Shock Tube Effect Inside a Pyrotechnic Igniter

Gavin A. Buttigieg,*[a] Gregory H. Paine,[a] and Ralph C. Hsiao[b]

Abstract: An output closure is a critical component of a pyrotechnic igniter. It controls the heat transfer duration of initiation train, stress loading on the propellant grain, and the pressure drop during closure deployment. Normally the pressure profiles calculated by a quasi-static interior ballistics code are adequate for igniter design evaluation. But following a case of premature closure deployment in which the propellant failed to ignite, the authors discovered that the design geometry mimicked that of a shock tube. The shock tube effect occurred whenever the high-temperature gases of the initiator were rapidly discharged into a long conduit. The shock resultant from the initiator opened the closure prior to ignition of the ignition aid. In this paper, we report results from both quasi-static computations for static pressure and time-dependent simulations for dynamic pressure. Designers need to consider both static and dynamic pressure when devices have a sudden high-pressure gas released into a conduit.

Keywords: Shock tube · Closure · Igniter · Finite-difference analysis · Hydrocode

1 Introduction

Pyrotechnic igniters are the most common devices used to ignite a one-time-use liquid engine due to their minimal mass, compact volume, and reliability without the need for maintenance. The ability to function with high reliability is a consequence of the tight control of the design parameters and processes during device manufacturing. In the following article, the authors present studies that focus on the design of the output closure, including factors that affect closure deployment and ignition train reliability (initiator, ignition aids, propellant).

A hermetically-sealed closure provides not only an environmental seal but controls the maximum pressure inside the igniter and transfer of thermal energy to the ignition train and propellant grain. Weak or early bursting of the closure allows hot gases and particles to exit the igniter without transferring adequate heat onto the propellant, which may result in a failure of the propellant combustion. A closure that bursts at a pressure higher than the optimal design imposes high-stress loads on the igniter components and can cause structural failure of the propellant grain or its case to grain inhibitor. A high pressure drop resulting from a closure that deploys prematurely can also create an unsustainable combustion condition for certain types of propellant due to the heat being rapidly removed from the combustion zone.

The authors describe a case, where an ignitor experienced premature closure deployment resulting in an ignition failure. The closure for the failed ignitor was designed to sustain static pressures produced by the initiator with what was deemed an adequate design margin. When the closure of the failed unit opened prematurely, an investigation showed that the initiator had functioned with little or no consumption of energetic material in the ignition train. Experiments and analyses were conducted to understand the phenomenon, which led us to establish and to verify the cause to be a shock-tube effect. In the following sections, the authors present studies on closure design methods that focus on improvement of ignition train robustness through mitigation of premature closure deployment due to high-dynamic pressure loading.

2 Theories and Computation

A thermochemistry equilibrium code was initially used to calculate the energy output of individual chemicals. These values were fed into a quasi-static interior ballistics code that provided expected nominal pressure over time profiles inside the igniter during the ignition event. These pressure loadings were then utilized to design a closure that would open after combustion of sufficient quantities of the ignition aids to ensure reliable function. But an unexpected premature deployment of the closure forced us to reconsider the design process. This led us to the hypothesis that
a shock may have formed inside the igniter. Formation of a shock of sufficient magnitude would certainly be capable of causing the closure to burst prematurely. To estimate the magnitude of shock loading on the closure, a closed-form, air-shock equation was first utilized. This subsequently led us to employ a shock-wave propagation code (commonly called a hydrocode) to create two- and three-dimensional simulations of hot gases being released from the initiator. This allowed the determination of shock profiles inside the igniter that were the direct consequence of the output of hot gases from the initiator.

2.1 Static Pressure

2.1.1 Thermochemistry Equilibrium Combustion Computation

There are three major energetic components in this igniter (see Figure 1): the initiator, ignition aids, and propellant. Combustion products of all energetic materials (primer and output charge in initiator, ignition aids in housing, and surface of enhanced end of propellant grain) are calculated by thermal-chemical-equilibrium code such as the Propellant Evaluation Program (PEP) [1]. The propellant was treated as an inert substance for the scope of this paper.

PEP was used to calculate the values required by the interior ballistics code; values such as the adiabatic flame temperature, specific volume of gas, specific heat at constant volume, molecular weight of combustion gases, and chamber pressure. However, determination of the chamber pressure at a representative combustion pressure required performing an iterative calculation until the solution converged. A partial list of thermodynamic properties, and their respective values derived from a PEP calculation, is provided in Table 1.

