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Analysis of Linear Shaped Charge Igniting Rapid Deflagration Cord

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An ordnance device typically is composed of several components that are initiated sequentially. Reliability of this initiation train is critical to its performance. This paper describes the testing and analysis methods used to understand the mechanisms involved and to achieve a high reliability. The scope of this paper begins with the output of the linear shaped charge (LSC) creating a stimulus received by the rapid deflagration cord (RDC) pickup charge. This stimulus travels through a narrow channel and makes several turns before impacting the target. The degree of confinement can vary significantly during the event due to perforation of the housing by the LSC jet. In order to understand this complex and dynamic event, a 3-dimensional Explicit Dynamics analysis is used to study the gases/condensates flow and pressure exerted onto the target under various design configurations. Explicit Dynamics is a Finite Element Analysis method that integrates the time of all meshes at stable time steps and ensures solutions representative to the real time behavior. Computational results describe the LSC function and interaction of its reaction products and liner material with the RDC end-tip. Results of the ignition gap test are presented and discussed in this paper. This approach enabled PSEMC to understand the mechanism of the event and improve the design based on knowledge acquired through these analyses.

Nomenclature

At	=	throat area
*c**	=	characteristic exhaust velocity
CAD	=	cartridge actuated devices
EOS	=	equation of state
FCDC	=	flexible confined detonation cord
FEA	=	finite element analysis
g_c	=	gravitational conversion constant
JWL	=	Jones, Wilkins and Lee
LSC	=	linear shaped charge
M	=	gas molecular weight
MDC	=	mild detonation cord
ms	=	millisecond
NA	=	not available
PAD	=	propellant actuated device
PBX	=	plastic bonded explosive
P_{b0}	=	initial burn off pressure
Pc	=	chamber pressure
R_0	=	universal gas constant
RDC	=	rapid deflagration cord
RDM	=	rapid deflagration material
t	=	time
Tc	=	chamber gas temperature
TLX™	=	Thin Layer Explosive

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Vc = chamber volume

I. Introduction

ENERGY transfer systems composed of linear products like MDC, TLX™, and RDC have broad applications in aircraft crew escape systems and aerospace industry. They are capable of initiating several CAD/ PAD components following predefined path and sequence automatically. Frank B. Burdoll published a report of descriptions and theories of many CAD product designs used for energy transfer systems[1]. Linear products of typical energy transfer systems have end-tip at their terminals to provide stimulus towards the end-tips of target components housed in a manifold. This end-tip to end-tip initiation is very common and reliable. The initiation train in this project starting from LSC directly towards RDC end-tip poses a unique challenge due to the functional properties of LSC. The dimensional envelope of this system further constrains the relative positions of LSC and RDC arrangement. The author and his team developed a reliable design based on the results of this analysis.

The LSC can be lead, aluminum, copper, or silver sheath containing consolidated explosives in their core. All LSC design has a groove at output side so the detonation pressure will focus detonation products and metal sheath towards the "legs" direction (upward direction in Figure-1). LSC is mainly used for severing target material but it also can transfer initiation as in this project. RDC was developed in the 1970's and is manufactured by Pacific Scientific Energetic Material Company (PSEMC) as a non-detonation version of MDC containing very fast burning pyrotechnics. RDC is a completely contained material when over-braided with textile material and propagates at about 10,000 in/s.

Figure 1 and 2 are to show the device segment as the area of interest of this paper. Green arrows in Figure-2 show LSC function from right to left and its output (metal liner and detonation products) impacting the end-tip of RDC through a perpendicular passage. The LSC/RDC initiation gap test results seemed counterintuitive at the first review. The team wanted to understand the gap test results, implication of passage design on RDC initiation reliability, and whether the metal jet is essential or detrimental in initiating RDC. Analyses are performed to assist achieving these goals.

