Systems – Radford Ballistics Excel Format burn rate analysis format, the GUI as shown in figure 7 will be displayed onscreen.
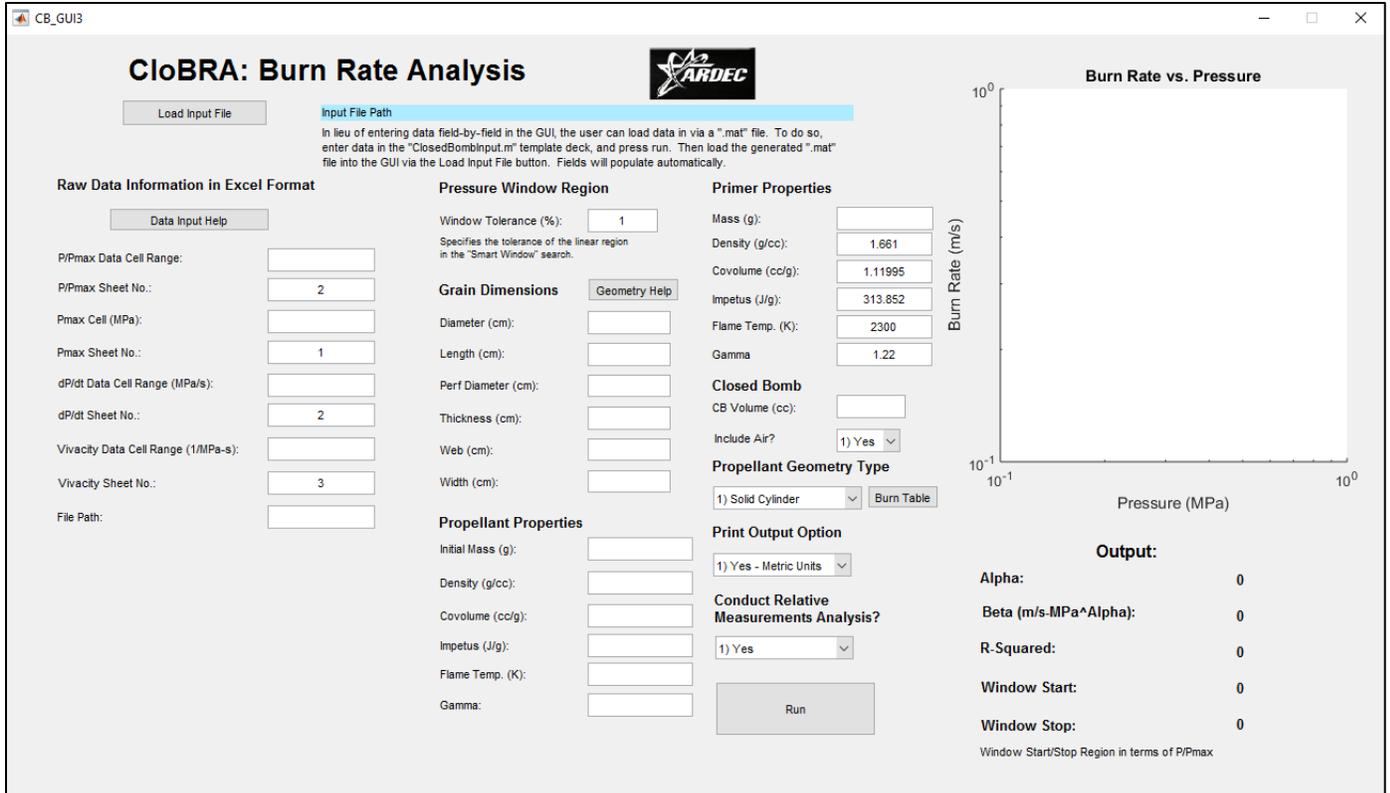
Figure 7
CloBRA: Burn rate analysis GUI for BAE Systems – Radford Ballistics Excel Format

Upon observation of figure 7, one will note that the structure of this GUI is almost identical to the two previously shown GUIs. However, the key differences between these GUIs are as follows: (1) The format of the Raw Data Information in Excel Format input deck has been altered and (2) The Savitzky-Golay filtering input deck has been removed. The filter option has been removed since the data provided in this format has already been filtered and has been reduced to 99 data points (in normalized pressure increments of 0.01). Since all other input decks are the same, they will not be discussed again in this section to mitigate redundancy. For more information on these fields, the reader is directed to consult the appropriate sections of the Walkthrough of Voltage versus Time GUI Format section provided previously in this document.

Raw Data in Excel Format Input Deck

The CloBRA program exclusively reads in raw data provided in an Excel worksheet format. Conveniently, the Radford Ballistics Relative Force/Relative Quickness Analysis raw data format is provided in a compatible Excel format for this program. In order for CloBRA to properly read in the raw data for this format type, the input fields of the GUI must be filled out appropriately. Detailed descriptions of the input fields for this section are provided in table 6.

Table 6
Description of fields in Raw Data Information in Excel Format Input Deck

Field Name	Description	How to Enter Information
P/Pmax Data Cell Range	This field corresponds to the normalized pressure trace of the data set. Since all data is provided in normalized pressure increments of 0.01, only one normalized pressure trace array is needed to be entered for the CloBRA program.	* Single and Multi-Shot Example: **A2:A100**
P/Pmax Sheet No.	This field corresponds to the Excel worksheet in which the normalized pressure trace was stored. Typically, this is the second worksheet of the Excel file and thus, the default value is 2.	* Single and Multi-Shot Example: **2**
Pmax Cell	This field corresponds to the cell containing the maximum pressure for a given shot in units of MPa. Note that when multiple shots are analyzed, the length of the Pmax Cell array entered must correspond to the number of shots analyzed.	* Single Shot Example: **L3** * Multiple Shot Example: **L3,L4** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
Pmax Sheet No.	This field corresponds to the Excel worksheet containing the Pmax cell for a given shot. Note that the maximum pressures for each shot are stored on the same sheet so only one index needs to be entered for this field, regardless of how many shots were fired. The default sheet number is 1.	* Single and Multi-Shot Example: **1**
dP/dt Data Cell Range (MPa/s)	This field corresponds to the Excel cells containing the time derivative of pressure array for a given shot. It is assumed that this array is in units of MPa/s. Note that when multiple shots are analyzed, the length of the dP/dt Data Cell Range array entered must correspond to the number of shots analyzed.	* Single Shot Example: **C2:C100** or **C:C** * Multiple Shot Example: **C2:C100,D2:D100** or **C:C,D:D** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
dP/dt Sheet No.	This field corresponds to the sheet that contains the dP/dt data for the shots analyzed. Note that the dP/dt traces for each shot are stored on the same sheet so only one index needs to be entered for this field, regardless of how many shots were fired. The default sheet number is 2.	* Single and Multi-Shot Example: **2**
Vivacity Data Cell Range (1/(MPa-s))	This field corresponds to the Excel cells containing the vivacity array for a given shot. It is assumed that this array is in units of 1/(MPa-s). Note that when multiple shots are analyzed, the length of the Vivacity Data Cell Range array entered must correspond to the number of shots analyzed.	* Single Shot Example: **C2:C100** * Multiple Shot Example: **C2:C100,D2:D100** or **C:C,D:D** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
dP/dt Sheet No.	This field corresponds to the sheet that contains the vivacity data for the shots analyzed. Note that the vivacity traces for each shot are stored on the same sheet so only one index needs to be entered for this field, regardless of how many shots were fired. The default sheet number is 3.	* Single and Multi-Shot Example: **3**
File Path	This field corresponds to the file name and path in which the Excel sheet with the data is stored. Note that all shots analyzed must be contained within the same Excel file.	Example: **C:\Users\Documents\File**

Unlike the other data formats, the BAE Systems – Radford Ballistics Excel format does not include a time trace for the collected pressure, time derivative of pressure, and vivacity data traces. However, since the data is provided in evenly-spaced, normalized pressure increments of 0.01, the time trace can be determined by first determining the time step at a given data increment via equation 20, and then summing the time steps together. In doing so, the time trace is established at each data point provided. The calculations discussed earlier are then performed in the same manner when performing the burn rate analysis.

$$\Delta t = \frac{0.01 \cdot P_{max}}{dP/dt} \tag{20}$$

Where,

Δt = The time step at a given data point (s)

P_{max} = Maximum pressure of the shot analyzed (MPa)

dP/dt = The time derivative of pressure at a given data point (MPa/s)

Running the CloBRA: Burn Rate Analysis GUIs

Once the chosen GUI format is set up appropriately per the previous instructions, the user would click the Run button. Upon doing so, a pressure versus time plot will be displayed onscreen to show how the pressure trace has been filtered according to the parameters defined for the Savitzky-Golay filtering method. Note that this step in the job-stream is skipped for the BAE Systems - Radford Ballistics Excel format since the pressure-time data is not filtered due to the low number of data points. An example plot of this figure is provided in figure 8, where the blue trace exhibits the filtered data trace produced, and the red points denote the unfiltered data points. Note that this figure was produced using the default Savitzky-Golay filters defined in the GUI. Additionally note that pressures that occur after the peak pressure of the test are removed from the analysis since it is assumed that all the solid propellant is consumed at this point.
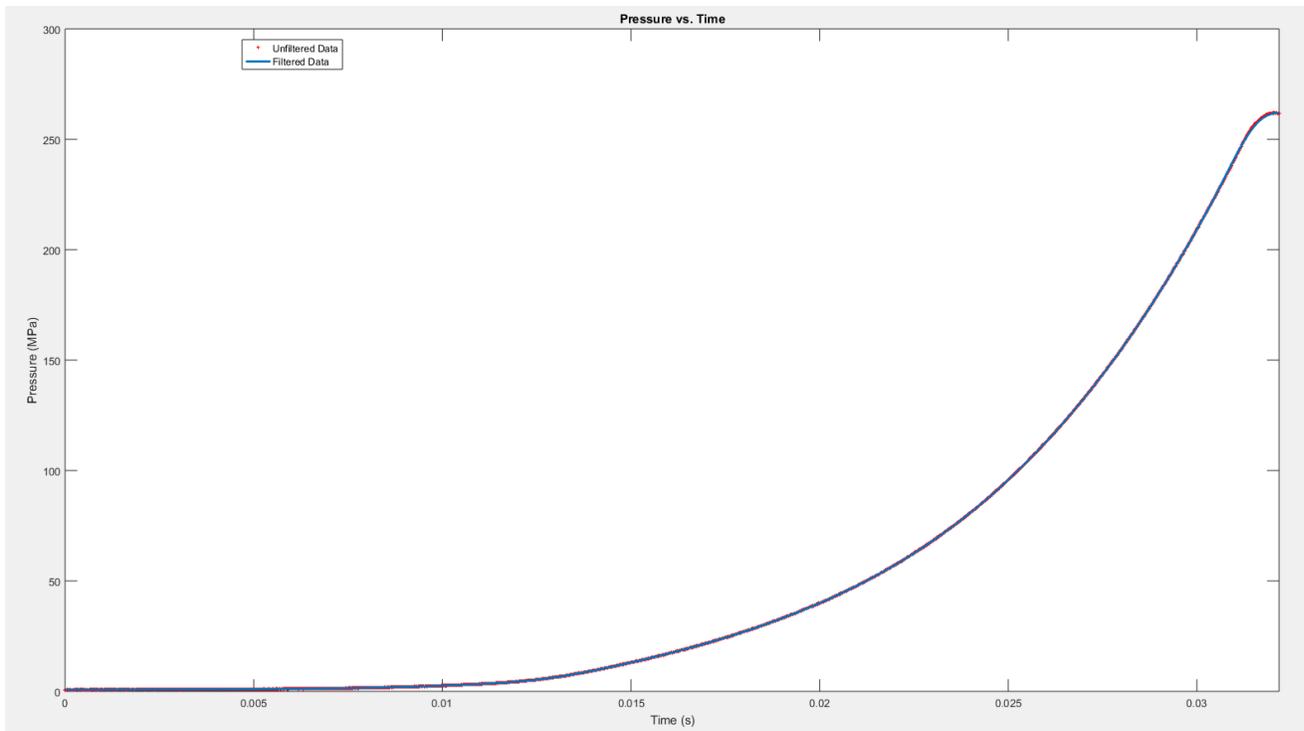
Figure 8
Example pressure versus time plot for burn rate analysis

The plot shown in figure 8 is also accompanied by a Filter Options display prompt window that asks the user to click "yes" if the data has been smoothed sufficiently or "no" if they would like to redefine the filter parameters. This Filter Options display prompt is shown in figure 9.
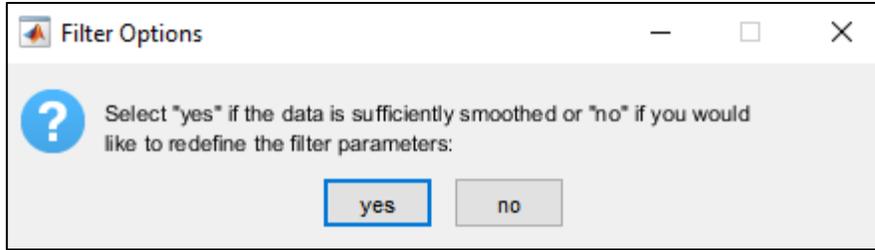
Figure 9
Filter Options display prompt

If the user clicks "yes", the CloBRA program will proceed to the next step of the job-stream. Else, if the user clicks "no", a Define New Filter Parameters input window will be displayed to allow the user to interactively update the filtering parameters as shown in figure 10. Note that once the user enters the new filtering parameters into the input window, the pressure versus time plot will update accordingly and the Filter Options display prompt will come onscreen again. The user can iteratively continue to update the filtering parameters by repeating the previously mentioned process until the data is sufficiently filtered.
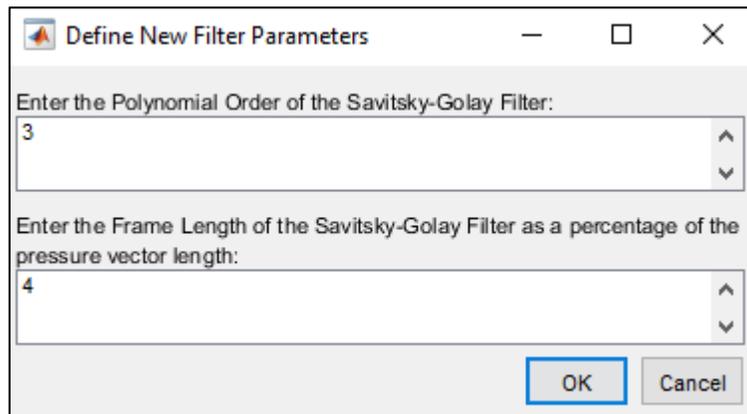
Figure 10
Define New Filter Parameters input window

Once the user selects "yes" on the Filter Options display prompt, a vivacity versus normalized pressure plot will be displayed onscreen. An example plot is shown in figure 11.
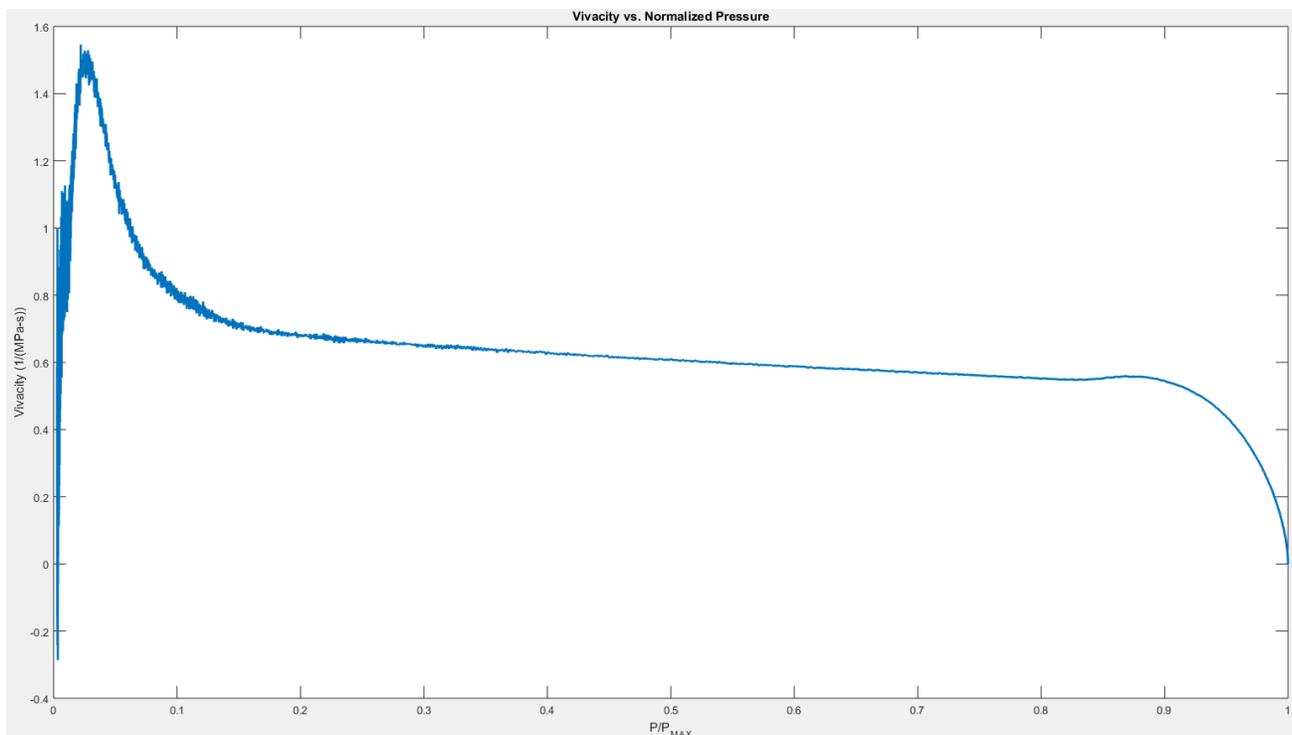
Figure 11
Example vivacity versus normalized pressure plot for burn rate analysis

       The vivacity versus normalized pressure plot is accompanied by an Initialize Smart Window Algorithm instruction prompt that provides the user with instructions on selecting the characteristic slope region of the vivacity versus normalized pressure plot. Specifically, once the user reads the prompt and presses the "OK" button, the mouse will turn into a data cursor that will allow the user to select two points on the vivacity versus normalized pressure plot. As discussed earlier, the characteristic slope region is used to determine the curve fitting region of the log(burn rate) versus log(pressure) plot. The Initialize Smart Window Algorithm instruction prompt is shown in figure 12.
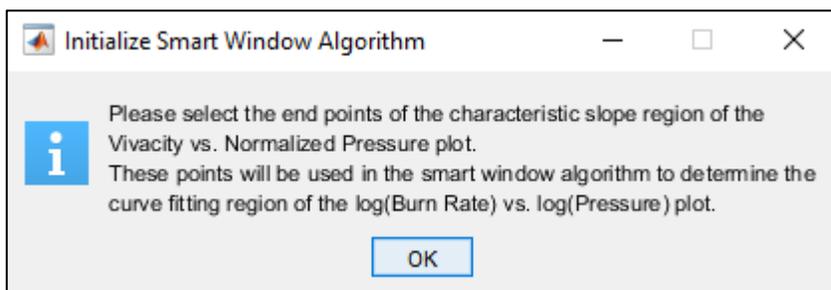
Figure 12
Initialize Smart Window Algorithm instruction prompt