2.1.2 Quasi-static Pressure Calculation by Nobel-Abel Equation

A US Navy quasi-static ballistics code computes the equilibrium pressure of a free volume at every time step by using a Nobel-Abel Equation of state [see Equation (1) below]. The interior ballistics code also takes into account the equation of motion, burning rate equation, propellant form function, nozzle flow equation, mass continuity equation, and the energy balance equation.

The Nobel-Abel equation of state is similar in form to the ideal gas equation of state except for the introduction of an additional parameter, called the co-volume. This parameter usually represents the effective volume the gas molecules occupy, and is normally determined by experiments using the extrapolated intercept of the peak pressure vs. the loading density in a closed bomb [2]. For this study, the co-volume represents the effective volume of all combustion products in a condensed phase. Because the effective volume of the pyrotechnic combustion gases is considered negligible, the co-volume for gases will not be considered explicitly in the calculations. The Nobel-Abel Equation of state thus takes the following form:

\[ P = \frac{RT}{(v - b)} \]  

(1)

where \( b \) is the co-volume for combustion products in a condensed phase, \( P \) is the pressure (dependent in computation), \( R \) is the specific gas constant (gas constant divided by gas molar mass), \( T \) is the absolute temperature (adiabatic flame temperature from PEP), and \( v \) is specific volume (energetics loading density).

Thermodynamic properties of energetic loads, such as the example of Table 1, are calculated only at their combustion pressure. Phase changes and changes in the combustion species consequently are not considered when using this code. The burning rate equation and form function are required in order to calculate per time step the mass addition of combustion products. The authors assumed the initiator primer completed combusted at time equal to zero seconds. Combustion of the initiator output charge, igni-

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**Table 1. Partial PEP output results of boron potassium nitrate (B/KNO3).**

<table>
<thead>
<tr>
<th>Thermodynamic properties, Enthalpy, and Pressure</th>
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<tbody>
<tr>
<td>Equilibrium composition</td>
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<tr>
<td>Chamber</td>
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<tr>
<td>Enthalpy [kJ per 100 g]</td>
</tr>
<tr>
<td>Chamber</td>
</tr>
<tr>
<td>Hazardous material</td>
</tr>
<tr>
<td>b [g cm(^{-3})]</td>
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<tr>
<td>Assumed</td>
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<tr>
<td>Gases</td>
</tr>
<tr>
<td>Co-volume</td>
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<tr>
<td>b [g cm(^{-3})]</td>
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<tr>
<td>Assumed</td>
</tr>
</tbody>
</table>

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Figure 1. Simplified illustration of pyrotechnic igniter.
tion aid granules, and ignition aid pellets was based on their form functions and burning rate equations. Additional mass from the initiator output and ignition aids is calculated sequentially using 10 μs time steps to establish the equilibrium pressure under an isentropic expansion.

2.2 Dynamic Pressure

The closures for the igniter were initially designed to withstand the expected pressure delivered by the initiator. The closure design was evaluated in a heavy wall characterization fixture, where peak pressures far exceeded the quasi-static pressures calculated using the aforementioned methods. Due to higher than expected peak pressure measured prior to the chamber reaching the quasi-static pressure, and due to the transient nature of the pressure front, an evaluation of the dynamic pressure event was undertaken.

Following a review of the data collected during the design phase of the project, specifically the presence of a pressure event with higher than expected peak pressure preceding the quasi-static pressure, and the geometry of the device, an investigation into shock tube effects within the device was explored. A shock tube is configured by separating a high pressure “driver gas section” from a low pressure “driven gas section” with a diaphragm [3]. Once the diaphragm fails, a shock front is induced in the driven section and moves through the driven section eventually to be reflected at the shock tube termination. The igniter “driver” section was determined to be the baffle portion of the igniter, with the “driven” section being the adapter. Although the system did not include a diaphragm, a shock would either be incident at the initiator, or at the end of the baffle due to expansion of combustion gas. The hypothesis was that the shock reflection at the closure greatly increased the pressure induced on the closure, which caused the premature opening of the closure. The latter event resulted in the failure of the initiator to ignite the ignition aide.