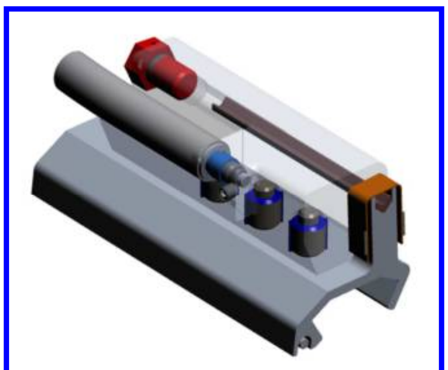


Figure 1. A Segment of Product showing LSC and RDC locations.

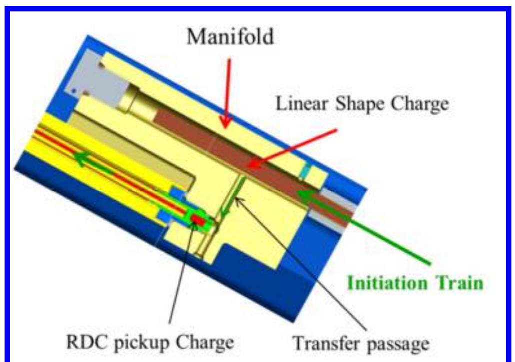


Figure 2. Cross-sectional illustration of LSC/ RDC initiation train.

II. Gap Test Configurations and Results

One approach of studying the initiation reliability is to conduct initiation tests at different stimulus level and determining its 50% go/ no go level through statistics. Tests like Bruceton and Neyer test are examples of this type of testing. It will be difficult and costly if we were to conduct RDC initiation test by using LSC of various coreloads. Even if we performed and completed this testing, the desired coreload could be very difficult if not impossible to implement because of the negative impacts of changing explosive load in this application. Therefore, a more feasible variable passage length, was chosen to adjust the stimulus level in this testing. Figure 3 describes the test fixture setup. The figure on the left shows the cross-sectional view of the fixture without spacer. The picture in the middle shows the test fixture with a 2.5x nominal gap passage length. The figure on the right shows the various passage lengths created by application of spacers. Pictures in Figure 4 are tear down pictures of post-functioned units. There is no clear distinction between "Go" post-function fixtures and "No Go" ones.

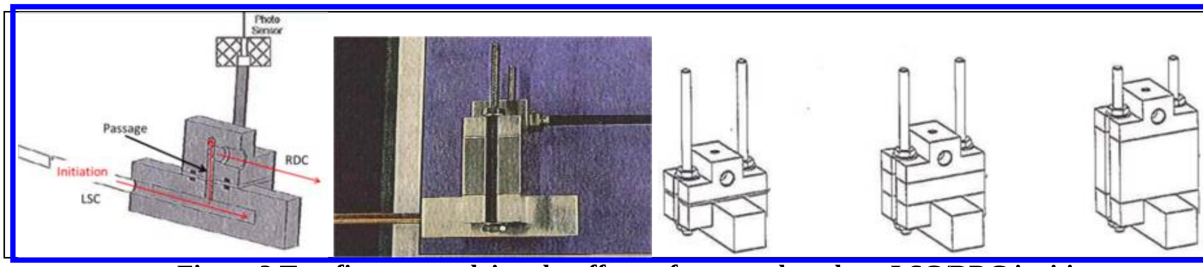
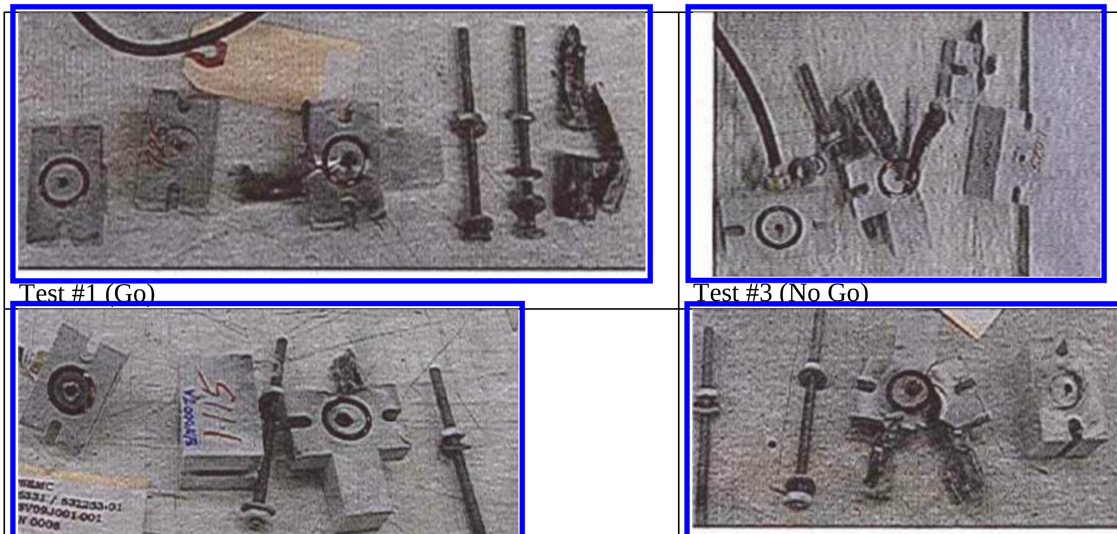