       Once the endpoints of the characteristic slope region are selected, a tangent line will be fitted to the plot to determine the linear region of the selection. This linear region is referred to as the smart window in the CloBRA code. The corresponding tangent line will be displayed as a red line that spans the linear region within the endpoint selection. As discussed earlier, the Window Tolerance input field determines the tolerance of this tangent line. Essentially, any data point that does not vary

by more than the specified tolerance from the tangent line in the selected region is considered valid in the prescribed characteristic slope region. An example of this tangent line fit is shown in figure 13.
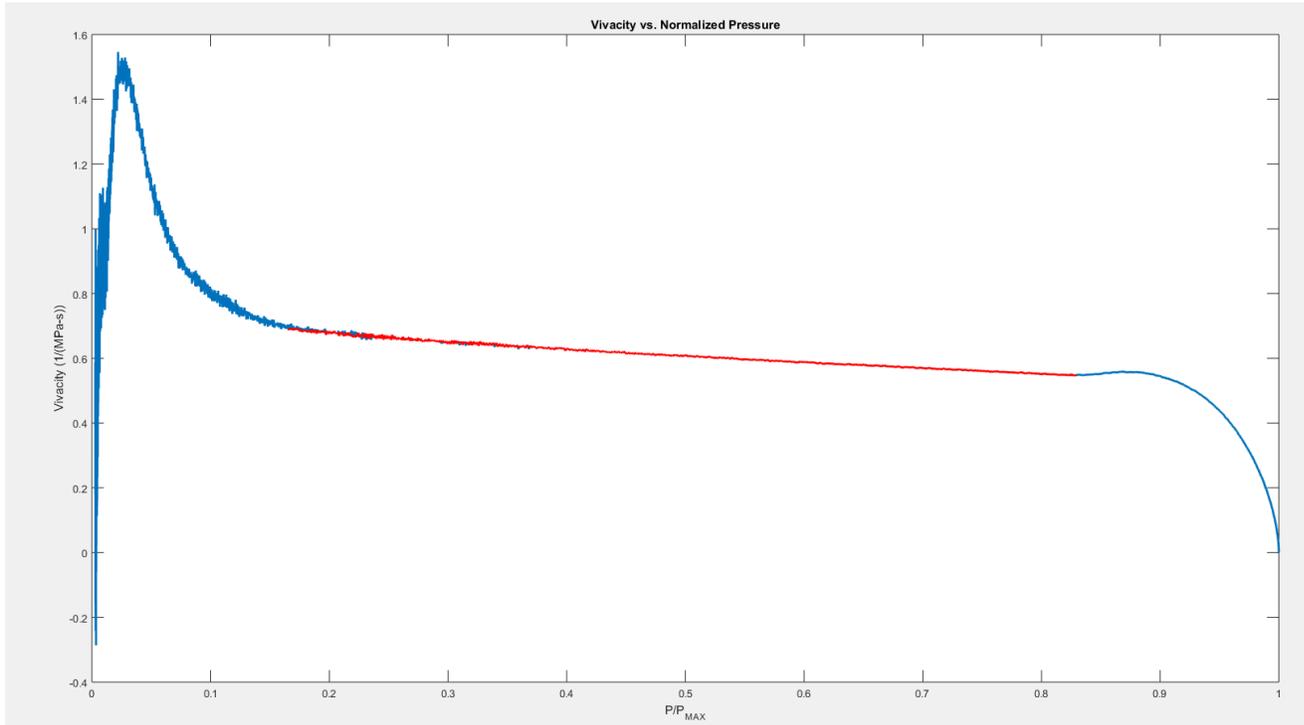
Figure 13
Smart window example plot for burn rate analysis

The CloBRA program will then begin to perform the burn rate analysis from the initial time step to the time at which the maximum pressure of the data trace occurs. The algorithm logic follows the methodology discussed previously in the Overview of Methodology section of this report. Once the burn rate analysis is complete for a given shot, the log-log plot on the GUI will display the burn rate versus pressure relationship for all data points analyzed. Additionally, the output parameters on the GUI will display their respective values based on the smart window fit. An example of this is shown in figure 14.
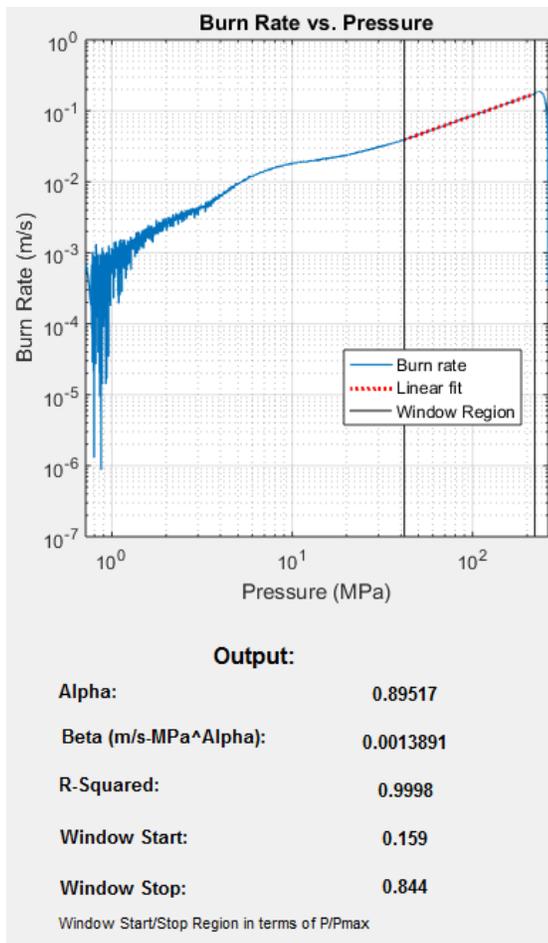
Figure 14
Example output in burn rate analysis GUI

As shown in figure 14, a dotted red linear fit is applied to the log(burn rate) versus log(pressure) curve within the window region prescribed earlier from the smart window fit. This window region is shown as the vertical black lines on the plot. The parameters governing Vielle's law, Alpha and Beta, are determined via a linear regression fit of the aforementioned plot. The R-squared value on the GUI corresponds to the coefficient of determination associated with the fit. Additionally, the Window Start and Window Stop values displayed on the GUI correspond to the initial and end points of the window region, respectively. Note that these values are in terms of the normalized pressure trace as noted on the GUI.

The aforementioned output on the GUI is also accompanied by a Redefine Window Region Option display prompt. This display prompt asks the user to select "yes" if the result is sufficient or "no" if they would like to redefine the window region. As discussed earlier, CloBRA allows the user to iteratively update the curve fit of the data until they achieve an acceptable coefficient of determination. Since CloBRA initially performs the burn rate analysis over the entire pressure trace, the window region can be updated almost instantaneously. The aforementioned display prompt is shown in figure 15.
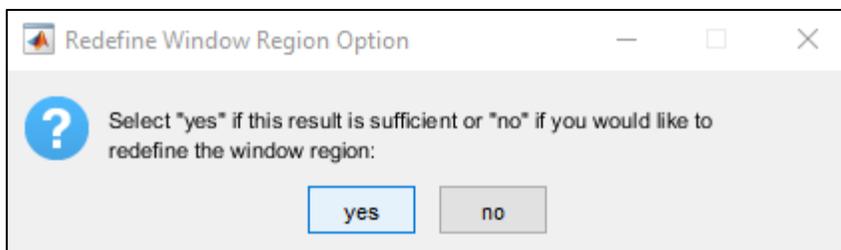
Figure 15
Redefine Window Region Option display prompt

If the R-squared value is not sufficient based on the initial endpoint selection of the vivacity versus normalized pressure plot, the user can click "no" to update the window region. Upon doing so, the Define New Window Region input prompt will display onscreen asking the user to enter new window starting and stopping locations in terms of the normalized pressure trace. An example of this prompt is shown in figure 16.
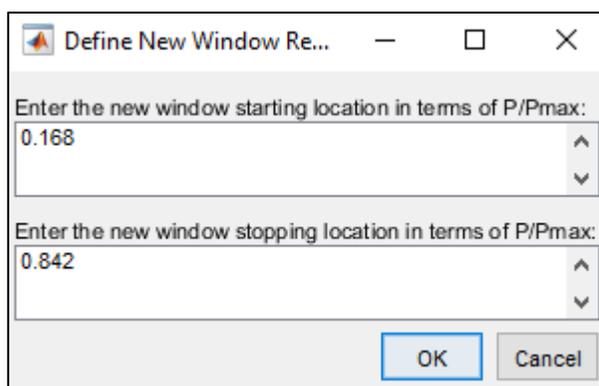
Figure 16
Define New Window Region input prompt

Upon entering new window starting and stopping locations, the window region displayed on the GUI will update to reflect the user's new selection. The Redefine Window Region Option display prompt will appear onscreen again to allow the user to repeat the process until the R-squared value is sufficient.

Once the burn rate analysis of the first shot is completed, a save file prompt will appear onscreen if the Print Output Option drop down menu was set to "yes". The user can then name the collection of output files via the "File name:" field in the save file prompt. The files produced will be as follows in table 7. Note that *Filename* in the Extension column of table 7 corresponds to the arbitrary filename specified by the user.

Table 7
Files generated by CloBRA burn rate analysis

File Type	Description	Extension
Excel results file	Prints all the computational results from the burn rate analysis into an Excel worksheet. If multiple shots are analyzed, each shot has their own worksheet in the Excel file that contains the inputs and outputs (e.g., Alpha) shown in the GUI as well as the pressure, time derivative of pressure, burn rate, distance burned, solid volume remaining, vivacity, and percent burned for each data point in the fitted window space discussed previously. Additionally, the last worksheet of the Excel file is the averaged results of the shots and contains the averaged valued outputs discussed previously. If only one shot is analyzed, only one sheet is generated in the Excel file to contain the inputs and outputs discussed earlier for the multiple shot case. Additionally, it is worth mentioning that each shot specific worksheet contains output that is used for the relative measurement analysis portion of the CloBRA program. These values were determined/selected according to the prescribed approach discussed in Method 801.1.2 of Reference 12. **In order to properly conduct the Relative Measurements Analysis, the user must not rename these files and/or manipulate the data. More information on the relative measurement computations is provided later in this document.**	For Test Shot: *Filename*_Results_TestShot For Reference Shot: *Filename*_Results_ReferenceShot
Raw data text files	Prints the time, pressure, time derivative of pressure, vivacity, and normalized pressure arrays for all time steps analyzed into separate text files for each shot analyzed. Note that these text files are required for the Relative Measurement Analysis when inputting the data for the test shot. **In order to properly conduct the Relative Measurements Analysis, the user must not rename these files and/or manipulate the data.**	For Test Shot: *Filename*_ShotZ_RawData_TestShot For Reference Shot: *Filename*_ShotZ_RawData_ReferenceShot [Where Z = shot number 1,2,3…]
Shot specific plots in PDF file format	Pressure versus time, vivacity versus normalized pressure, time derivative of pressure versus pressure, and burn rate versus pressure plots are generated for each shot analyzed. These plots are saved as a PDF file for each shot analyzed.	For Test Shot: *Filename*_Figures_Shot Z_TestShot For Reference Shot: *Filename*_Figures_Shot Z_ReferenceShot [Where Z = shot number 1,2,3…]
Composite plot in PDF file format	If multiple shots are analyzed, a composite plot is generated (i.e., containing all shot data on a given plot) and saved as a PDF file. This file contains the same plots as the shot specific files discussed above.	For Test Shot: *Filename*_Figures_Composite_Plot_TestShot For Reference Shot: *Filename*_Figures_Composite_Plot_ReferenceShot
Average plot in PDF file format	The shot averaged vivacity versus normalized pressure, time derivative of pressure versus pressure, and burn rate versus pressure plots are generated and saved as a PDF file.	For Test Shot: *Filename*_Figures_Average_Plot_TestShot For Reference Shot: *Filename*_Figures_Average_Plot_ReferenceShot

If multiple shots are analyzed, the entire process discussed previously (starting from the pressure versus time filter plot) will be conducted for the subsequent shots. Once all shots have been successfully analyzed, the Relative Measurements GUI will appear onscreen if the user selected "yes" in the Burn Rate Analysis GUI. Note that this analysis can only be performed if burn rate analyses have been conducted for both the reference and test shots with the Print Output Option set to "yes" (regardless of output units). However, if the user selected "no", a Run Successful display window will appear onscreen. Once the user selects "OK", the CloBRA: Burn Rate Analysis GUI will close and the user will be directed to the main directory of the CloBRA code.

In order to further clarify the job-stream of the CloBRA burn rate analysis, a simplified flowchart of the programming logic up until the relative measurements analysis is provided in figure 17.
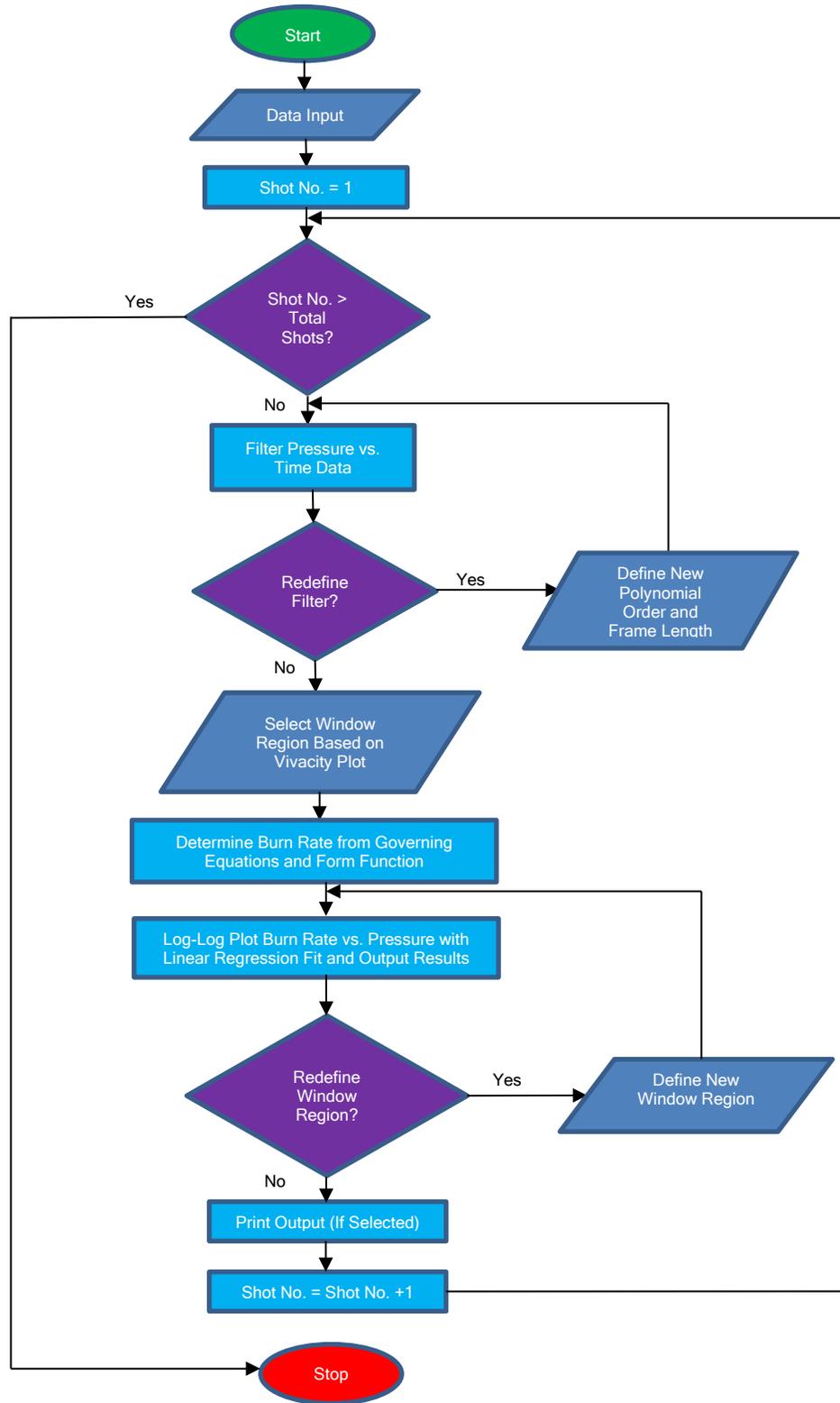
Figure 17
Simplified flowchart of CloBRA burn rate analysis

USER MANUAL – RELATIVE MEASUREMENTS ANALYSIS

Running the CloBRA: Relative Measurements GUI

The relative measurements analysis can be initiated via the CloBRA Program display prompt (shown in fig. 3) or via the Burn Rate Analysis GUI. If selecting the relative measurements analysis via the CloBRA program display prompt, the empty fields of the display prompt do not need to be filled out as discussed earlier. Additionally, it is important to again emphasize that the relative measurements analysis can only be performed if burn rate analyses have been conducted for both the reference and test shots with the Print Output Option set to "yes" (regardless of output units). This is because the CloBRA: Relative Measurements GUI uses the output Excel files as well as the raw data test shot text files as input to perform the required calculations. As briefly mentioned in table 7, it is particularly important to note that the data in the output Excel files is not altered by the user if a relative measurements analysis is performed. The CloBRA: Relative Measurements GUI is shown in figure 18.
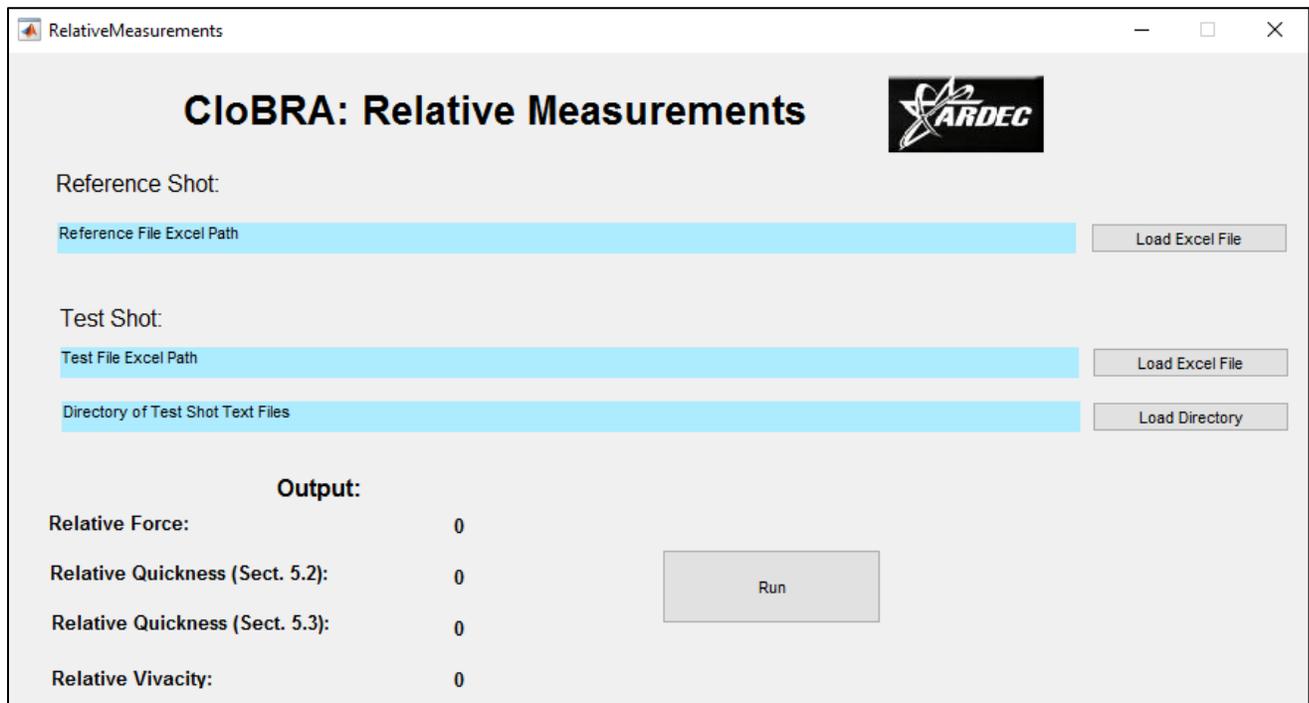
Figure 18
CloBRA: Relative Measurements GUI

As shown in figure 18, the CloBRA: Relative Measurements GUI only requires three inputs as follows: both the reference and test shot output Excel files and the directory containing the raw data test shot text files. The Excel files can be loaded into the GUI via the "Load Excel File" buttons next to the respective blue fields and the test shot directory is determined via the "Load Directory" button next to the "Directory of Test Shot Text Files" blue field. By default, the directories for both "Load Directory" buttons are set to the Output folder of the CloBRA directory; however, the user can navigate to wherever their data is stored if they chose to store their output files elsewhere. Note that as shown in table 7, the output Excel files and the text files automatically specify if the data analyzed were test or reference shots. In order to properly conduct the relative measurements analysis, the user must not rename these files and/or manipulate the data. If the files are renamed prior to the relative measurements analysis, the CloBRA program will not be able to identify which raw data test shot text files correspond to their respective test shot Excel file. Upon loading the files into the GUI,

the blue fields will display the appropriate directories. Note that all text files for the test shots must be stored in the same location and the directory is determined by the user selecting one file of the file set. By default, this directory is set to where the Excel file containing the test shots data is stored.

Once all files are specified in the GUI, the user can press the "Run" button to perform the analysis. After all the data from the Excel and text files are read into the program, a save file prompt will be displayed onscreen. The user can then name the output file via the "File name" field in the save file prompt. Note that the default directory for the output file is the Output folder of the CloBRA directory; however, the user can specify a different directory if warranted. Once the run is complete, the output fields of the CloBRA: Relative Measurements GUI populate with the computed relative measurement values, and a PDF file is generated that contains a relative quickness versus normalized pressure and relative vivacity versus normalized pressure for each shot as a well as a summary table that contains all the relative measurements computations (e.g., relative force). A Run Successful display window will then appear onscreen and once the user selects "OK", the CloBRA: Relative Measurements GUI will close and the user will be directed to the main directory of the CloBRA code.