2.2.1 Shock Tube Effect Calculated by Closed-form Equation

First order calculations used to describe the pre- and post-shock conditions, and ultimately the pressure reflected at the pyrotechnic igniter end closure are described by normal shock Equation [3]. The magnitude of the shock velocity is described by the equation:

\[
\frac{P_2}{P_1} = 1 + \frac{2\gamma}{(\gamma + 1)} \left(\frac{M_1^2 - 1}{M_2^2 - 1}\right) \tag{2}
\]

where \(P_1\) is the pressure of the driven gas (ambient pressure), \(P_2\) is pressure of the driver gas (empirical data), \(\gamma\) is the specific heat ratio (assumed constant, 1.4 for air), and \(M_1\) is the Mach number of the shock front. The magnitude of the shock reflected from the pyrotechnic igniter closure is described in terms of \(M_1\) and \(P_1\) by Equation (3):

\[
\frac{P_3}{P_1} = \frac{(4M_1^2 - 1)(7M_1^2 - 1)}{3M_1^2 + 15} \tag{3}
\]

where \(P_3\) is the reflected pressure of the shock.

2.2.2 Shock Tube Effect by CTH Computation

Computer simulations of the pyrotechnic igniter were performed using the software CTH, a physics-based, continuum-mechanics, finite-difference shock-wave propagation code developed by the Computational Physics Group at Sandia National Laboratories [4]. The CTH model for the pyrotechnic igniter consisted of accurate representations of the initiator, case, baffle, adapter, and closure disk. The liner of the initiator was aluminum alloy 6061-T6 filled with a high-temperature gas. The material for all other metallic components was stainless steel 304. An inert filler (propellant) and air were also placed inside the pyrotechnic igniter.

All simulations but one were done in two dimensions using a cylindrical coordinate system. Both a fine uniform mesh and an Adaptive Mesh Refinement (AMR) process were employed. An example of a uniform mesh is shown in Figure 2. Both types of mesh generation allow the simulation to capture the motion of the shock-wave front and dynamic behavior of the closure disk, consisting of a cruciform etched into a stainless steel disk. One limitation with using two-dimensional cylindrical coordinates, however, is that the thinner section of the closure disk does not form a true cruciform, but rather a simple circular indentation. Any two-dimensional simulation showing the closure disk rup-
turing should be interpreted accordingly. To observe the dynamic behavior of a true cruciform etched into a closure disk, a three-dimensional simulation using a quarter model of the pyrotechnic igniter was performed.

Hydrocode simulations of a pyrotechnic would employ normally a reactive burn model that can mimic the process of burning in its entirety, from ignition to completion, including the natural creation of combustion gas products. Unfortunately, a reactive burn model was available for neither zirconium potassium perchlorate (ZPP) nor boron potassium nitrate (B/KNO₃). It was decided instead to start the simulations at the moment the pyrotechnic had completed burning within the initiator, leaving behind primarily the high-temperature gas products. Because ZPP makes up the majority of the pyrotechnic within the initiator, further simplification was introduced by using only 16 milligrams of gaseous ZPP to represent the combined combustion products of ZPP and B/KNO₃. The thermodynamic state of the ZPP was represented by a Jones-Wilkins-Lee (JWL) Equation of state [5], which was determined using the thermochemical computer code CHEETAH 5.0 [6]. The final temperature of the combustion products, after the pyrotechnic achieved complete combustion, was estimated by PEP [1] to be 2061 K. Consequently the initial temperature of the 16 milligrams of ZPP gas was set at 2061 K. The high-temperature gas was also confined initially to a volume of 0.0115 cm³, which corresponds to an initial pressure of 5.6 GPa as calculated from the JWL equation of state. At later times, the combustion gas products, no longer constrained to a specific volume, were allowed to move into the baffle and adaptor sections of the pyrotechnic igniter naturally.

3 Results and Discussion

The focus of the study was to determine the cause of premature deployment of the igniter output closure, which resulted in the failure of the igniter to function as expected. Our efforts, in particular, concentrated on the output power of the initiator and the strength of the closure. The data from our analyses, that are summarized here, provide what we believe is a clear body of evidence as to why the igniter failed to function.