Figure 3 Test fixtures studying the effects of passage length on LSC/RDC ignition.



Test #1 (Go)

Test #3 (No Go)

Test #7 (No Go)

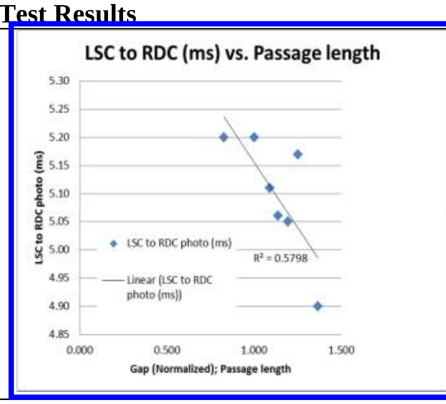
Test #8 (Go)

Figure 4. Post-function pictures of initiation tests.

All test assemblies are conditioned to -65°F before testing. Cold conditions are considered the worst case for initiation performance. In addition to RDC ignition success, transition time from LSC to RDC is also measured from break wire by LSC to photo sensor by RDC. The gap tests produced successful results and provided reliability for the gap design. Furthemore, the correlation results observed (correlation coefficient = 0.76) between "passage distance" and "LSC to RDC time" are shown in Table 1. A very strong correlation (correlation coefficient of 0.95) resulted if test #8 result is discounted. The correlation indicates that the longer the passage length, the shorter the transfer time. These results are counter intuitive and need to be further investigated.

Table 1. LSC/RDC Initiation Test Results

Test #	Gap (normalized)	Go/ No Go	Time (ms) LSC to RDC function
1	0.83	Go	5.2
2	1.00	Go	5.2
3	1.17	No Go	
4	1.09	Go	5.11
5	1.14	Go	5.06
6	1.19	Go	5.05
7	1.27	No Go	
8	1.25	Go	5.17
9	1.37	Go	4.9



III. Explicit Dynamics Analysis

The author used ANSYS Explicit STR[2]® and AUTODYN® for FEA analysis in this project. Similar to other Hydrocode type software, STR and Autodyn are the proper tools for analyzing systems under high strain rate and high pressure conditions. Explicit Dynamic analysis utilizes the basic equations of conservation of mass, momentum and energy. The conversation equations, together with material models and initial/ boundary conditions, define the complete solution to the problem[3]. A more detailed explanation about the theory and application by author can be found in his previous publication[4].