Calculations used in CloBRA: Relative Measurements GUI

The computations for the RF and RQ follow the procedures discussed in Method 801.1.2 of reference 12. For completeness, details of these calculations are provided herein. Per the aforementioned reference, RF is defined via equation 21 and RQ is defined via equation 22.

$$RF = \frac{100}{m} \sum_{i=1}^{m} \left(\frac{T_{pmax\,i}}{R_{pmax\,i}} \right) \tag{21}$$

Where,

RF = RF (%)

m = Number of reference or test firings

$T_{pmax\,i}$ = Maximum pressure of test propellant for ith firing (MPa)

$R_{pmax\,i}$ = Maximum pressure of reference propellant for ith firing (MPa)

$$RQ = \frac{1}{m} \sum_{i=1}^{m} \left(\frac{100}{n} \sum_{j=1}^{n} \frac{T_{ij}}{R_{ij}} \right) \tag{22}$$

Where,

RQ = RQ (%)

n = Number of data points per firings (at least 4)

T_{ij} = dP/dt test propellant value of ith firing and jth data point (MPa/s)

R_{ij} = dP/dt reference propellant value of ith firing and jth data point (MPa/s)

Note that the time derivative of pressure values used in equation 22 are determined at discrete pressure points per Section 5.2 of Method 801.1.2 of reference 12. These pressure points are at approximately 27, 40, 53, and 66% of the peak pressure measured for the reference propellant. Since the pressure points used for this formula are in terms of the reference propellant

data, the raw data test shot text files are required as another input to the CloBRA program. A linear interpolation function is then used on the data within the text files to determine the time derivative of pressure at the explicit pressure points stated previously. Additionally, an alternative reporting method is performed in conjunction with the aforementioned method per Section 5.3 of Method 801.1.2 of reference 12. With respect to Section 5.3, the rate of pressure rise values at 7, 14, 21, 28, and 35 MPa are reported as well as the average rate of pressure rise for higher pressures in increments of 35 MPa up until 280 MPa. These rate of pressure rise values are provided in units of MPa per millisecond and are printed in the output Excel files. Additionally, the RQ is computed for this method via equation 22.

Consistent with the CBA program of reference 1, the RV is computed by comparing the vivacity of the test propellant to the reference propellant at 30, 40, 50, 60, and 70% of the peak pressure. Unlike the computation of RQ, these intervals are shot specific. The RV is computed per equation 23:

$$RV = \frac{1}{m}\sum_{i=1}^{m}\left(\frac{100}{n}\sum_{j=1}^{n}\frac{TV_{ij}}{RV_{ij}}\right) \tag{23}$$

Where,

RV = RV (%)

TV_{ij} = Vivacity test propellant value of ith firing and j^{th} data point (1/(MPa-s))

RV_{ij} = Vivacity reference propellant value of ith firing and j^{th} data point (1/(MPa-s))

Note that the vivacity for a given shot is computed via equation 24:

$$Viv.(t) = \frac{\frac{dP(t)}{dt}}{P(t)\cdot P_{max}} \tag{24}$$

Where,

$Viv.(t)$ = Vivacity at a given time step (1/(MPa-s))

$\frac{dP(t)}{dt}$ = Time derivative of pressure at a given time step (MPa/s)

$P(t)$ = Pressure at a given time step (MPa)

P_{max} = Peak pressure of data trace (MPa)

USER MANUAL - PRESSURE-TIME CURVE GENERATOR

Upon selecting the Pressure-Time Curve Generator option from the CloBRA Program Display Prompt, the GUI shown in figure 19 will be displayed onscreen.
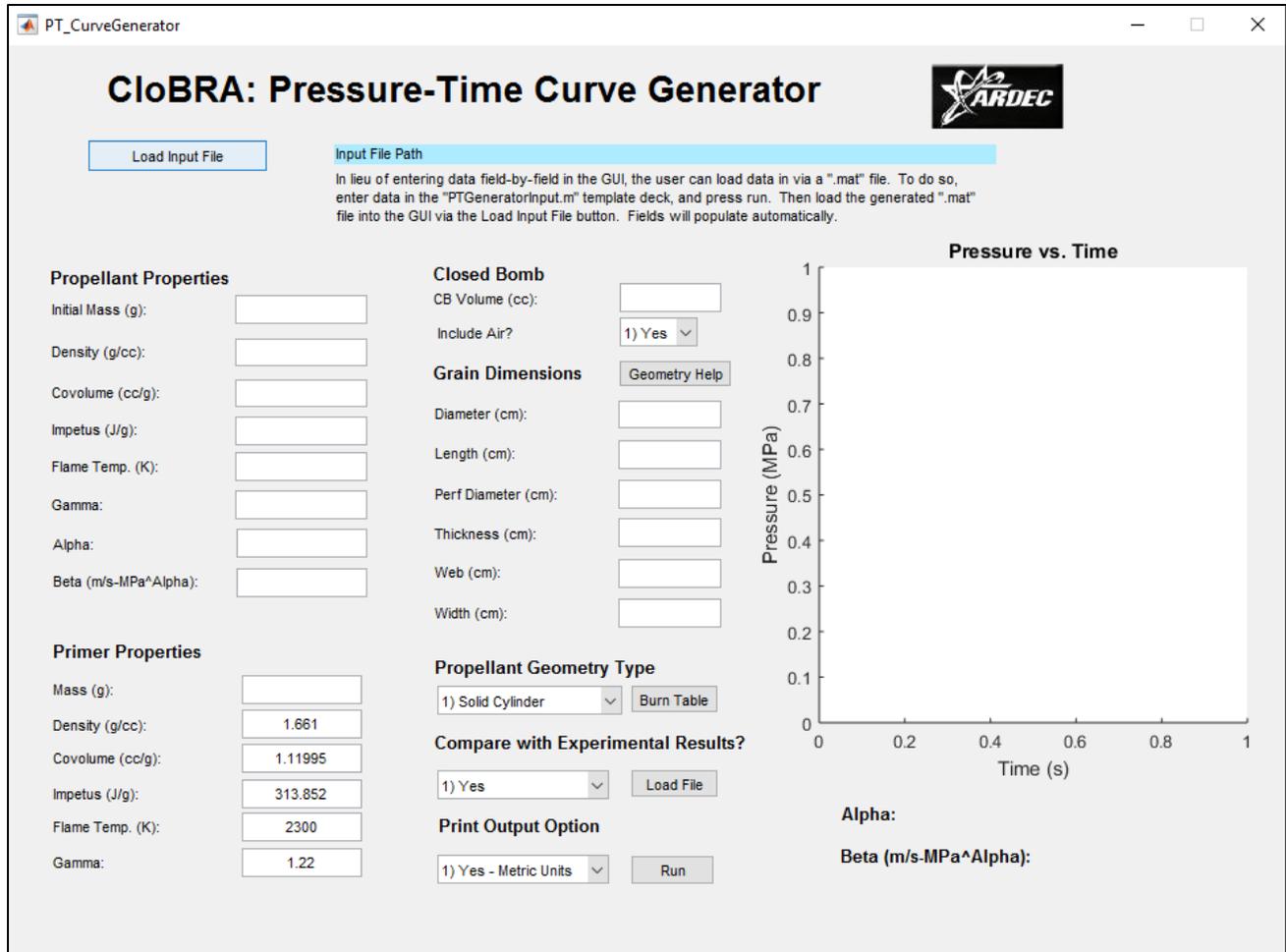
Figure 19
CloBRA: Pressure-Time Curve Generator GUI

As shown in figure 19, the Pressure-Time Curve Generator GUI requires very similar input options as the aforementioned Burn Rate Analysis GUIs and also contains a "Load Input File" button feature, which operates in the same manner as the Burn Rate Analysis GUIs. However, the Pressure-Time Curve Generator GUI only uses the Propellant Properties, Primer Properties, Closed Bomb, and Grain Dimensions input decks. In addition, the user will note that the Propellant Properties deck is also equipped with inputs for Alpha and Beta, which are the exponent and coefficient of Vielle's law, respectively. One last distinct feature to note is that the user can compare the predicted pressure-time trace with experimental data via the "Compare with Experimental Results?" drop down menu on the GUI. Upon selecting "yes", the user will then click the Load File button and load in an output text file produced from the CloBRA: Burn Rate Analysis (see the Raw Data Text Files discussion provided in table 7 for further information). Note that the aforementioned output text file can be in either English or metric units. For more information on the other fields, the reader is directed to consult the appropriate sections of the Walkthrough of Voltage versus Time GUI Format section provided earlier in this document.

Running the CloBRA: Pressure-Time Curve Generator GUI

Prior to proceeding with this section, it is important to clarify that the pressure-time curve generator utility can be used for two different means as follows:

- Option 1: The user can take a known formulation with well-established burn rate parameters and observe the behavior of the pressure-time curve trace for a given geometry and loading density. Essentially, this is a quick means of allowing the user to assess how a specific propellant configuration should burn in a closed bomb vessel. Note that the methodology used in the program is analogous to that of a well-stirred reactor, interior ballistics model with no projectile motion (i.e., fixed volume). This option is conducted via setting the "Compare with Experimental Results?" drop down menu on the GUI to "no".

- Option 2: The user can see how well the computed burn rate parameters, from the burn rate analysis, replicate the experimental results. The user can also employ an optimization routine that enhances the burn rate parameters such that the computed pressure-time trace can further align with the experimental data. This is done by reducing the sum of square error between the two curves. The original burn rate parameters as well as the optimized values can then be used in downstream interior ballistics analyses. Note that this option is conducted via setting the "Compare with Experimental Results?" drop down menu on the GUI to "yes". As an aside, more work should be conducted in the future to determine which set of burn rate parameters is more representative of true ballistic performance.

Option 1

After entering the appropriate parameters in the input deck fields and setting the "Compare with Experimental Results?" drop down menu on the GUI to "no", the user can then press the "Run" button. The corresponding pressure-time trace will then populate the graph space and the values for Alpha and Beta will also be reiterated on the GUI. An example plot is as shown in figure 20 for a 1-perforated propellant grain. For further guidance on the calculation method used, see the Governing Equations for Pressure-Time Curve Generation Analysis section, which is contained previously in this report.
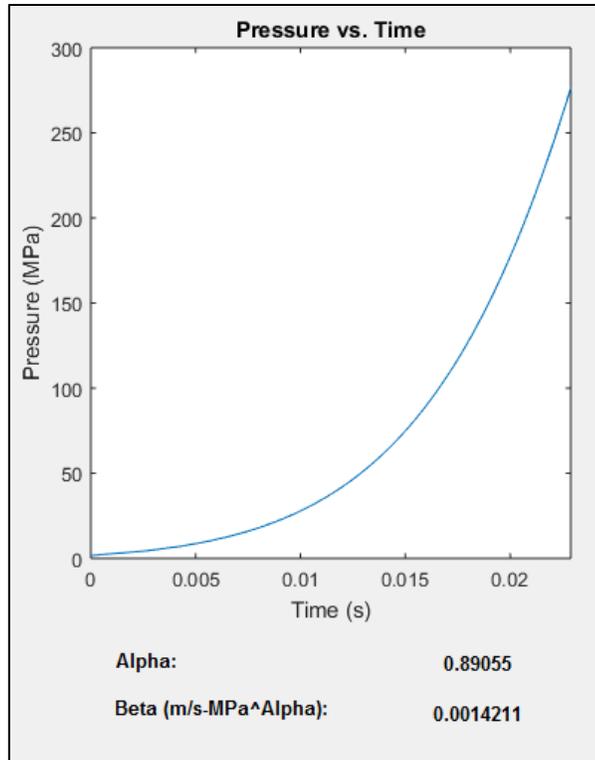
Figure 20
Option 1: Example output in Pressure-Time Curve Generator GUI

Once the pressure-time curve is generated for the case analyzed, a save file prompt will appear onscreen if the Print Output Option drop down menu was set to "yes". The user can then name the collection of output files via the "File name:" field in the save file prompt. The files produced will be as follows in table 8. Note that *Filename* in the Extension column of table 8 corresponds to the arbitrary filename specified by the user.

Table 8
Files generated by option 1 of CloBRA Pressure-Time Curve Generator GUI

File type	Description	Extension
Excel file	Echoes all input parameters and provides the predicted pressure versus time data in a tabular format.	*Filename*_PT_Curve_Prediction
PDF file	Prints the pressure versus time graph of the GUI to a PDF file.	

If the user did not set the Print Output Option drop down menu to "yes", a run successful prompt will be displayed onscreen. Once the user clicks "ok", the program will exit and redirect the user to the main directory of the CloBRA program.

Option 2

After entering the appropriate parameters in the input deck fields, the user must then set the "Compare with Experimental Results?" drop down menu on the GUI to "yes". The user will then click the "Load File" button and import the corresponding output text file from the CloBRA: Burn Rate Analysis. Note that the aforementioned output text file can be in either English or Metric units. After this, the user can then press the "Run" button. The computed pressure-time trace will then

populate the graph space on the GUI along with the experimental pressure-time trace and the R-squared value associated with the two curves. Additionally, the values for Alpha and Beta will also be reiterated on the GUI. An example plot is as shown in figure 21 for a 7-perforated propellant grain. For further guidance on the calculation method used, see the Governing Equations for Pressure-Time Curve Generation Analysis section, which is contained previously in this report.
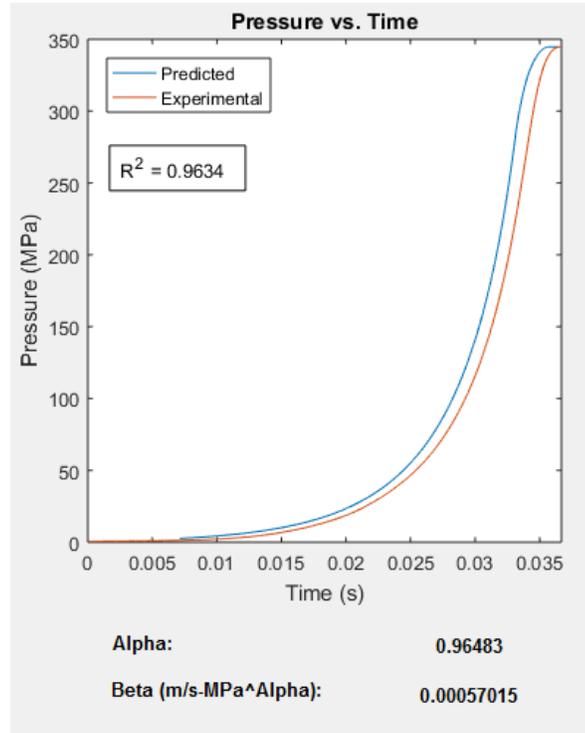
Figure 21
Option 2: Example output in Pressure-Time Curve Generator GUI for first iteration

A Redefine Burn Rate Option prompt will then be displayed onscreen asking the user if they would like to optimize the burn rate parameters such that the two traces come to better agreement with one another. This is done by an optimization routine that adjusts the burn rate parameters of the computed pressure-time curve until the sum of square error between the two curves reaches its minimum value. If the user selects "yes", then the optimization routine will be performed. The Redefine Burn Rate Option prompt is displayed in figure 22.
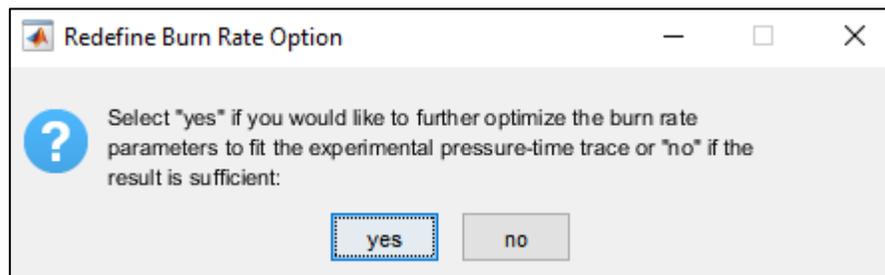
Figure 22
Redefine Burn Rate Option prompt

The results following the optimization routine for the aforementioned example case are demonstrated in figure 23. Per the figure, one will note that the R-squared value increased and the

pressure-time curves almost coincide with one another. Additionally, the Alpha and Beta values displayed on the GUI will be updated accordingly.
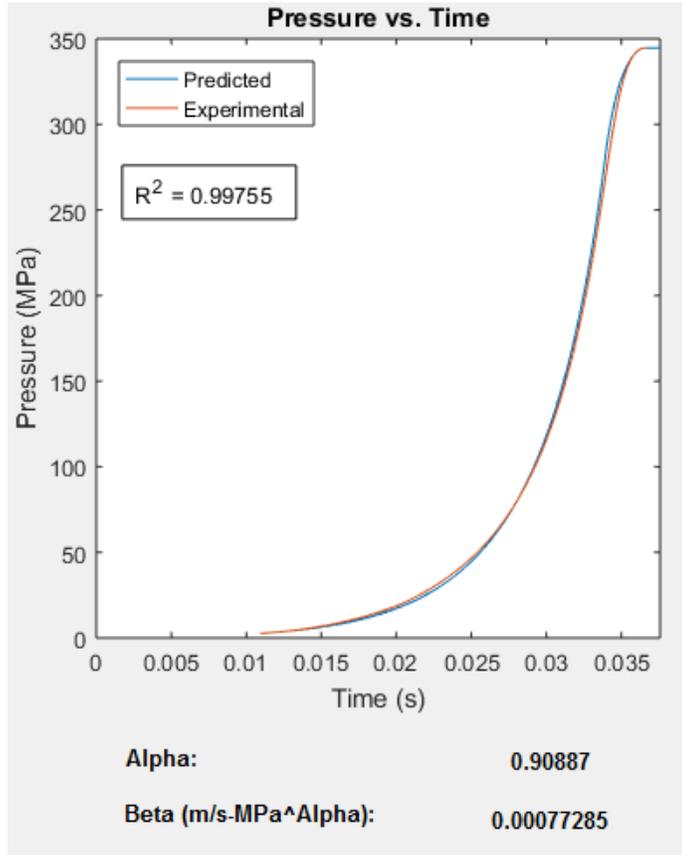
Figure 23
Option 2: Example output in Pressure-Time Curve Generator GUI for second iteration

Once the pressure-time curve is generated for the case analyzed, a save file prompt will appear onscreen if the Print Output Option drop down menu was set to "yes". The user can then name the collection of output files via the "File name:" field in the save file prompt. The files produced will be as follows in table 9. Note that *Filename* in the Extension column of table 9 corresponds to the arbitrary filename specified by the user.

Table 9
Files generated by option 2 of CloBRA Pressure-Time Curve Generator GUI

File type	Description	Extension
Excel file	Echoes all input parameters and provides the predicted pressure versus time data, as well as the experimental pressure versus time data in a tabular format. If the optimization routine was utilized, the optimized burn rate parameters will supersede the original values used as input. Furthermore, the Alpha and Beta values displayed in the file will be representative of the computed pressure-time trace produced in the PDF file.	*Filename*_PT_Curve_Comparison
PDF file	Prints the pressure versus time graph of the GUI, as well as the corresponding R-squared value to a PDF file.	

If the user did not set the Print Output Option drop down menu to "yes", a run successful prompt will be displayed onscreen. Once the user clicks "ok", the program will exit and redirect the user to the main directory of the CloBRA program.

COMPARISON OF BURN RATE RESULTS WITH LEGACY CODES

In order to validate the burn rate analysis of the CloBRA program, computed burn rates for tested propellants were compared to results produced by select legacy codes. The results are provided in the following subsections.