3.1 Closure Burst Pressure

To determine a burst-pressure distribution for the closure, seven separate closures were pneumatically pressurized to open in test fixtures. The results (see Figure 3) showed that the burst strengths of closures are very consistent (all within 7.6–9.0 MPa). The authors concluded that a weak closure was thus an unlikely cause for premature bursting.
3.4 Results from a CTH Simulation

Only the results from a single two-dimensional simulation will be discussed. In this particular simulation, the main section of the stainless steel closure disk was 150 μm thick, while an indentation (representing a cruciform) was etched into the exterior side of the closure disk. The thickness of the indentation was 80 μm. The simulation was performed in cylindrical coordinates using a fine uniform mesh.

After the constraint on the ZPP gas was removed, a shock wave was observed moving through the air inside the baffle and adapter sections of the pyrotechnic igniter. The speed of the shock wave through the air was estimated by using a set of tracer points equally spaced and fixed inside the adapter. By observing the abrupt change in pressure at each tracer, the arrival times for the shock wave were found to be consistent with a shock velocity of approximately Mach 4 (Figure 6).

Before the shock wave arrived at the closure disk, a small amount of strain was observed as indicated by a grey arrow pointing to a plateau in Figure 7. This strain was caused by a stress wave travelling through the steel case, reaching the closure disk 20 μs into the simulation. Approximately 10 μs later, the shock wave moving through the adapter reached the closure disk and induced an additional strain on the disk. Because the amplitude of the shock was 1.7 MPa, a small increase of about 0.1 percent from the original strain was observed as indicated by a cross hatched arrow pointing to a second plateau in Figure 7. Such a small strain indicates the pressure from the initial shock wave was insufficient to cause the disk to fail. Failure of the closure disk came instead as the bulk of the ZPP combustion gas products continued to build up, as well as the corresponding pressure, until the plastic strain reached a maximum value of 13.3 percent, as indicated by a black arrow in Figure 7. At this moment, the indentation (cruciform) of the closure disk failed and allowed the high-temperature gas to escape from the pyrotechnic igniter. The pressure on the indentation at rupture was 22 MPa.

3.5 Experimental Section

To validate the models, the internal pressure of the igniter was measured using a piezoelectric pressure transducer (range of 0 to 34.5 MPa) from PCB Piezotronic, Inc. This was accomplished by utilizing a housing designed and fabricated specifically for this purpose that attached the pressure...
transducer to a 2.5 mm diameter opening on the side of the igniter adapter. With such an assembly, the transducer was capable of measuring directly the internal pressure of the igniter. A photodiode detected the moment of output closure opening. All transducer signals were simultaneously captured with an oscilloscope (Figure 8).

4 Conclusions

The authors were confronted with an unexpected pyrotechnic igniter failure to function as designed due to a premature closure deployment. Following thermochemical and ballistic code analysis, the authors determined that the initiator that contained ZPP could not open the closure by a static force alone. Analytic air-shock equations provided some insight into the magnitude of shock-induced loading on the closure. These calculations were followed up with 2D and 3D CTH hydrocode analysis, which provided a high fidelity verification of the cause of the premature deployment. Finally the authors caution designers of pyrotechnic devices to evaluate carefully the designs which couple a rapidly combusting initiator with a linear geometry.

Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>AMR</td>
<td>Adaptive mesh refinement</td>
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<tr>
<td>b</td>
<td>Co-volume for combustion products</td>
</tr>
<tr>
<td>B/KNO₃</td>
<td>Boron potassium nitrate</td>
</tr>
<tr>
<td>CHEETAH</td>
<td>Thermochemical computer code</td>
</tr>
<tr>
<td>CTH</td>
<td>Shock-wave propagation code</td>
</tr>
<tr>
<td>JWL</td>
<td>Jones-Wilkins-Lee Equation of state</td>
</tr>
<tr>
<td>γ</td>
<td>Specific heat ratio</td>
</tr>
<tr>
<td>M</td>
<td>Mach number</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>PEP</td>
<td>Propellant evaluation program</td>
</tr>
<tr>
<td>R</td>
<td>Specific gas constant</td>
</tr>
<tr>
<td>T</td>
<td>Temperature (Kelvin scale)</td>
</tr>
<tr>
<td>v</td>
<td>Specific volume</td>
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<tr>
<td>ZPP</td>
<td>Zirconium potassium perchlorate</td>
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References


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Figure 8. Pressure profile and photo sensor measurement during closure opening. The dip in photo sensor output is the result of an ignitor ignition delay due to premature closure opening.
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