Detonation of explosive in LSC is modeled as high speed gas expansion. They are best simulated by the Euler solver. The meshes (and elements) used with an Euler solver is fixed in space and material adverted from an element into its neighbors as a result of pressure. This solver enables modeling gas expansion without distortion of the elements. Analysts need to specify the space of interest for the complete analysis so that material can flow into previously unoccupied regions. Lagrange elements always supersede Euler elements and they need to be coupled for the computation. For each time step, these equations are solved explicitly for each element in the model, based on forces resulting from initial and boundary conditions for the first cycle (time step). Subsequent cycles use the resultant forces at the end of the previous time step.

Analyses are setup to answer questions regarding to “How is the RDC initiated?” and “Is manifold confinement critical to RDC initiation?”. The author setup a baseline model using parameters from actual configurations for the initiation mechanism study. A second model studied study the significance of manifold confinement by weakening manifold strength (input lower failure criteria) from the baseline model.

IV. Model Setup and Analysis Results

The initiation of burning or deflagration is entirely a thermal phenomenon. As explosives decompose, they generate heat that can accelerate the rate of decomposition leading to a runaway or thermal ignition condition[2]. Pyrotechnics in RDC end-tip is a hydroborate/ inorganic nitrate mix called Rapid Deflagration Material (RDM). In order to model the RDM initiation and its combustion reactions, the analyst will need to define the critical temperature of RDM. Once the RDM receives adequate heat and reaches a temperature above the critical temperature, thermochemical equilibrium and linear burn rate needs to be defined for computing reactions.
Lee-Tarver EOS is used to model detonation initiation. This EOS, as with the Forest Fire model, is based on the assumption that ignition starts at local hot spots and grows outward from these sites.The initial version of this model described a two-part reaction rate model with a term for ignition of the explosive and a term describing the growth[3]. One of the classical three-dimensional heat transfer equations that relates the rate of heat production to the rate of temepratrure of the material and to its sourroindings is the Frank-Kamenetskii equation[2]. Autodyn has the capability of running computations using Lee-Tarver EOS if a proper EOS for RDM is available. Autodyn has limited capability for heat transfer computation. A multi-physics code is required for this type of computation. Initiation of LSC was never a concern/ interest of this project. This project focuses on LSC/RDC relative locations and manifold design, by studying the stimulus received by the RDM.

Three-dimensional geometry models were imported directly from the Computer Aided Design program into Explicit Dynamics for meshing and other pre-process operations. The analyst is required to balance between computation expense and accuracy because Explicit Dynamics analysis demands high computation power to complete the analysis. Simplification of non-critical features and proper mesh size were determined at an early phase of the modeling after several trials. Structural components of little concern were treated as rigid bodies to save computation time. The end-tip closure is omitted and RDC end-tip housing is treated as a rigid body to save computation without compromising quality. A rigid body defines an un-deformable object that has mass, initia and momentum. Its meshes are only active on the contact surface because the whole body is treated as one mass point and volume is not needed. The default material, structural steel, is inputed for RDM just to receive stimulus loading for comparison purpose. Once the element meets failure criteria it becomes invisible and disappears (otherwise it will distort and obscure the results appearance). Once an acceptable baseline model run was completed and its results considered acceptable, meaningful parametric studies could be formulated with the baseline model being modified by single parameter iterations. The analyst varied the failure criteria of manifold material to study the confinement effects on RDC ignition.

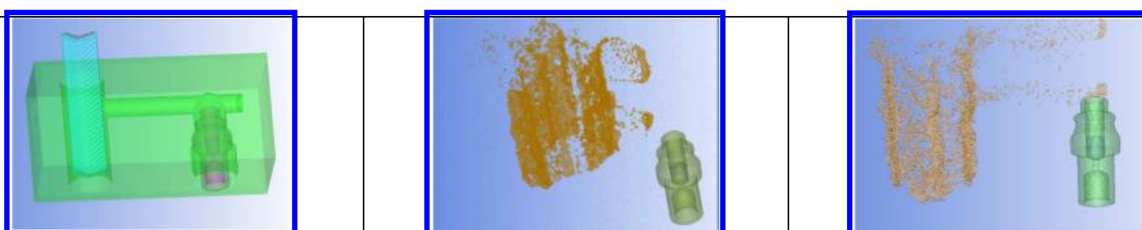
Table 2 describes input parameters used for all materials in this analysis. Selection of the EOS is dominated by availability because creating an EOS is not a trivial effort. This project focused on comparing the loadings on target material (RDM) surface. All material properties were extracted from the ANSYS engineering data library and published data. Failure criterion is not needed for Al 2024 Rigid because it's assigned as rigid material in the computations for all cases. Failure criterion is also not needed for copper and PBX-9502 because it's assigned as Euler parts and expected to be highly deformed. All other Lagrange parts have global material cut-off criteria to maintain computation quality. Unless specified otherwise, all time indications in Section IV are time step time in these analyses.