CloBRA versus ARDEC CBA Program

Due to ease of accessibility, most trial validations of the CloBRA program were compared to the legacy ARDEC CBA program. Raw closed bomb data collected at Picatinny Arsenal was analyzed with both closed bomb analysis programs. For all cases tested, the CloBRA program produced burn rates that were less than 2% different than the burn rates produced by the legacy ARDEC CBA program. Potential differences in the burn rates could be attributed to how the raw data was filtered, the heat loss correlation used in CloBRA, the inclusion of air in the closed bomb vessel in CloBRA, and/or CloBRA's inclusion of the ignitor to pressurize the closed bomb vessel at time zero. Despite these known differences, the results are relatively consistent and are provided in figures 24 through 28 for each case analyzed. Note that the burn rates are only compared at the applicable pressure ranges for each test.
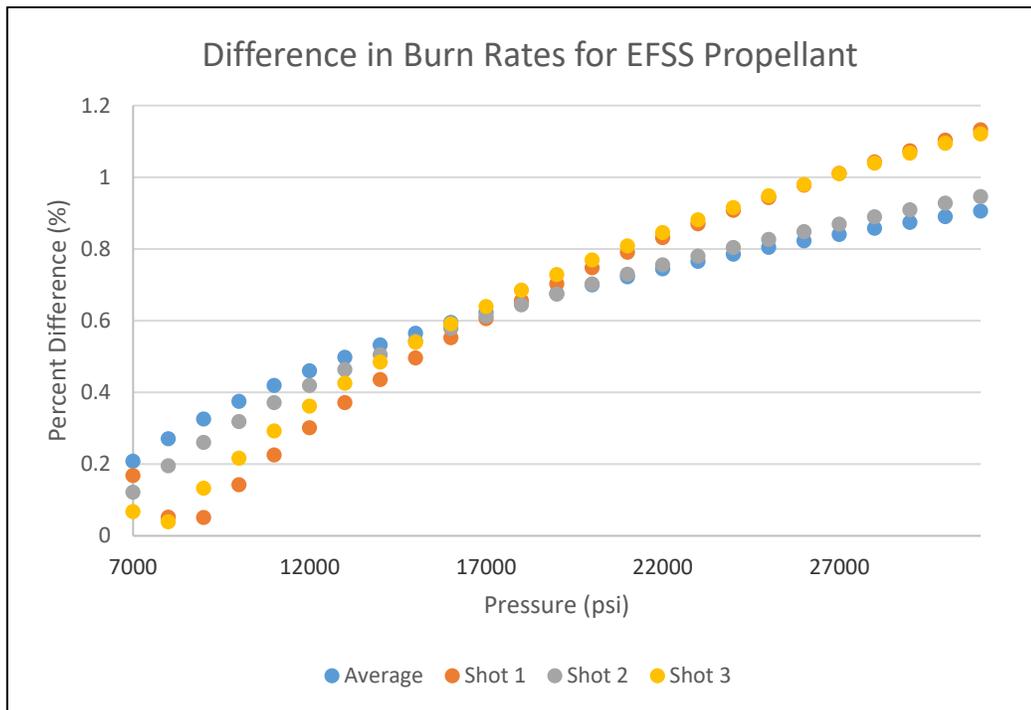
Figure 24
Expeditionary fire support system (EFSS) propellant – 1-perf cylinder geometry
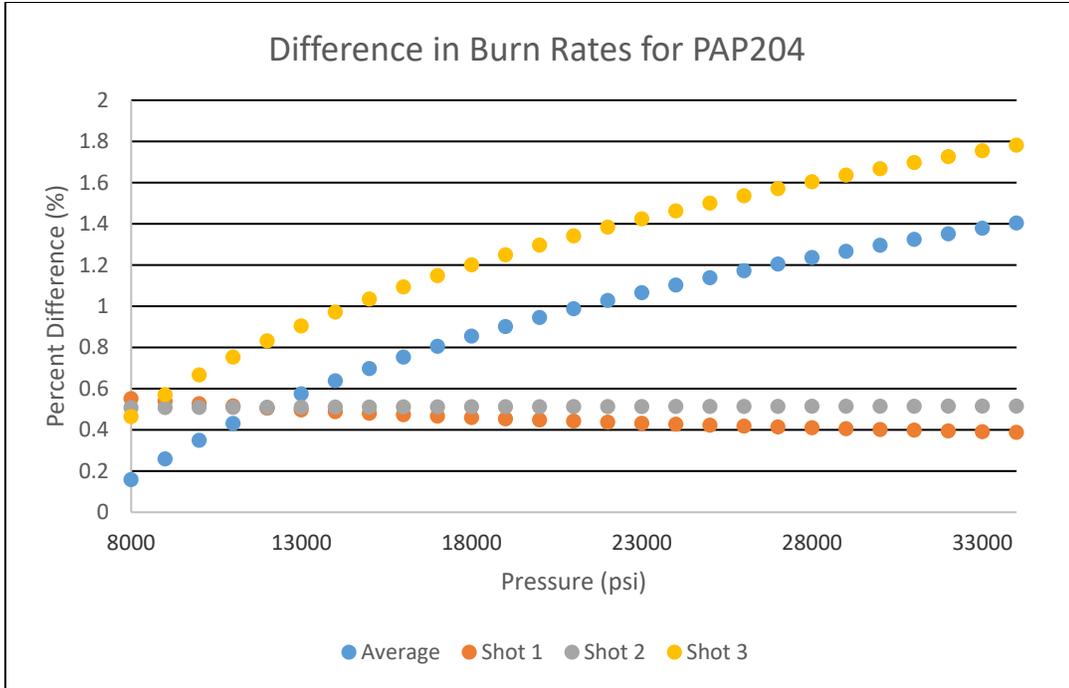
Figure 25
Picatinny Arsenal propellant (PAP) 204 – 7-perf cylinder geometry
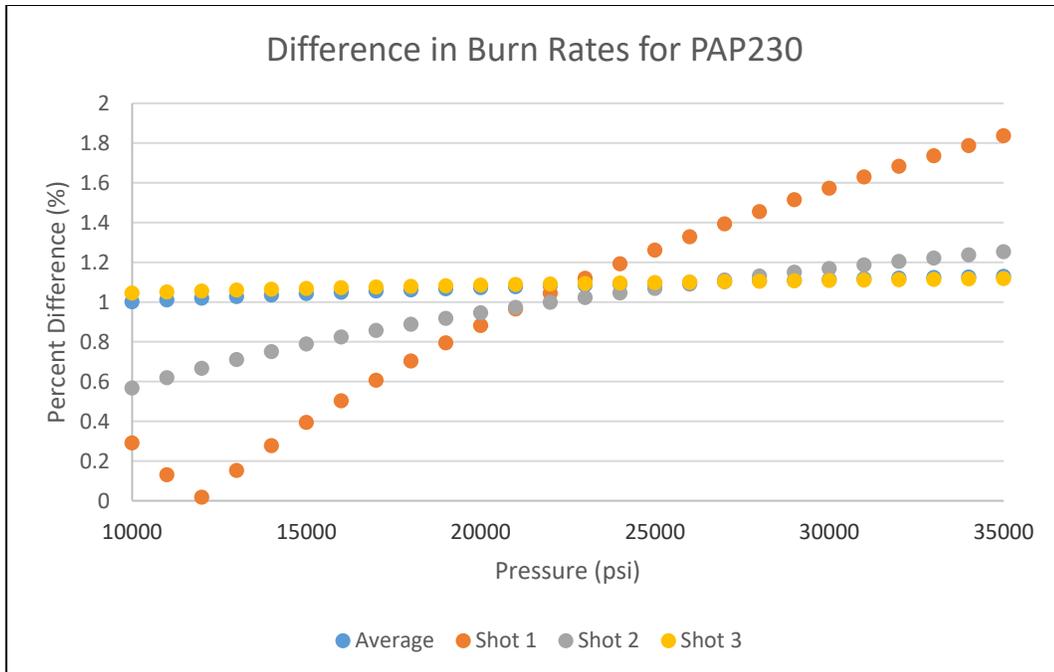
Figure 26
PAP 230 – 7-perf cylinder geometry
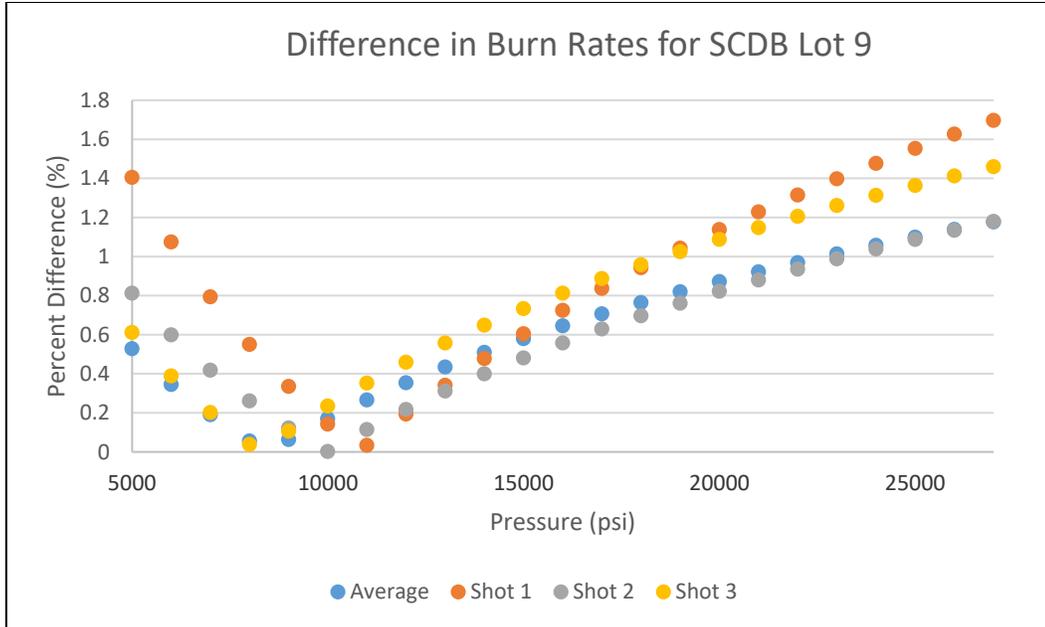
Figure 27
Single-coated double base (SCDB) propellant lot 9 – 19-perf cylinder geometry
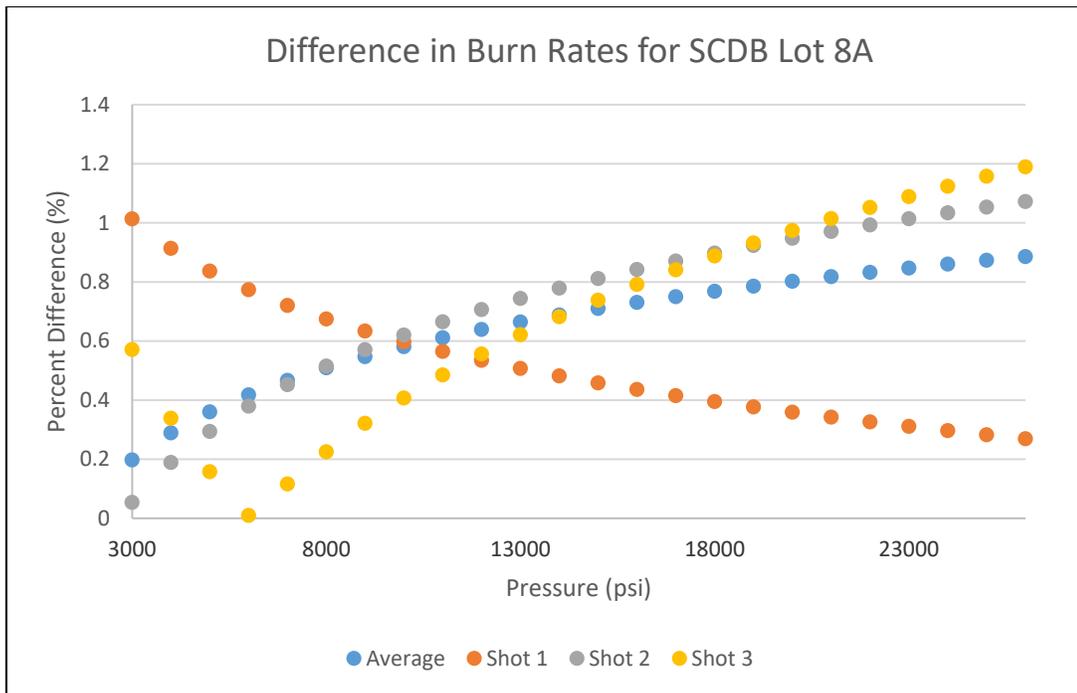
Figure 28
SCDB propellant lot 8A – 19-perf cylinder geometry

Additionally, a relative measurements comparison study was conducted between the two aforementioned codes using lot 9 of the SCDB propellant as the reference shot and lot 8A of the SCDB propellant as the test shot. As shown in table 10, the results were less than 0.3% within one another. This small error can be due to how the raw data was filtered between the two codes.

Table 10
Relative measurements comparison for SCDB lots 8A and 9

Parameter	CloBRA value (%)	ARDEC CBA value (%)	Difference (%)
RF	99.63	99.62	0.01
RQ (Section 5.2 of MIL Spec)	99.30	99.56	0.26
RV	99.95	99.88	0.07

CloBRA versus Radford Closed Bomb Program

Prior to discussing the results, it is important to first note that the format of the Radford Ballistics Relative Force/Relative Quickness data sets are truncated to 99 data points, which are incremented in terms of 1% of the normalized pressure trace. With that said, some of the key features of the raw data are inherently attenuated due to the reduced data set. Despite this, the methodologies employed by the CloBRA program demonstrated the burn rates were within 4% of those predicted by the Radford Closed program. Furthermore, CloBRA is capable of adequately reproducing burn rates from crude data sets. The results are shown in the figures 29 through 31 for the applicable pressure ranges analyzed.
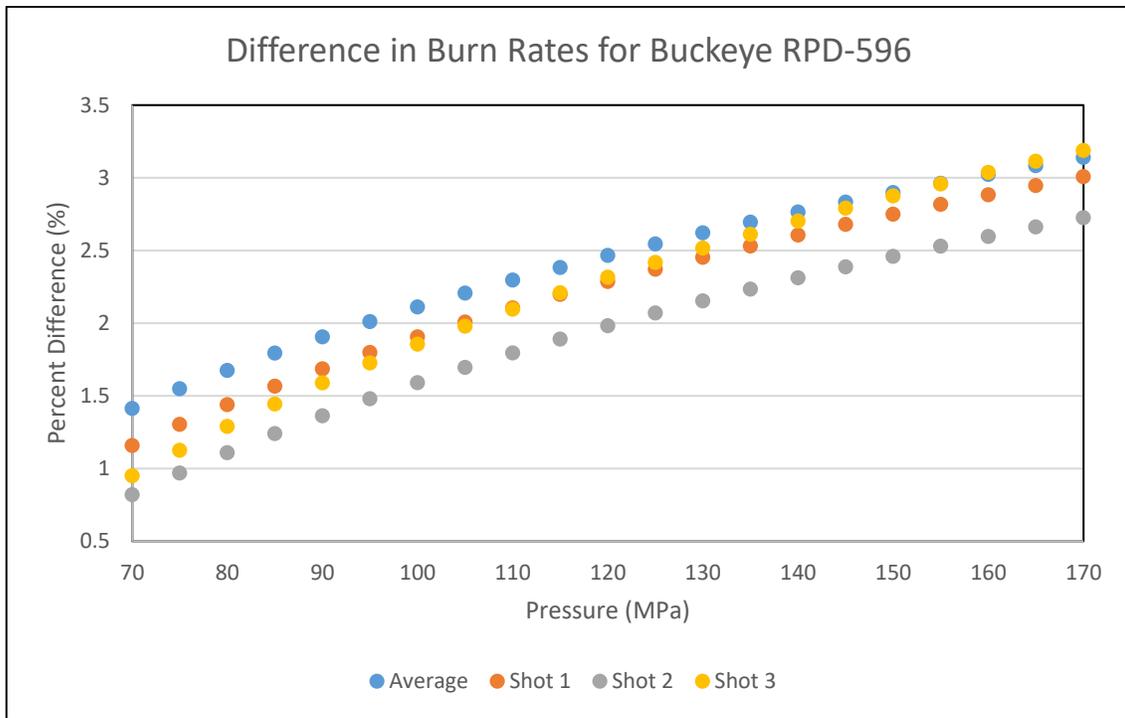
Figure 29
Buckeye RPD-596 propellant – 7-perf cylinder geometry
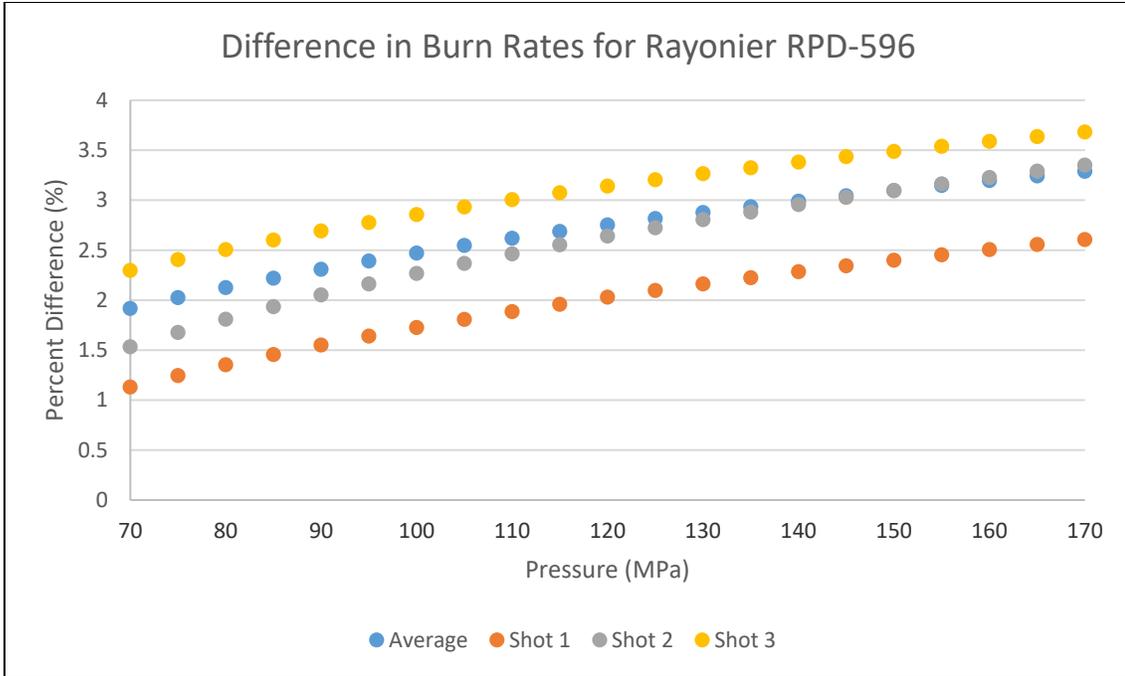
Figure 30
Rayonier RPD-596 propellant – 7-perf cylinder geometry
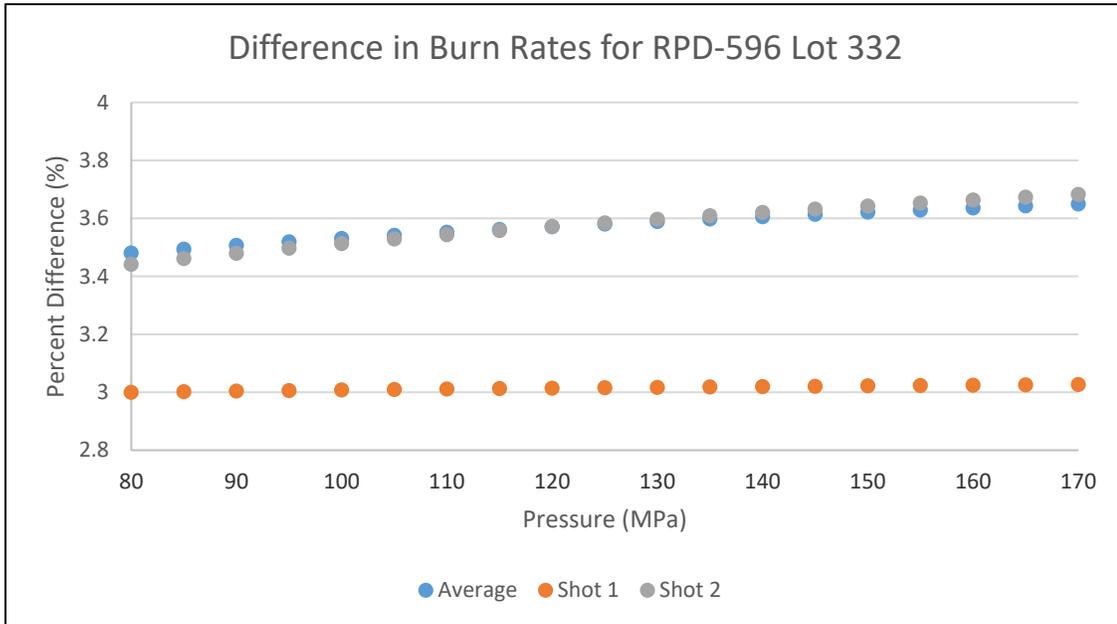
Figure 31
RPD-596 lot 332 propellant – 7-perf cylinder geometry

CloBRA versus XLCB Program

CloBRA was also compared against a legacy test case produced by XLCB in 2004. For this case, three shots of JA2 propellant were tested in a small closed bomb vessel of 25.9 cm^3. The average pressure trace as a function of time as well as the burn rates in discrete intervals of 10 MPa were provided in a summary report sent to DEVCOM AC. In order to compare the results, a CloBRA

Burn Rate analysis was conducted using the aforementioned pressure-time trace to produce Alpha and Beta values governing the burn rate equation. These parameters were then used to compare burn rates at the discrete pressures intervals identified previously. The results are provided in figure 32.
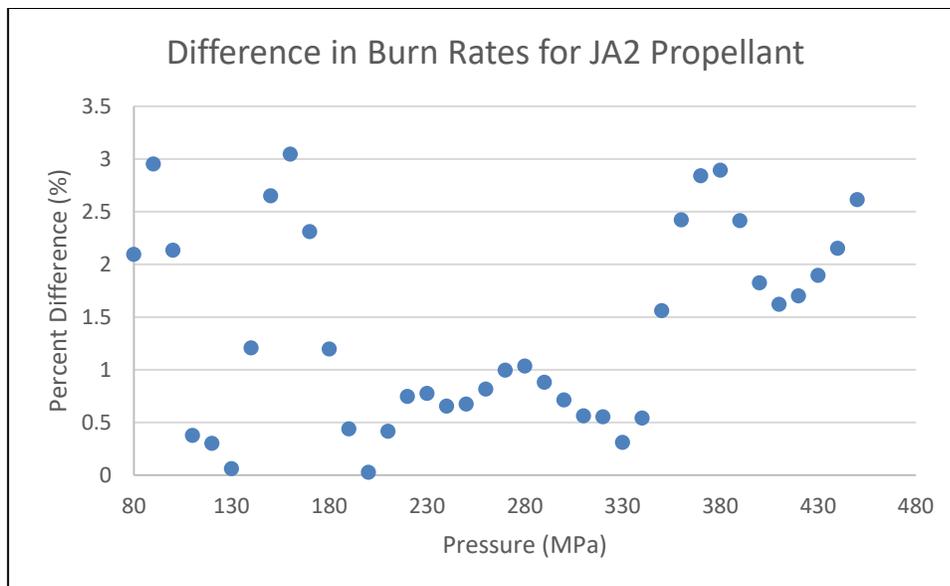
Figure 32
JA2 propellant – solid cylinder geometry

As shown by the figure, the largest percent difference in computed burn rates between the two programs was around 3%. On average, the percent difference was 1.66% for the pressure range analyzed. The differences in the results can be attributed to the average pressure-time trace used to reduce the data and also the absence of Alpha and Beta parameters determined by the XLCB. While the two codes are in reasonable agreement with one another, further alignment between the two codes would most likely be exhibited if the true raw data was processed through both programs.