Table 2. Inputs of materials used in Autodyn computation

Material	Solver type	EOS	Strength model	Failure criteria
Manifold/ Al 6061-T6	Lagrange	Shock	Steinburg Guinan	Plastic strain
LSC liner/ Copper	Euler	Shock	Piecewise JC	NA
LSC explosive/ PBX-9502	Euler	JWL	NA	NA
RDM/ Structural steel	Lagrange	Linear	Elastic	NA
RDC end-tip/ Al 2024 Rigid	Lagrange	Rigid	NA	NA

A. Initiation Mechanism

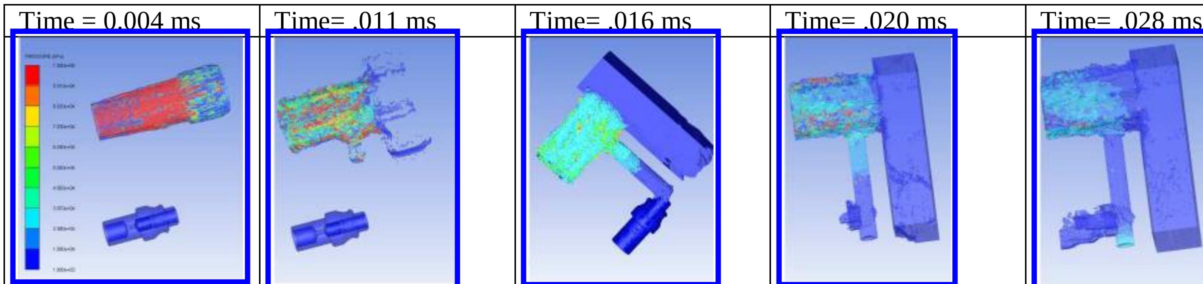
Pictures in Figure 5 show the model setup and LSC copper jet results of baseline configuration at time 0.20 and 0.028 ms. All analyses also generated results of pressure, velocity, density, internal energy, .. and other parameters. The LSC copper jet will have to make a 90° turn in order to reach the RDM inside the end-tip housing which is very unlikely to occur. Analyses doesn't support the copper jet igniting RDC. PBX detonation products travel at 2.4km/s and fill the manifold cavity of the RDC end-tip housing. Copper travels at 1.5km/s and creats a 3 times (4500 vs. 1500psi) pressure differential before and after the copper jet by "holding" the gas. Gases and copper eventually reache the end of the passage and copper deposits at the passage end while gases flow to RDC line axes. Based on the analysis of copper jet movements and post-function observation of copper deposit, detonation products from LSC explosive is the stimulus initiating RDM. Figure 6 clearly showed the PBX detonation gases pass copper jet and reach RDC first. Neither test nor analysis can determine whether gases before or behind copper are more critical for RDC ignition. The copper jet is probably more of an interference rather than assisting in the RDM initiation in this design.