CONCLUSIONS

The U.S. Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC) Closed Bomb Reduction Analysis (CloBRA), Picatinny Arsenal, NJ, program has been developed to reduce closed bomb test data using a refined, user-friendly, and interactive approach. Although the program uses the same governing assumptions embellished in most other legacy closed bomb analyses, CloBRA uses state of the art tools to modernize the data reduction effort (e.g., burn table feature for geometries that do not adhere to analytical form functions) and streamline the output of reduced data. Based on sensitivity studies conducted in the preceding section, the CloBRA program produces burn rates that align closely with legacy analyses. In addition, CloBRA is equipped with a pressure-time curve generator that can predict the pressure-time trace of a given propellant in a closed bomb vessel, compare the predicted burn rate for a given lot of propellant to experimental data, and optimize burn rates based on comparisons with experimental test data. Furthermore, the DEVCOM AC CloBRA program is available for use and is fully capable of supporting future closed bomb testing efforts.

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APPENDIX A
INPUT DECKS FOR CLOBRA PROGRAM

Burn Rate Analysis Input Decks

The CloBRA Burn Rate Analysis GUIs are equipped with a Load Input File button that allows the user to populate the fields of the GUI with a predefined input deck. This input deck is in the form of a MATLAB script containing the parameter names assigned to the selected Burn Rate Analysis GUI. If the user decides to use this feature, they would enter the appropriate data to the corresponding parameters, specify a file name for the generated MATLAB formatted data file (i.e., .mat file), and would then hit the "Run" button to generate the corresponding .mat file. The data contained in the .mat file can then be directly load into the CloBRA Burn Rate Analysis GUI.

Each GUI has different parameter names assigned to them since they require different input; however, a universal template can be used for any Burn Rate Analysis GUI type selected. This universal template deck is provided below. The text below can be directly loaded into a new MATLAB script file and can be used as discussed above once the user provides the appropriate data input. When entering data into the template deck, the user is cautioned to enter "[];" (without the quotation marks) for fields that are not used in the selected GUI. Also, note that when entering data, the user should delete the square brackets and enter the information between the equal sign and the semicolon for a given field.

```matlab
%CloBRA Burn Rate Input File
clear;
clc;
close all;

%Run this code first after all inputs have been entered

%% Enter the Following User Defined Parameters and Options:

%---Calibration Factors for Voltage-Pressure Conversion------------------%
% in form:(A0.*voltage.^3 + A1.*voltage.^2 + A2.*voltage + A3);
A0 = [];
A1 = [];
A2 = [];
A3 = [];
%Unit Conversion for Transducer Reading
%1 = Volts to PSI, or PSI if input is Pressure vs. Time
%2 = Volts to MPa, or MPa if input is Pressure vs. Time
ConversionFormat = 1;

%---Raw Data Information-------------------------------------------------%
%Only reads excel files
%transducer and time reading vectors must be the same size!
TransducerDataInput = []; %pressure/voltage vector
TimeInput = []; %time vector
Sheet = []; %Sheet number where data is stored
File = []; %name and location of file where data is stored

%Fields Specific to Radford Ballistics Format
NomPData = []; %P/Pmax
NomPSheet = []; %Excel sheet number where P/Pmax is stored
PMaxData = []; %Cell containing Pmax value
PMaxSheet = []; %Excel sheet number where Pmax is stored
dPdtData = []; %dP/dt data
dPdtSheet = []; %Excel sheet number where dP/dt is stored
VivacityData = []; %Vivacity data
VivacitySheet = []; %Excel sheet number where vivacity is stored
```

```matlab
%---Savitzky-Golay Filtering--------------------------------------------------%
PolyOrder = 3; %order of polynomial for Savitzky-Golay filter
framelength = 4; % percent of data points.


%---Pressure Window Region----------------------------------------------------%
tol = 1; %This tolerance (%) corresponds to the variance in the linear fit
%of the vivacity vs P/Pmax curve (window region).


%---Grain Dimensions----------------------------------------------------------%
diameter = []; %cm
length_grain = []; %cm
perf_diameter = []; %cm
web = []; %cm
width = []; %cm
thickness = []; %cm


%---Propellant Properties-----------------------------------------------------%
initialMass = []; %g
rho = []; %density of propellant, g/cc
covol = []; %covolume of propellant, cc/g
Impetus = []; %J/g
flameTemp = []; %K
gamma = [];


%---Primer Properties---------------------------------------------------------%
primerMass = []; %g
primerRho = 1.661; %g/cc
primerCovol = 1.11995; %cc/g
primerImpetus = 313.852; %J/g
primerFlameTemp = 2300; %K
primerGamma = 1.22;


%---Closed Bomb---------------------------------------------------------------%
bombVolume = []; %cc


%---Propellant Geometry Type--------------------------------------------------%
% 1) Solid Cylinder
% 2) 1 Perf Cylinder
% 3) 7 Perf Cylinder
% 4) 19 Perf Cylinder
% 5) Rectangular Slab
% 6) Rolled Ball
% 7) Sphere
% 8) 7 Perf Hex
% 9) 19 Perf Hex
% 10) Burn Table
FormType = 1; %Type the number corresponding to the selected geometry
%(e.g., if analyzing sphere geometry, type: 7)


%---Save generated MATLAB File------------------------------------------------%
%specify a name [e.g., save('Test.mat')]
save('Test.mat') %change the name before the .mat extension
```

The following table provides guidance on how the user must enter data into the template deck for each parameter. Note that text input must be entered as a string in the input deck and thus the apostrophes as shown in the table below must be included in the input. All inputs to the Raw Data Information deck are entered as strings and also, propellant web thickness arrays must be entered as a string. Also, the Raw Data Information fields highlighted in light grey are specific to the Radford Ballistics Excel format only; however, note that a file name must also be provided for this format.

Section	Parameter	Input Format
Calibration Factors for Voltage-Pressure	A0	* Enter corresponding numerical values
	A1	
	A2	
	A3	
	ConversionFormat	* For volts to psi or psi if input is pressure vs. time format, enter: **1** * For volts to MPa or MPa if input is pressure vs. time format, enter: **2** [For the pressure vs. time CloBRA Burn Rate Analysis format, this parameter is defined in the Raw Data Information Deck]
Raw Data Information	TransducerDataInput	* <u>Single Shot Example:</u> **'B2:B4097'** or **'B:B'** * <u>Multiple Shot Example:</u> **'B2:B4097,D2:D4097'** or **'B:B,D:D'** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
	TimeInput	* <u>Single Shot Example:</u> **'A2:A4097'** or **'A:A'** * <u>Multiple Shot Example:</u> **'A2:A4097,C2:C4097'** or **'A:A,C:C'** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
	Sheet	* <u>Single Shot Example:</u> **'1'** (as an example) * <u>Multiple Shot Example:</u> **'1,1'** (if on same worksheet) or **'1,2'** (if on different worksheets) [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
	File	Example: **'C:\Users\Documents\File'**
	NomPData	* Single and Multi-Shot Example: **'A2:A100'**
	NomPSheet	* Single and Multi-Shot Example: **'2'**
	PMaxData	* <u>Single Shot Example:</u> **'L3'** * <u>Multiple Shot Example:</u> **'L3,L4'** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
	PMaxSheet	* Single and Multi-Shot Example: **'1'**
	dPdtData	* <u>Single Shot Example:</u> **'C2:C100'** or **'C:C'** * <u>Multiple Shot Example:</u> **'C2:C100,D2:D100'** or **'C:C,D:D'** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
	dPdtSheet	* Single and Multi-Shot Example: **2**
	VivacityData	* <u>Single Shot Example:</u> **'C2:C100'** * <u>Multiple Shot Example:</u> **'C2:C100,D2:D100'** or **'C:C,D:D'** [ensure commas are used with no spaces in between array sets if multiple shots are analyzed]
	VivacitySheet	* Single and Multi-Shot Example: **'3'**
Savitzky-Golay Filtering	PolyOrder	* Enter corresponding numerical values
	Framelength	
Pressure Window Region	tol	* Enter corresponding numerical value
Grain Dimensions	diameter	* Enter corresponding numerical values in units of centimeters
	length grain	
	perf diameter	
	web	<u>Single Web Thickness Specification Example:</u> **0.10** <u>Multiple Web Thickness Specification Example:</u> **'0.10,0.15'** [ensure commas are used with no spaces in between web thicknesses if multiple webs are specified]
	width	* Enter corresponding numerical values in units of centimeters
	thickness	
Propellant Properties	initialMass	* Enter corresponding numerical values based on units specified
	rho	
	covol	

Section	Parameter	Input Format
	`Impetus`	
	`flameTemp`	
	`gamma`	
Primer Properties	`primerMass`	* Enter corresponding numerical values based on units specified
	`primerRho`	
	`primerCovol`	
	`primerImpetus`	
	`primerFlameTemp`	
	`primerGamma`	
Closed Bomb	`bombVolume`	* Enter corresponding numerical value in units of cubic centimeters
Propellant Geometry Type	`FormType`	* Enter number of list corresponding to geometry type Example for Sphere Geometry: **7**

Pressure-Time Curve Generator Input Decks

The pressure-time curve generator program uses very similar inputs to that of the burn rate analysis program; however, only the propellant properties, primer properties, closed bomb, and grain dimensions/geometry decks are utilized. In addition, the burn rate parameters, Alpha and Beta, are required for this analysis. These parameters are listed under the propellant properties deck and are identified by their appropriate names in the input deck. Note that Beta must be provided in units of m/(s-MPa^Alpha) as prescribed on the GUI.

For convenience, a sample input deck is provided below. This text below can be directly loaded into a new MATLAB script file and can be used once the user provides the appropriate data input. The input deck functionally behaves consistently with the burn rate analysis input deck. When entering data into the template deck, the user is cautioned to enter "[];" (without the quotation marks) for fields that are not used in the selected GUI. Also, note that the appropriate data fields must be entered between the equal signs and the semicolons.

```matlab
%CloBRA Pressure-Time Curve Generator Input File
clear;
clc;
close all;
%Run this code first after all inputs have been entered to generate the
%respective file for the GUI.

%% Enter the Following User Defined Parameters and Options:

%---Propellant properties (metric units)
initialMass = []; %g
rho = []; %density of propellant, g/cc
covol = []; %cc/g
Impetus = []; %J/g
flameTemp = []; %K
gamma = [];
Alpha = [];
Beta = []; %m/s-MPa^Alpha

%---Primer properties (metric units)
primerMass = []; %g
primerRho = 1.661; %g/cc
primerCovol = 1.11995; %cc/g
primerImpetus = 313.852; %J/g
primerFlameTemp = 2300; %K
primerGamma = 1.22;

%---Closed bomb properties
```

```matlab
bombVolume = []; %cc

%---Grain dimensions (meters)
diameter = []; %cm
length_grain = []; %cm
perf_diameter = []; %cm
web = []; %cm
width = []; %cm
thickness = []; %cm

%---Specify which geometry is being analyzed:
% 1) Solid Cylinder
% 2) 1 Perf Cylinder
% 3) 7 Perf Cylinder
% 4) 19 Perf Cylinder
% 5) Rectangular Slab
% 6) Rolled Ball
% 7) Sphere
% 8) 7 Perf Hex
% 9) 19 Perf Hex
% 10) Burn Table
FormType = 2;

save('PTCG_Test.mat')
```

APPENDIX B
DYNAMIC FORM FUNCTIONS FOR MULTI-PERF GEOMETRIES

The burning of solid propellant is a surface phenomenon, in which the rate of gas evolution is dependent upon the solid propellant's available surface area. Additionally, the burn rate of solid propellant is directly related to the pressure at which combustion takes place. With these two behavioral observations noted, the rate of gas evolution can be greatly influenced via the geometry and confinement of the solid propellant. While numerous propellant grain geometries exist, they are categorized in terms of how surface area changes with the burning of solid propellant and are thus respectively termed as either regressive, neutral, or progressive by nature. Of particular interest in this section are the progressive propellant grain geometries.

Progressive propellant grain geometries increase available surface area as the propellant burns (until slivering/web burnout). As a result of this, the area under the pressure-travel curve for gun systems is increased for a given propellant formulation when compared to its regressive and neutral propellant grain geometry counterparts. Progressive geometries are achieved via use of multiple perforations (colloquially referred to as multi-perf) in extruded shapes. Per Reference 11, the number of perforations typically used are 1,7,19, or 37 due to radial symmetry; however, in the United States, the largest number of perforations used is typically 19. Based on this, the progressive propellant grain geometries in the CloBRA program, which are the cylindrical and hexagonal geometries, can be assigned 7 or 19 perforations.

Unlike other propellant geometries, multi-perf grains break apart into slivers upon web burnout. Due to this, the form functions governing the surface area regression become much more mathematically complex. Historically, several closed bomb codes have used polynomial based form functions to model the surface area regression of solid propellants as a function of the burn distance (e.g., ARDEC CBA program). These polynomial based form functions assume all grains are uniform and use the initial dimensions of the grain to parameterize the corresponding form function. For the ARDEC CBA program, the polynomial based form functions are capable of adequately characterizing the surface area regression in the characteristic slope region of the vivacity vs. normalized pressure plot; however, the code is not capable of extending these computations to the post web burnout region (i.e., where slivering occurs). In order to properly analyze the surface area regression rate of multi-perf propellants up until solid propellant burnout, the CloBRA program was developed with dynamic multi-perf grain form functions.

There are currently four multi-perf geometric form functions programmed in the CloBRA program as follows: 1) 7-perf Cylindrical Grain, 2) 19-perf Cylindrical Grain, 3) 7-perf Hexagonal Grain, and 4) 19-perf Hexagonal Grain. In lieu of using polynomial based form functions, the surface area regression of a given grain is computed explicitly with a geometry specific solver. Due to the complexity of developing these dynamic form functions, the specific details of the derivation are not provided in this appendix; however, the methodology used for performing the surface area regression analysis is briefly outlined below:

- The geometry of interest is first simplified into a sector representation of the grain due to the assumption of radial symmetry (consistent with legacy analyses). For the 7 perf grains, the sectors are 60 degrees symmetric and for the 19 perf grains, the sectors are 30 degrees symmetric. Note that the sector representations are converted back in terms of the total grain geometry via scalar multiplication (i.e., the volume of the 7 and 19 perf grains are equal to 6 and 12 times the volume of their sector representations, respectively). Additionally, although the geometry is solved on a per grain basis, the computed volume is scaled based on the number of grains tested.

- The initial grain dimensions are used to establish the geometrical layout of the sector representation and establish the fixed center points of the perforation circles. Note that when web thicknesses are specified, the perf center point locations update accordingly. The initial volume of the grain is then computed simply as the volume of the grain with no perforations minus the space occupied by the perforations.

- During deflagration of the propellant, Piobert's law is used to determine the burn distance, x, normal to each surface layer. With Piobert's law, it is assumed that the grain's outer radius regresses uniformly by x, the radii of the perforation circles grow uniformly by x, and the total length of the grain regresses by 2x.

- Based on the burn distance computed via solving Equation 10, the geometrical layout of the grain is updated accordingly and the surface area of the end region of the grain is computed as the current surface area of the grain with no perforations minus the surface area occupied by the perforations. Note that when slivering occurs, the CloBRA program accounts for overlapping geometries and updates the surface area computation accordingly. The effective grain volume is then computed simply as the surface area of the end region multiplied by the current length of the grain.

- The aforementioned procedure is repeated for each time step until the solid propellant completely burns out at peak pressure.

In order to ensure that the dynamic form functions accurately predict the propellant grain volume during the combustion process, the 3D modeling software, PTC Creo Parametric, was used to facilitate some sensitivity studies for each geometry of interest. These sensitivity studies are shown below.

7 Perforation Cylindrical Grain

For this sensitivity study, the initial propellant grain was assigned the initial dimensions provided in the bulleted list below. Note that the specified units do not matter for this sensitivity study since the resulting volume would be scaled accordingly.

- Outer Radius = 15 units
- Length = 10 units
- Perforation Radii = 1 unit
- Web = 6 units (assumed uniform)

Both the PTC Creo Parametric model and the dynamic form functions were subjected to arbitrary burn distances such that the resulting computed volumes could be compared. Burn distances were selected to capture the various stages of deflagration. In all cases, the results produced between models were within rounding error and thus, this dynamic form function is suitable for the CloBRA program. The results are shown below:

Initial Volume
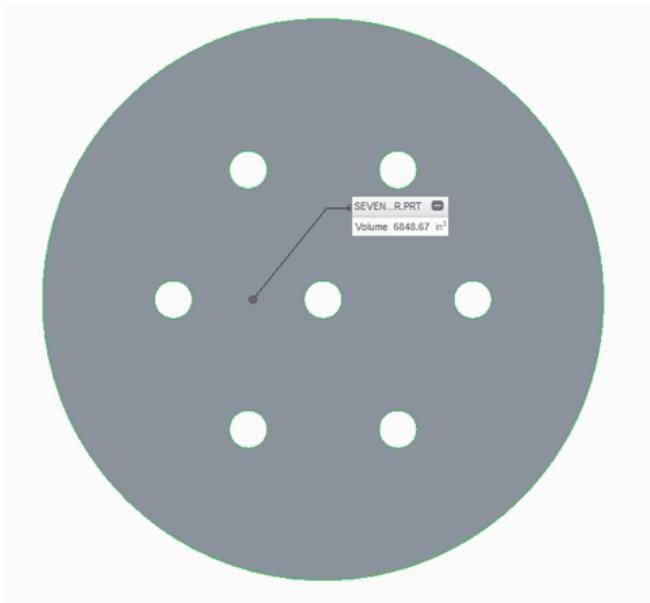
Total Grain Volume
CREO Volume = 6848.67 units^3
MATLAB Volume = 6.8487e+03 units^3
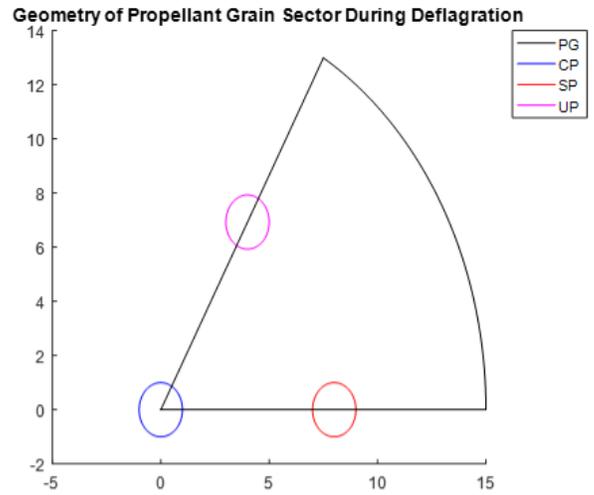
Volume for Burn Distance (x) = 1 unit
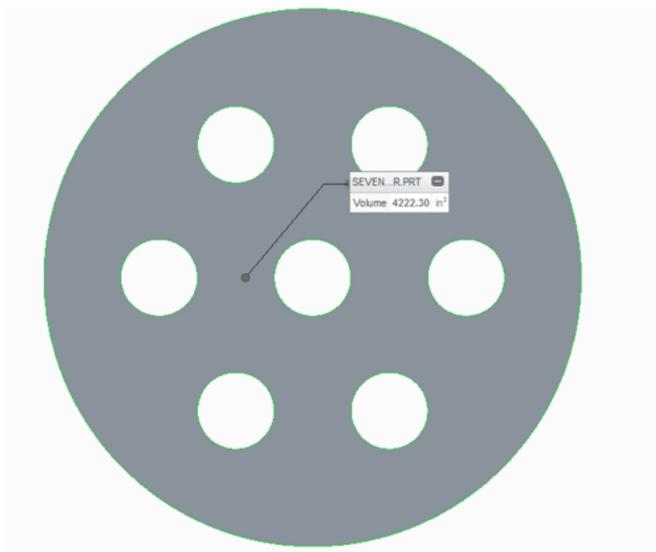
Total Grain Volume
CREO Volume = 4222.3 units^3
MATLAB Volume = 4.2223e+03 units^3
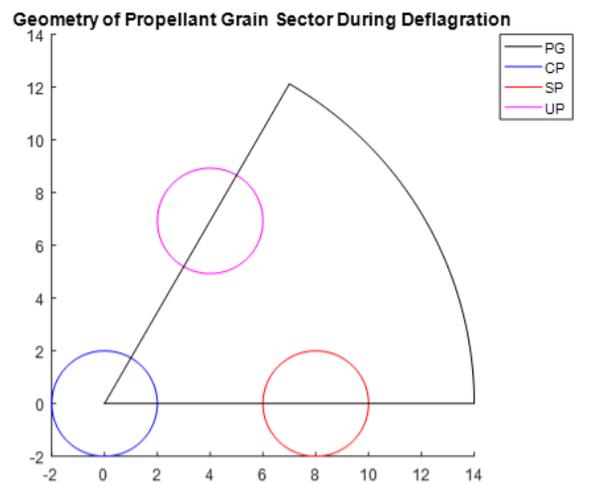
Volume for Burn Distance (x) = 2.2 units
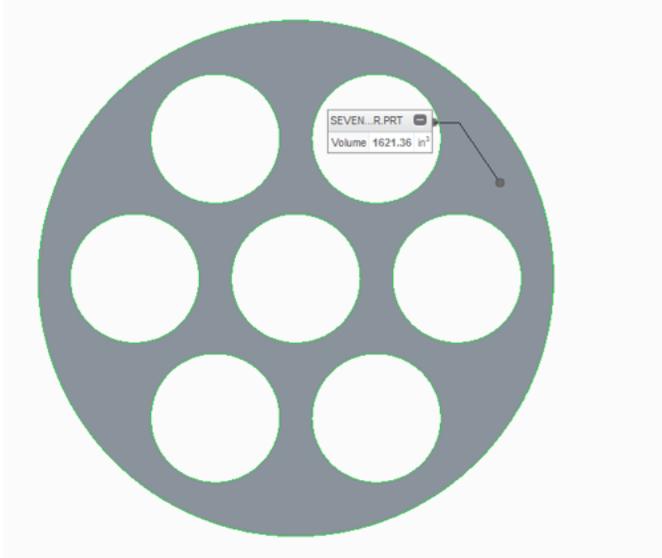
Total Grain Volume
CREO Volume = 1621.36 units^3
MATLAB Volume = 1.6214e+03 units^3

Geometry of Propellant Grain Sector During Deflagration
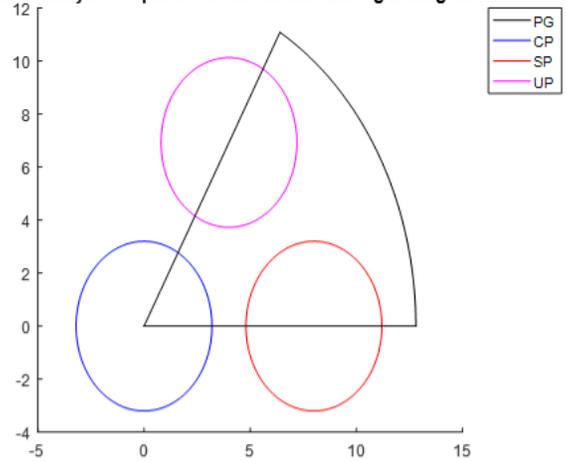
Volume for Burn Distance (x) = 3 units
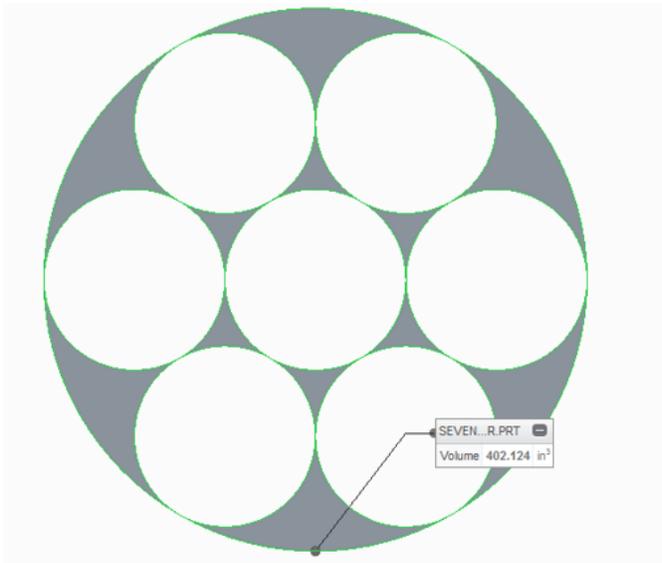
Total Grain Volume
CREO Volume = 402.124 units^3
MATLAB Volume = 402.1239 units^3

Geometry of Propellant Grain Sector During Deflagration
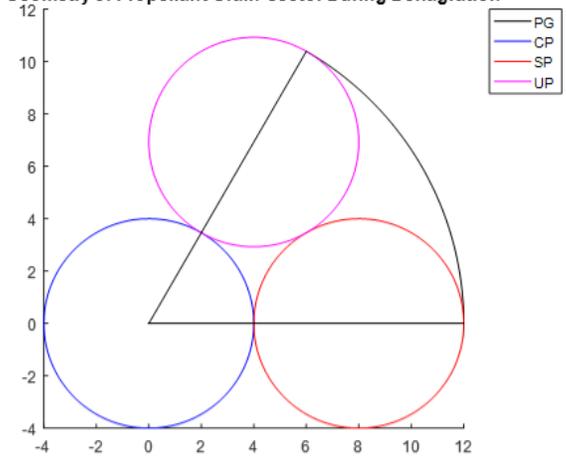
Volume for Burn Distance (x) = 3.2 units
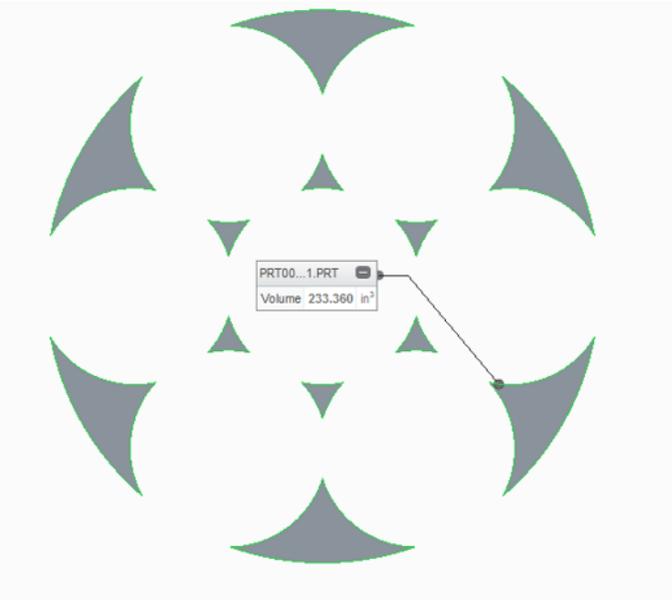
Total Grain Volume
CREO Volume = 233.360 units^3
MATLAB Volume = 233.3597 units^3

Geometry of Propellant Grain Sector During Deflagration

PRT00...1.PRT
Volume 233.360 in³
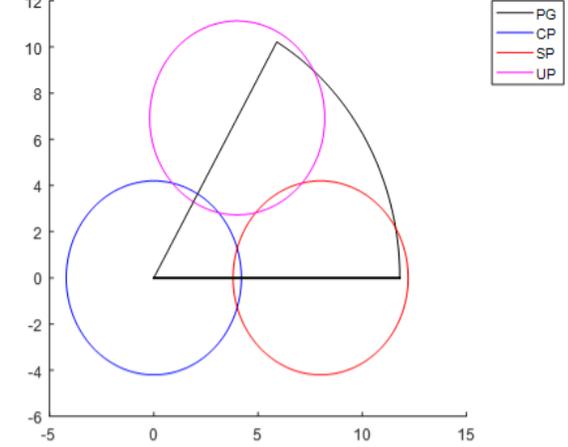
Volume for Burn Distance (x) = 3.5 units
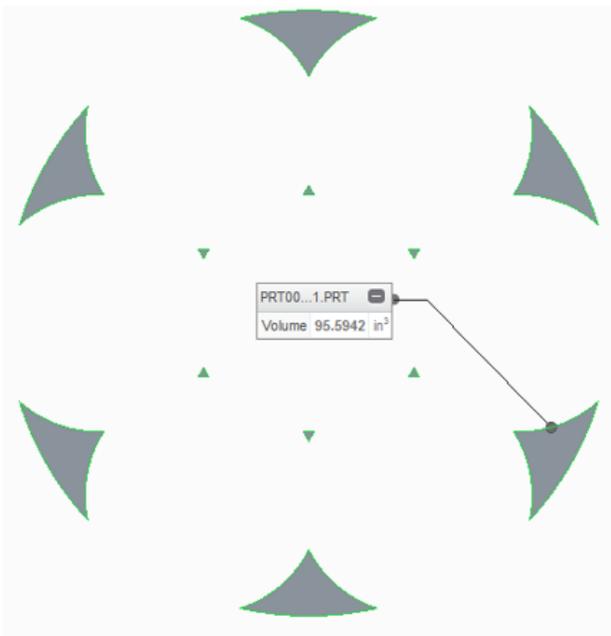
Total Grain Volume
CREO Volume = 95.5942 units^3
MATLAB Volume = 95.5942 units^3

Geometry of Propellant Grain Sector During Deflagration

PRT00...1.PRT
Volume 95.5942 in³
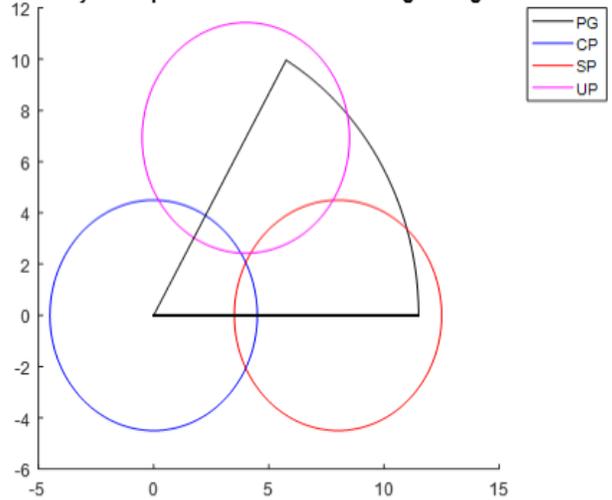
Volume for Burn Distance (x) = 3.8 units
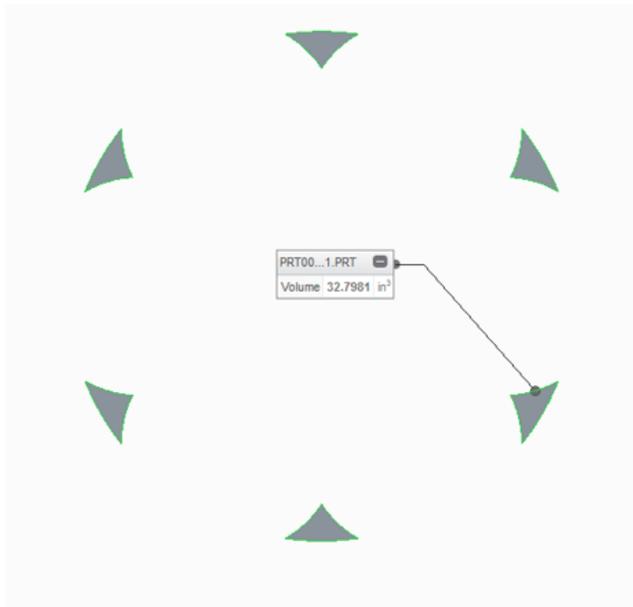
Total Grain Volume
CREO Volume = 32.7981 units^3
MATLAB Volume = 32.7981 units^3

Geometry of Propellant Grain Sector During Deflagration
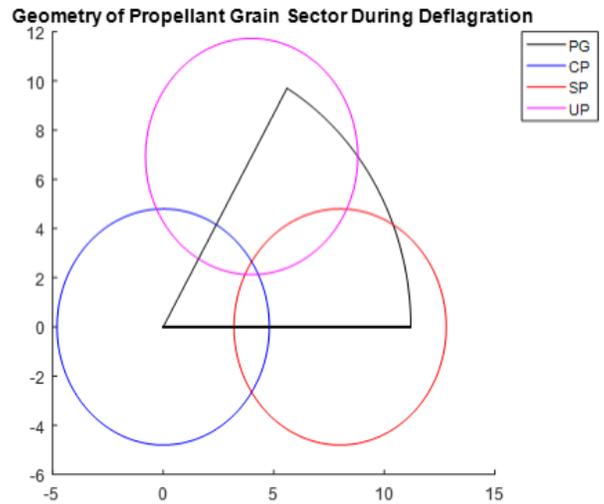
Volume for Burn Distance (x) = 4 units
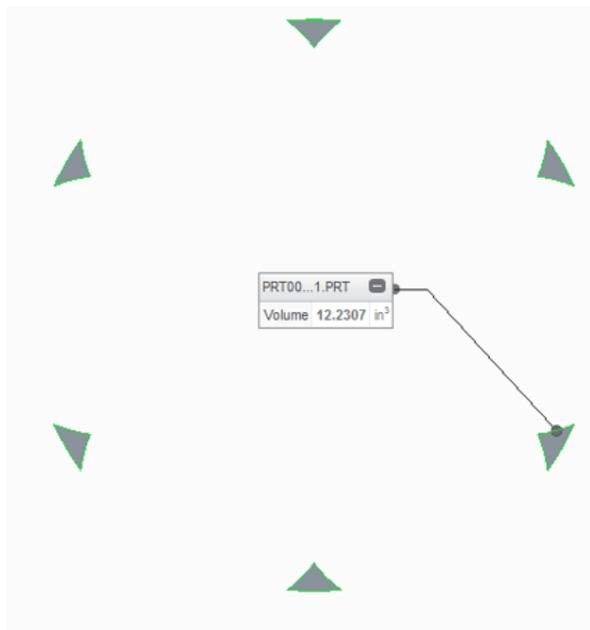
Total Grain Volume
CREO Volume = 12.2307 units^3
MATLAB Volume = 12.2307 units^3

Geometry of Propellant Grain Sector During Deflagration
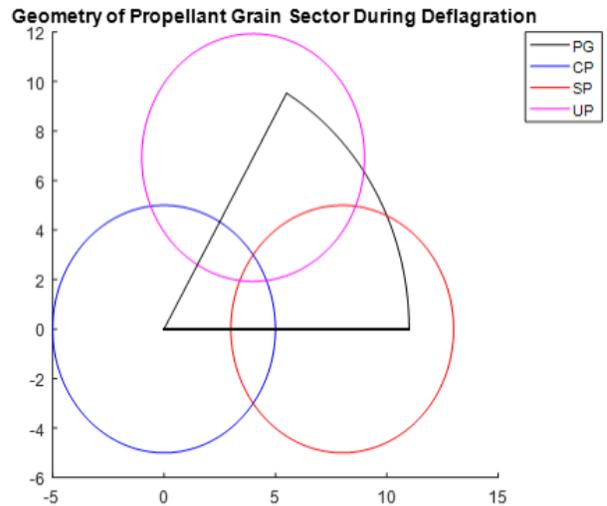
Volume for Burn Distance (x) = 4.3 units
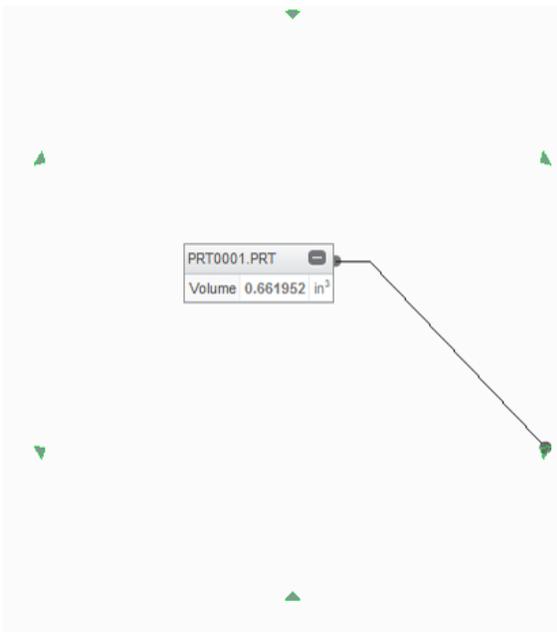
Total Grain Volume
CREO Volume = 0.661952 units^3
MATLAB Volume = 0.6620 units^3

Geometry of Propellant Grain Sector During Deflagration

PRT0001.PRT
Volume 0.661952 in³
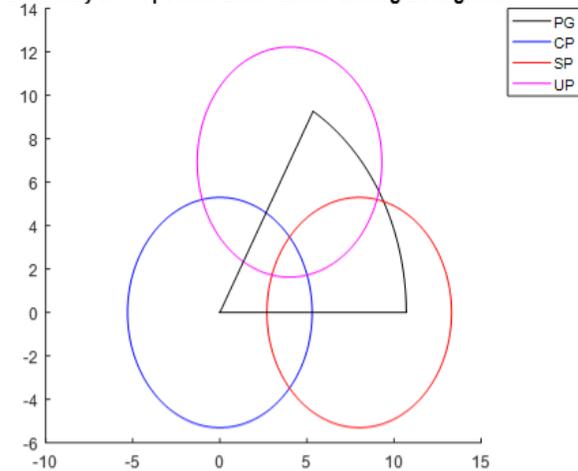
19 Perforation Cylindrical Grain

For this sensitivity study, the initial propellant grain was assigned the initial dimensions provided in the bulleted list below. Note that the specified units do not matter for this sensitivity study since the resulting volume would be scaled accordingly.