Time = 0 ms | Time= .020 ms; Copper and RDC | Time= .028 ms; Copper and RDC

Figure 5. FEA model and LSC liner deployment

Time = 0.004 ms | Time= .011 ms | Time= .016 ms | Time= .020 ms | Time= .028 ms



Pressure | Pressure | Pressure | Pressure | Pressure

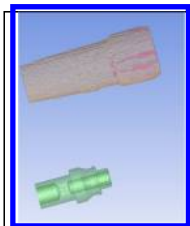
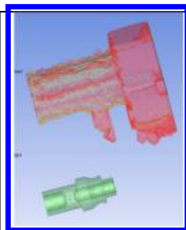
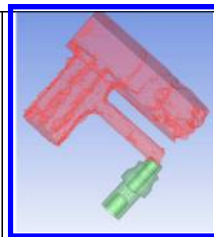
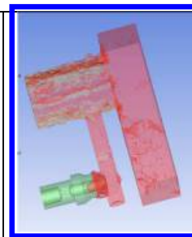
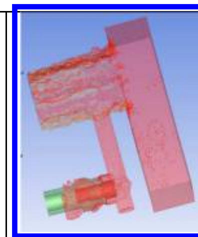
 PBX and RDC	 PBX and RDC	 PBX and RDC	 PBX and RDC	 PBX and RDC

Figure 6. Pressure profiles (all pressure plots are using the same scale (10^3 to 10^5 kPa) and material locations at various timing.

B. Confinement/ Manifold Strength Effects on RDM Initiation

A model was setup changing the manifold material failure criteria from 24% principal strain to 8% to assess the effects of manifold confinement on RDC initiation. The manifold was sealed at the end of LSC by boundary condition and manifold elements become invisible after material elements fail.

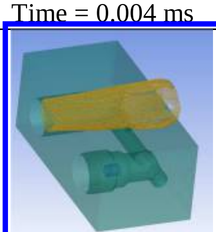
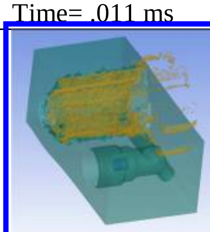
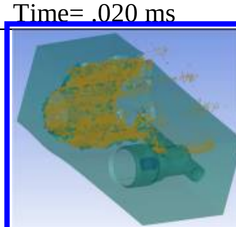
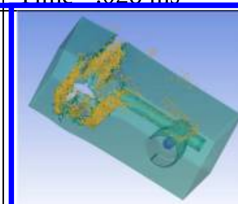
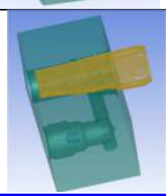
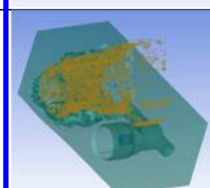
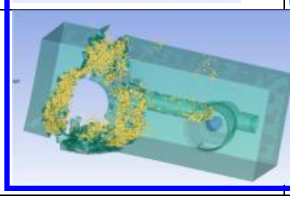
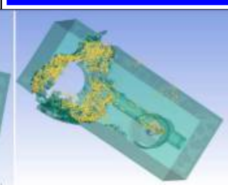
	Time = 0.004 ms	Time= .011 ms	Time= .020 ms	Time= .028 ms
Baseline				
Weaker manifold				

Figure 7. Comparison of baseline and weaker manifold damage conditions at various timing.

Figure 7. shows the manifold damage conditions for both baseline and weaker manifold. The LSC cut open both top and bottom of the weaker manifold compared to only the top portion of the baseline. Baseline damage conditions were validated by post-function observation of actual device while the weaker one was not tested nor validated. Figure 8 compares the pressure profiles between two models. High pressure reaches further toward RDM at 0.028 ms than observed for case of higher confinement/ manifold strength. Gases also expand in more directions on the weaker manifold due to larger openings. At 2km/sec, it takes 0.015ms to travel the nominal gap distance. The time duration of 0.015ms is very insignificant compared to 0.3 ms (difference between 4.9 and 5.2 ms at gap tests). There should be other mechanism affecting the gap test time difference. Manifold damage conditions affect gas expansion but doesn't appear to be significantly different based on observation of the entire run duration (0.028 ms). This run duration is not long enough to cover the complete gas pressure impulse un til complete equalization to ambient.

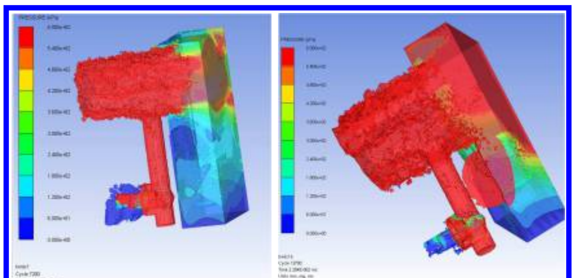


Figure 8. Comparison of pressure profiles of PBX reaction products between baseline (left) and weaker manifold (left)

C. Pressure bleeddown

It is a gas expansion phenomenon inside the manifold cavity after complete PBX detonation reactions inside LSC. Its pressure-time profile after peak pressure can be explained by equation (1) as a typical solid rocket tail off pressure bleeddown[5]. Openings of LSC perforated manifold simulates the throat area, At, in equation (1). Various passage lengths in gap testing are essentially various chamber volumes, Vic. Results of bleeddown pressure over time calculations are presented in figure 9 showing the effects of chamber volume varied by gap length.

$$P_c = P_{bo} \exp\left(- \frac{R_0\, T_c\, A_t\, g_c\, t}{\overline{M}\, V_c\, c^*} \right) \tag{1}$$

Longer gap/ higher passage volume in gap tests impose a higher pressure impulse on RDM and enhance its heat transfer and burn rate therefore shortening the RDC ignition time. Although this calculation doesn't derive the 0.3 ms difference in Table 1 directly, it gives the correct order of magnitude of time duration and provides a reasonable hypothesis explaining its time-passage length relationship. Shorter passages allow the RDC to receive the pressure impulse quicker but also allows dissipation of pressure faster. Pressure bleed down accounts for longer LSC to RDC ignition times.

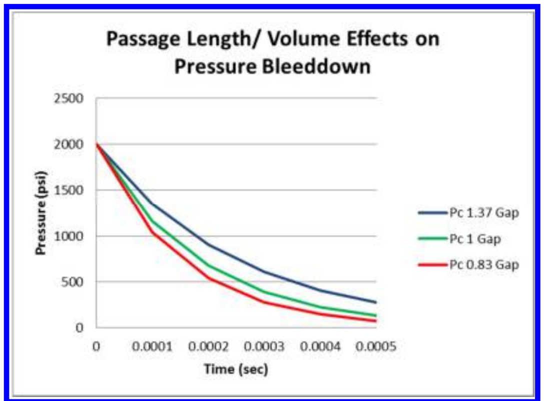


Figure 9 Pressure bleeddown

V. Conclusions

Explicit Dynamics analysis showed the ignition mechanism and the effects of manifold strength on this initiation train. RDM in RDC is ignited by detonation products from LSC explosives. LSC copper jet delays the gas flow and can be an interference if it blocks the RDC entrance. There is no indication this blockage ever occurred. A stronger manifold enables a higher gas pressure reaching the target RDM. The manifold cavity volume and geometry of the LSC/ passage/RDC housing becomes a significant factor affecting ignition once it is filled with detonation products. The results in Table 1 appear to be counter intuative but can be explained by the effects of volume variation created in gap testing and the bleeddown equation. These analyses support test measurements and observations but their implication on RDM ignition is not quantified. Gap test results are valid and its calculated reliablility was used in the design.

To further increase the design margin, the designer can create an additional volume at the end of the passage so that the gas pressure reaches target in the front but still has larger volume at the end for longer bleeddown impulse. Higher and longer pressure pulse is beneficial to heat transfer and ignition. The LSC copper can be thinned at the passage interfacing area to minimize the passage interference possibility.

Acknowledgments

Author thanks his coworkers, Victor Sanchez, Meizhen Chen, and Terry Gansberger performing testing and supporting this project.

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