- Outer Radius = 15 units
- Length = 10 units
- Perforation Radii = 0.5 units
- Web = 4.1667 units (assumed uniform)

Both the PTC Creo Parametric model and the dynamic form functions were subjected to arbitrary burn distances such that the resulting computed volumes could be compared. Burn distances were selected to capture the various stages of deflagration. In all cases, the results produced between models were within rounding error and thus, this dynamic form function is suitable for the CloBRA program. The results are shown below:

Initial Volume
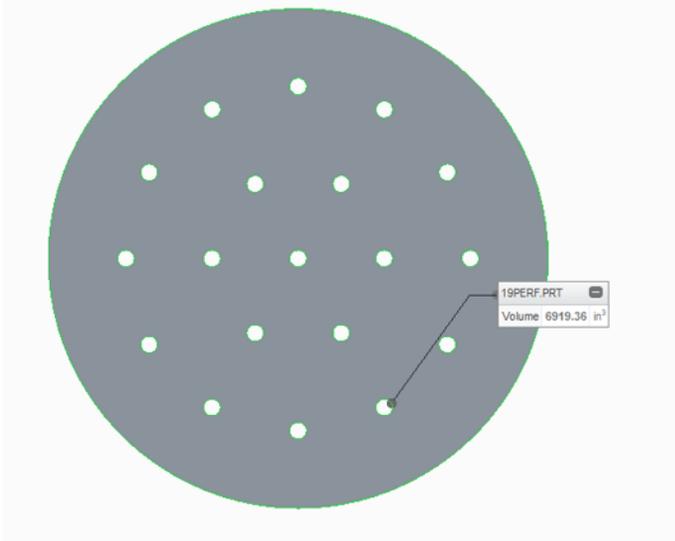
Total Grain Volume
CREO Volume = 6919.36 units^3
MATLAB Volume = 6.9194e+03 units^3
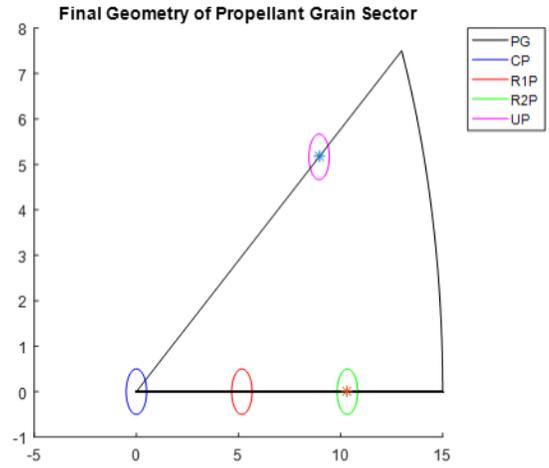
Volume for Burn Distance (x) = 1 unit
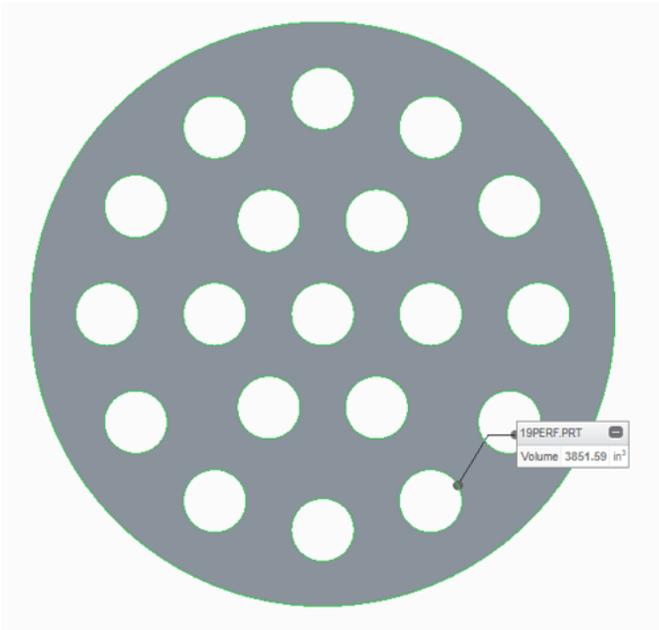
Total Grain Volume
CREO Volume = 3851.59 units^3
MATLAB Volume = 3.8516e+03 units^3
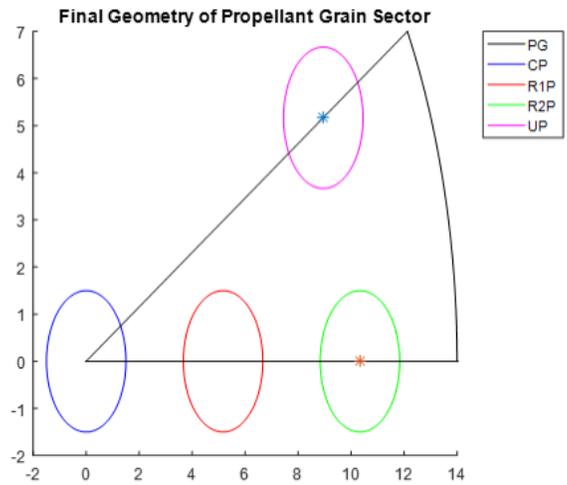
Volume for Burn Distance (x) = 2.2 units
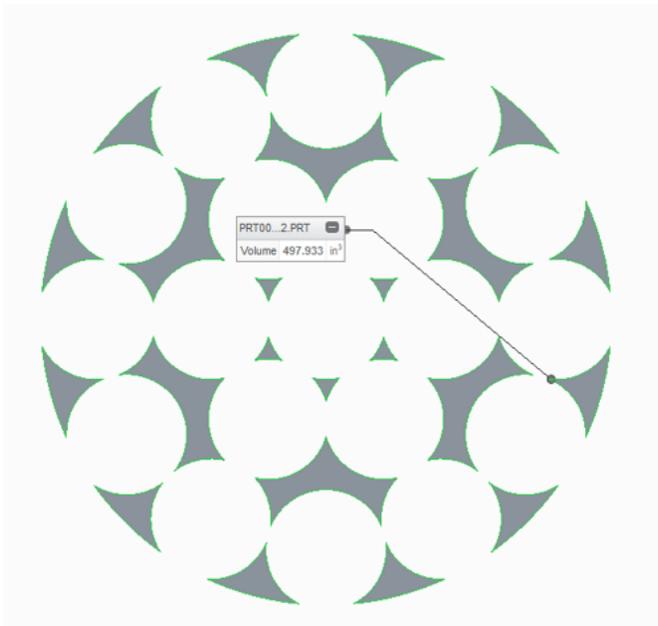
Total Grain Volume
CREO Volume = 497.933 units^3
MATLAB Volume = 497.9325 units^3
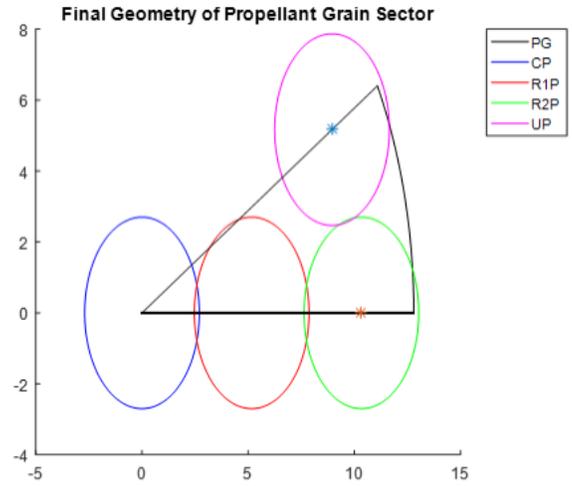
Volume for Burn Distance (x) = 2.6 units
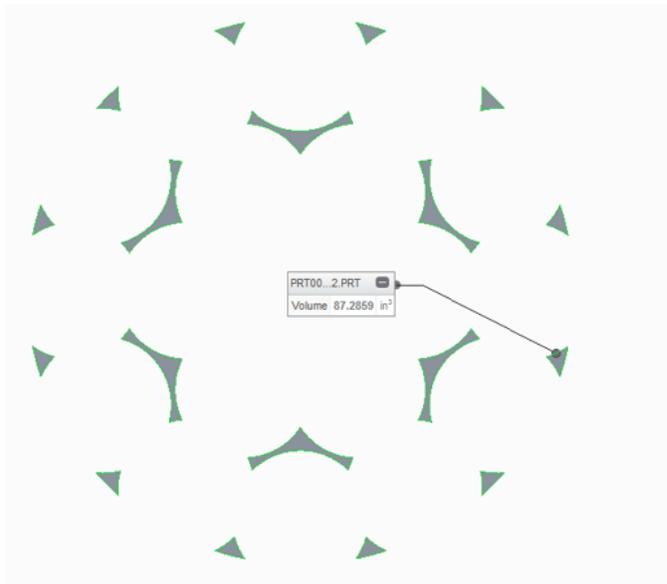
Total Grain Volume
CREO Volume = 87.2859 units^3
MATLAB Volume = 87.2859 units^3
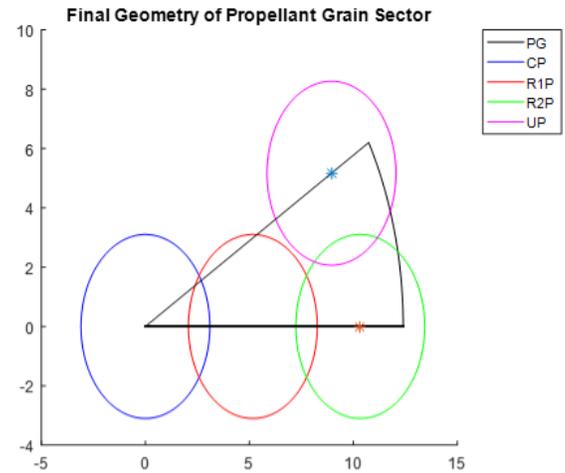
Volume for Burn Distance (x) = 2.8 units
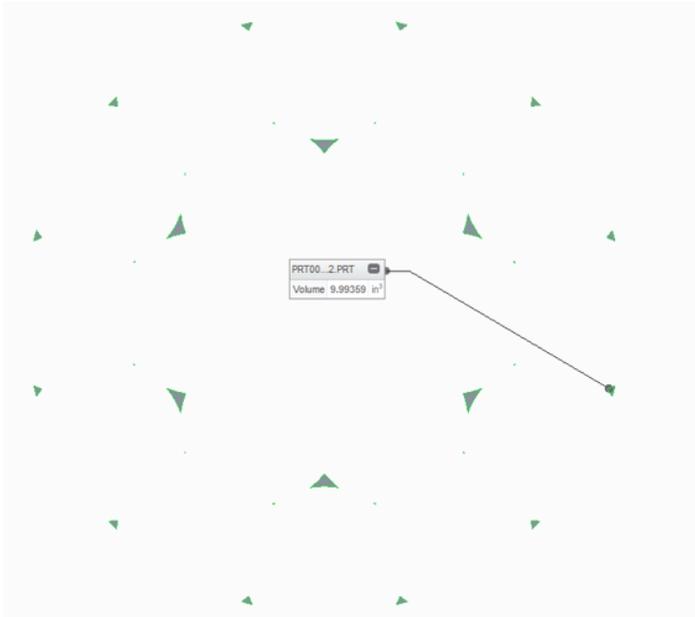
Total Grain Volume
CREO Volume = 9.99359 units^3
MATLAB Volume = 9.9936 units^3
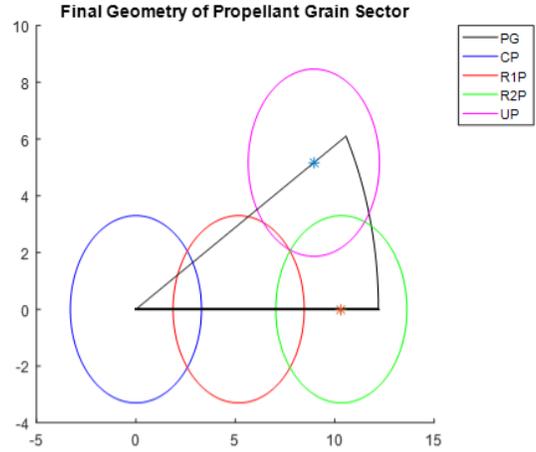
Volume for Burn Distance (x) = 2.95 units

Total Grain Volume
CREO Volume = 0.339361 units^3
MATLAB Volume = 0.3394 units^3
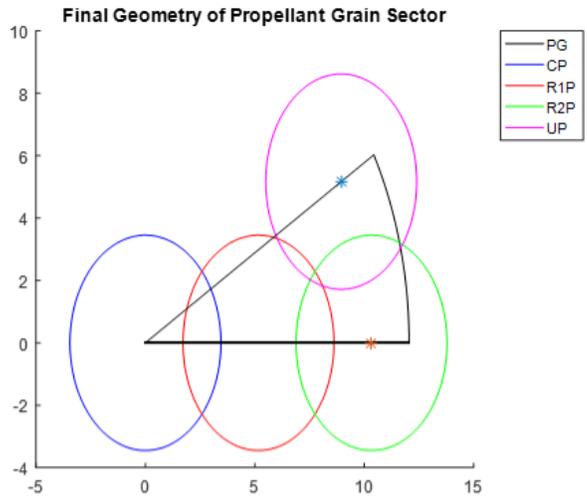
7 Perforation Hexagonal Grain

For this sensitivity study, the initial propellant grain was assigned the initial dimensions provided in the bulleted list below. Note that the specified units do not matter for this sensitivity study since the resulting volume would be scaled accordingly.

- Outer Radius = 10 units
- Length = 10 units
- Perforation Radii = 0.5 units
- Web = 3.9090 units (assumed uniform)

Both the PTC Creo Parametric model and the dynamic form functions were subjected to arbitrary burn distances such that the resulting computed volumes could be compared. Burn distances were selected to capture the various stages of deflagration. In all cases, the results produced between models were within rounding error and thus, this dynamic form function is suitable for the CloBRA program. The results are shown below:

Initial Volume
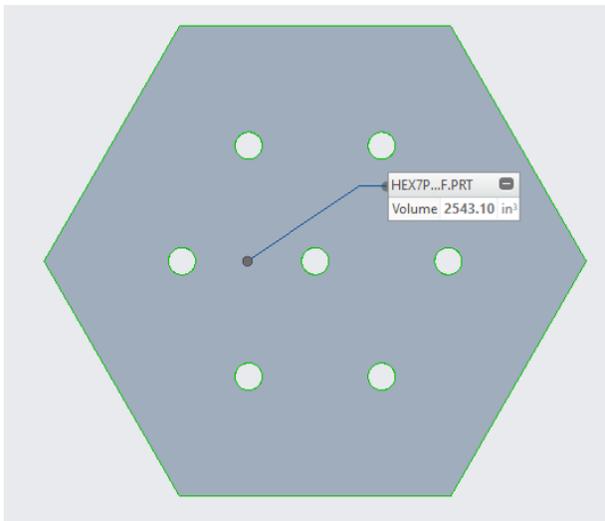
Total Grain Volume
CREO Volume = 2543.10 units^3
MATLAB Volume = 2543.10 units^3
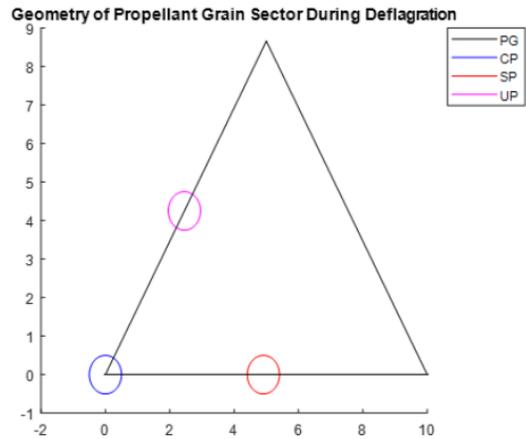
Volume for Burn Distance (x) = 1 unit
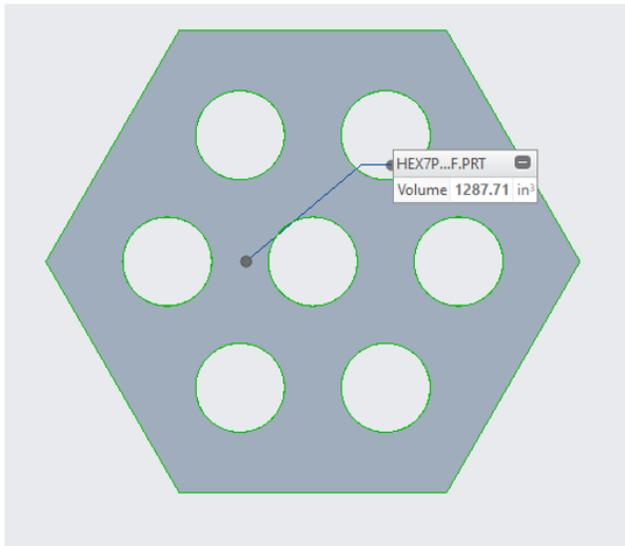
Total Grain Volume
CREO Volume = 1287.71 units^3
MATLAB Volume =1287.71 units^3
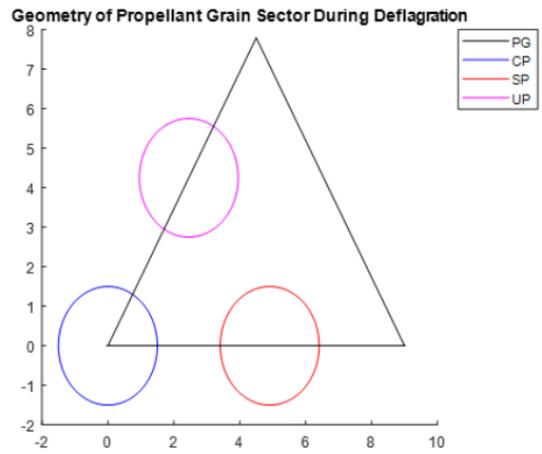
Volume for Burn Distance (x) = 2 units
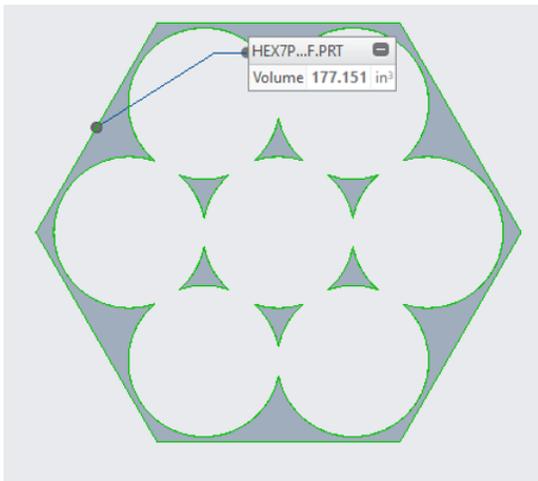
Total Grain Volume
CREO Volume = 177.151 units^3
MATLAB Volume = 177.151 units^3
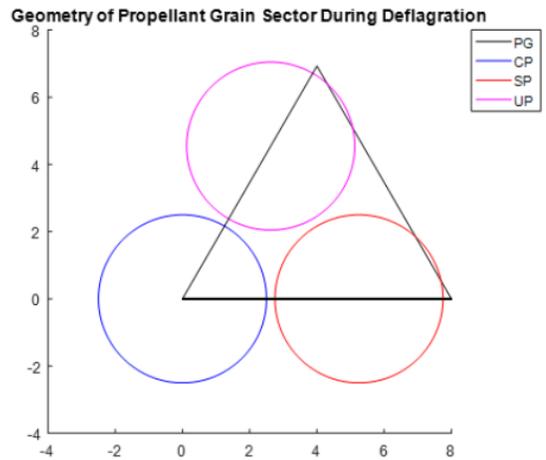
Volume for Burn Distance (x) = 2.1 units
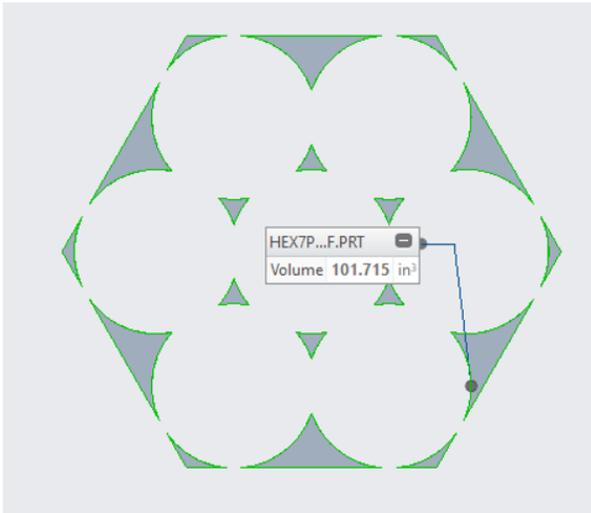
<u>Total Grain Volume</u>
CREO Volume = 101.715 units^3
MATLAB Volume =101.715 units^3

Geometry of Propellant Grain Sector During Deflagration
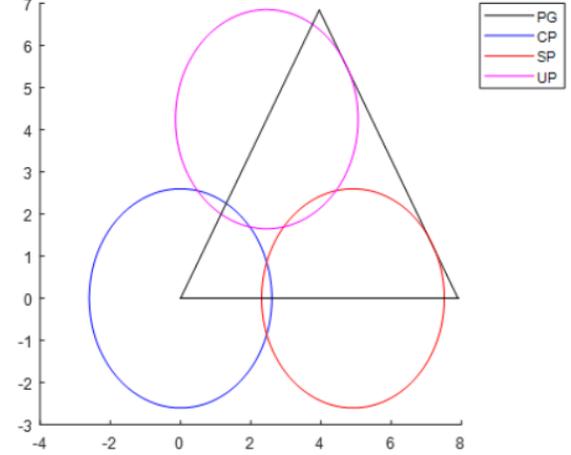
Volume for Burn Distance (x) = 2.2 units

<u>Total Grain Volume</u>
CREO Volume = 55.2793 units^3
MATLAB Volume =55.2793 units^3

Geometry of Propellant Grain Sector During Deflagration
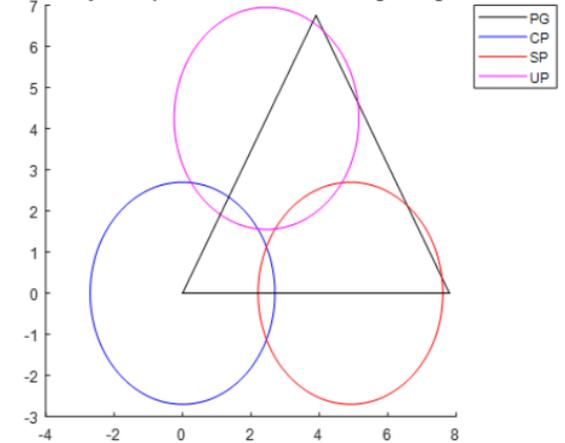
Volume for Burn Distance (x) = 2.3 units
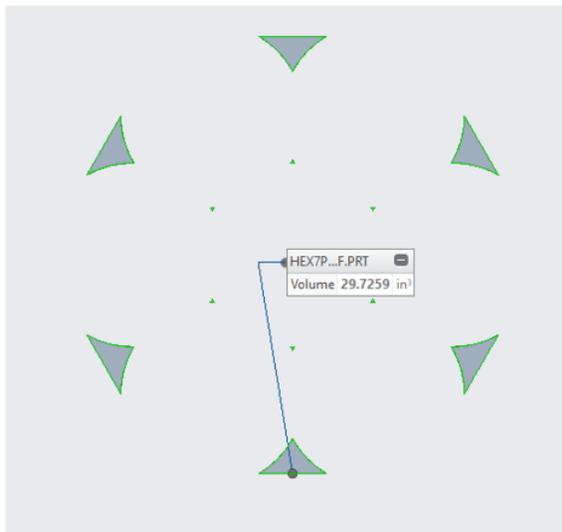
Total Grain Volume
CREO Volume = 29.7259 units^3
MATLAB Volume = 29.7259 units^3

Geometry of Propellant Grain Sector During Deflagration

HEX7P...F.PRT
Volume 29.7259 in³
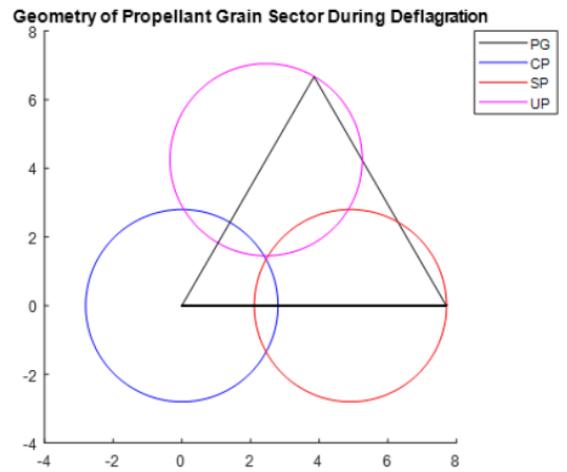
Volume for Burn Distance (x) = 2.6 units
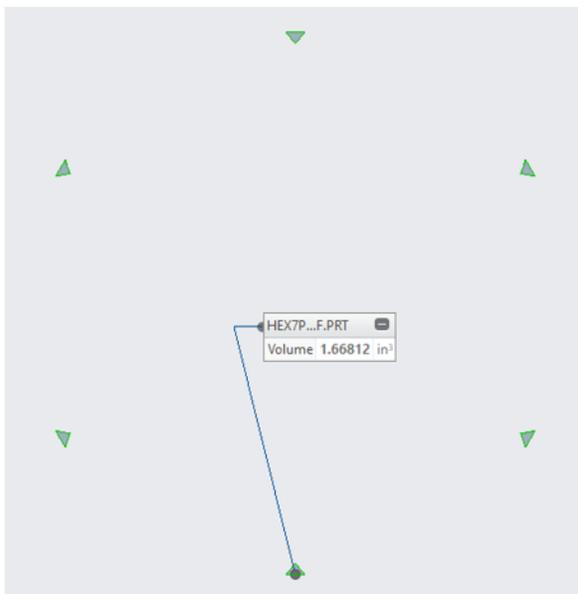
Total Grain Volume
CREO Volume = 1.66812 units^3
MATLAB Volume = 1.66812 units^3

Geometry of Propellant Grain Sector During Deflagration

HEX7P...F.PRT
Volume 1.66812 in³
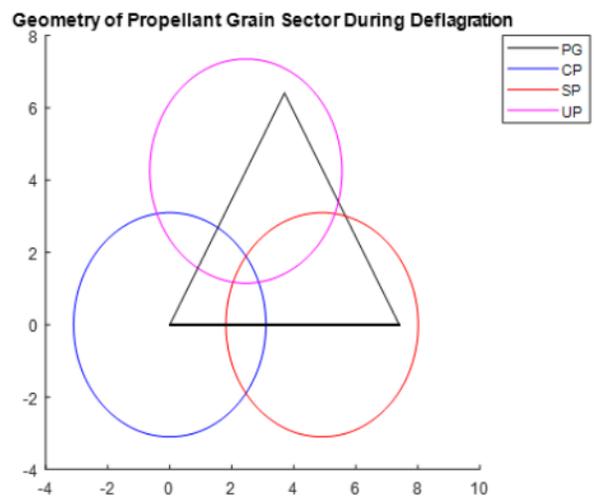
19 Perforation Hexagonal Grain

For this sensitivity study, the initial propellant grain was assigned the initial dimensions provided in the bulleted list below. Note that the specified units do not matter for this sensitivity study since the resulting volume would be scaled accordingly.

- Outer Radius = 15 units
- Length = 10 units
- Perforation Radii = 0.5 units
- Web = 3.9378 units (assumed uniform)

Both the PTC Creo Parametric model and the dynamic form functions were subjected to arbitrary burn distances such that the resulting computed volumes could be compared. Burn distances were selected to capture the various stages of deflagration. In all cases, the results produced between models were within rounding error and thus, this dynamic form function is suitable for the CloBRA program. The results are shown below:

Initial Volume
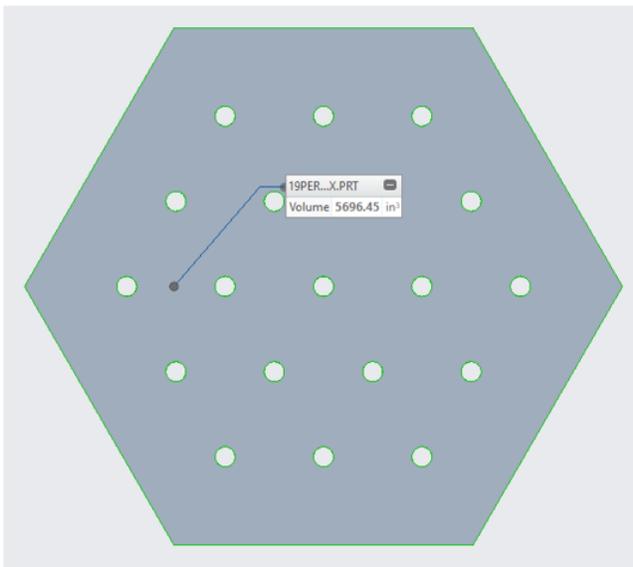
Total Grain Volume
CREO Volume = 5696.45 units^3
MATLAB Volume = 5696.45 units^3
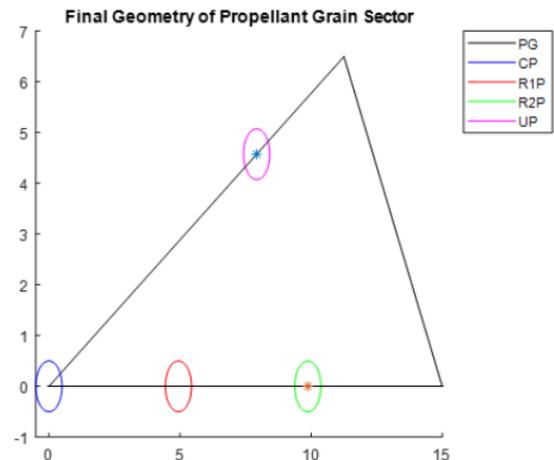
Volume for Burn Distance (x) = 1 unit
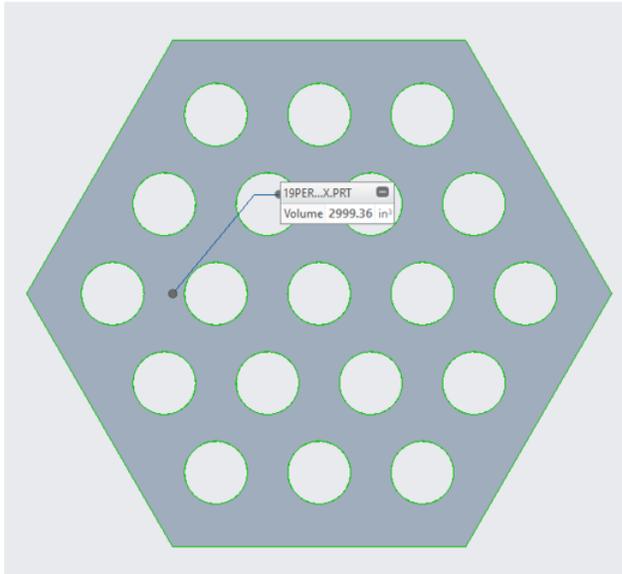
Total Grain Volume
CREO Volume = 2999.36 units^3
MATLAB Volume = 2999.36 units^3
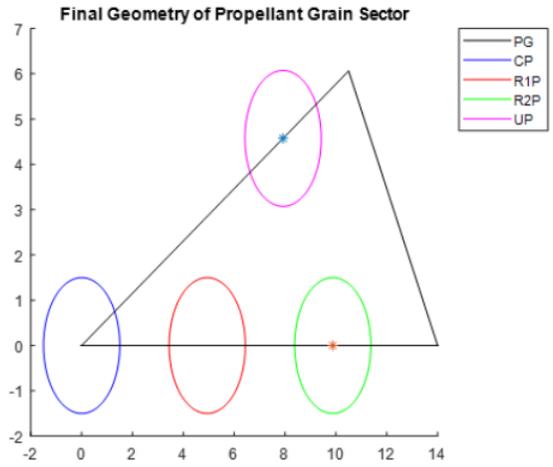
Volume for Burn Distance (x) = 2 units
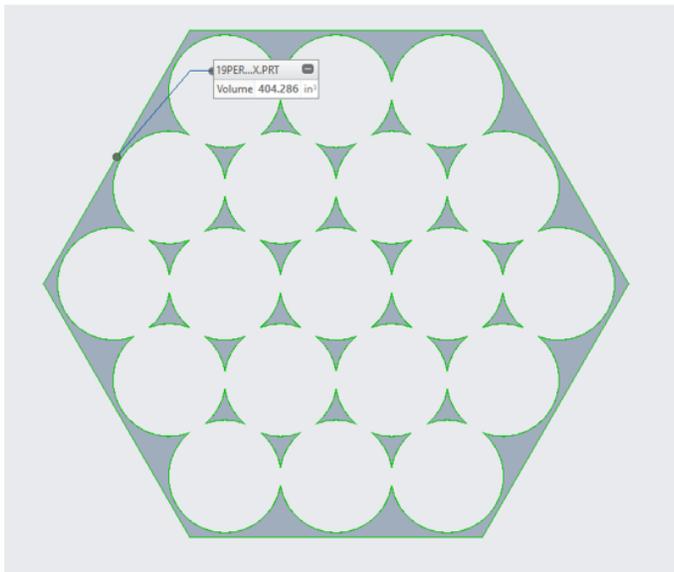
Total Grain Volume
CREO Volume = 404.286 units^3
MATLAB Volume = 404.286 units^3
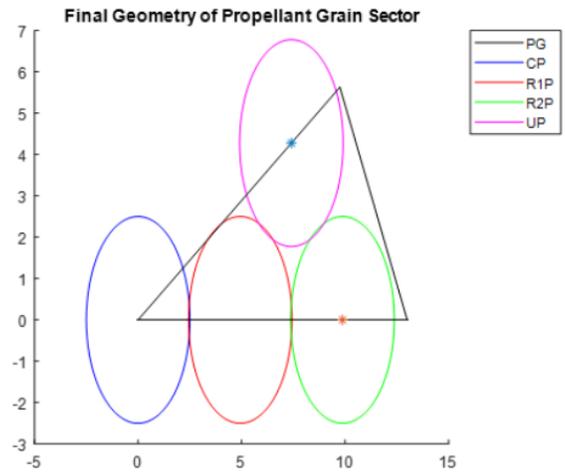
Volume for Burn Distance (x) = 2.2 units
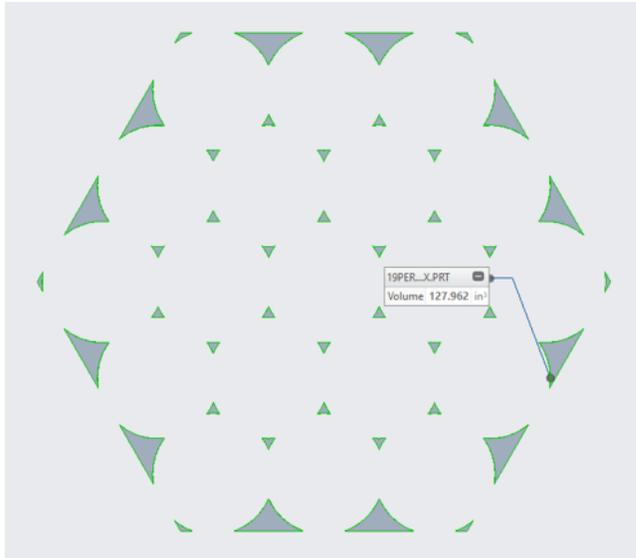
Total Grain Volume
CREO Volume = 127.962 units^3
MATLAB Volume = 127.962 units^3

Volume for Burn Distance (x) = 2.3 units

Total Grain Volume
CREO Volume = 66.9277 units^3
MATLAB Volume = 66.9277 units^3

Volume for Burn Distance (x) = 2.5 units
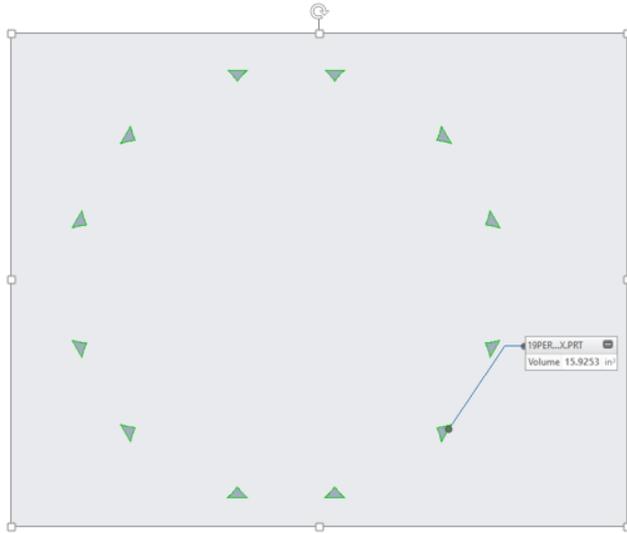
Total Grain Volume
CREO Volume = 15.9253 units^3
MATLAB Volume = 15.9253 units^3

Final Geometry of Propellant Grain Sector
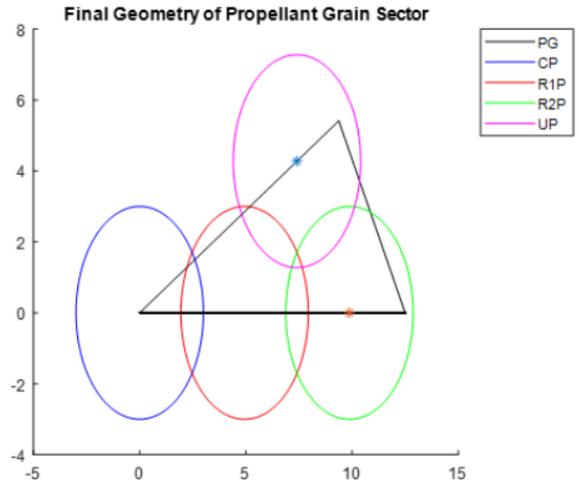
APPENDIX C
BURN TABLE FORMAT

The CloBRA program allows users to enter form functions in a tabular format via the "Burn Table" option. This capability is a distinguishing feature for closed bomb data reduction programs as it allows users to analyze the closed bomb data of propellant grain geometries that don't adhere to analytically derived form functions. In order to use the burn table feature, the user must specify the volume of a single grain as a function of the depth burned, x. The first tabular entry must correspond to the initial volume of the grain prior to deflagration or equivalently stated, at a burn distance corresponding to 0 cm. The subsequent entries will then contain the volume of the grain as a function of an increasing burn distance. Note that the burn distance intervals do not need to be evenly spaced; however, the user should use burn distance intervals that do not attenuate any key features of the volume vs. distance burned curve (i.e., slope change regions). The final tabular entry must correspond to where the grain is burnt out, or in reasonably close proximity to burning out.

The burn table is to be provided to the CloBRA program in a strict Excel format and must be entered on the first sheet of the Excel file. The structure for the burn table is as follows: the first column of data (column A) corresponds to the distance burned in units of centimeters, the second column of the data (column B) corresponds to the volume of the grain in units of cubic centimeters, and the third column (specifically cell C2) corresponds to an optional geometry name the user can define if warranted. Cells A1:C1 of the Excel file are unused and are solely intended to be used as headers for the user to ensure that they put their data in the appropriate columns. The data can then be entered in the corresponding columns from the second to nth row of the spreadsheet. An example burn table Excel file is provided below in Figure 33 for a single perf grain with the following dimensions: outer diameter = 0.8486 cm, length = 2.391 cm, perf diameter = 0.2977 cm.

	A	B	C
1	Distance Burned (cm)	Volume (cc)	Name
2	0	1.185895937	Single Perf Grain
3	0.0025	1.161935479	
4	0.005	1.138065052	
5	0.0075	1.114284655	
6	0.01	1.090594289	
7	0.0125	1.066993954	
8	0.015	1.043483648	
9	0.0175	1.020063374	
10	0.02	0.99673313	
11	0.0225	0.973492916	
12	0.025	0.950342733	
13	0.0275	0.927282581	
14	0.03	0.904312459	
15	0.0325	0.881432367	
16	0.035	0.858642306	
17	0.0375	0.835942276	
18	0.04	0.813332276	
19	0.0425	0.790812307	
20	0.045	0.768382368	
21	0.0475	0.74604246	
22	0.05	0.723792582	
23	0.0525	0.701632735	
24	0.055	0.679562918	
25	0.0575	0.657583132	
26	0.06	0.635693376	
27	0.0625	0.613893651	
28	0.065	0.592183957	
29	0.0675	0.570564292	
30	0.07	0.549034659	
31	0.0725	0.527595056	
32	0.075	0.506245484	
33	0.0775	0.484985942	
34	0.08	0.46381643	
35	0.0825	0.442736949	
36	0.085	0.421747499	
37	0.0875	0.400848079	
38	0.09	0.38003869	

Sheet1

	A	B	C
38	0.09	0.38003869	
39	0.0925	0.359319331	
40	0.095	0.338690003	
41	0.0975	0.318150705	
42	0.1	0.297701438	
43	0.1025	0.277342201	
44	0.105	0.257072995	
45	0.1075	0.23689382	
46	0.11	0.216804675	
47	0.1125	0.19680556	
48	0.115	0.176896476	
49	0.1175	0.157077423	
50	0.12	0.1373484	
51	0.1225	0.117709407	
52	0.125	0.098160445	
53	0.1275	0.078701514	
54	0.13	0.059332613	
55	0.1325	0.040053743	
56	0.135	0.020864903	
57	0.1375	0.001766094	
58	0.137729908	1.42262E-05	
59			

Sensitivity studies have demonstrated that burn rates computed with use of the burn table are consistent with those predicted by the analytical form functions. The caveat to emphasize to the reader is that the incremental changes between each tabular entry must be fine enough such that non-specified burn table values can be accurately computed via interpolation methods. A template burn table Excel file is included with the CloBRA program and can be found in the "Input_Decks" folder. The user is encouraged to use this template for their analyses.

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Title   Project

Chris Heathcare
Author/Project Engineer   Report number/Date received (to be completed by LCSD)

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Scott A. McDonald
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Division Chief   (Date)

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Scott A. McDonald
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Division Chief   (Date)

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