



**Combustion Light Gas Gun Technology Demonstration**

Final Report

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<b>14. ABSTRACT</b> The Combustion Light Gas Gun, or CLGG, has been investigated for over ten years. During this time, the research has shown that the technology provides a <u>minimum of 30% more</u> muzzle energy than advanced solid propellant guns which translates to significant advantages in range and/or throw weight. For the Navy Barrage round fired from a 155mm bore CLGG, the predicted <u>range is up to 200 nm</u> , sufficient to provide effective amphibious and in-shore fire support without endangering capital assets. In addition, the CLGG provides: <ul style="list-style-type: none"> <li>o The ability to "manufacture" propellant as needed on board ship</li> <li>o The ability to remotely discharge propellant in damage control situations</li> <li>o The ability to automatically adjust the propellant charge as needed</li> </ul> <p>This year's work built on last year's effort by continuing to address remaining issues associated with successful system demonstration such as cryogenic propellant handling, multi-shot demonstration, modeling, and proof of principal at 155mm scale.</p>					
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# Combustion Light Gas Gun Technology Demonstration Outline

<b>Technical Information</b> .....	<b>1</b>
Abstract.....	1
Response to ONR Objectives.....	1
<b>Summary</b> .....	<b>2</b>
<b>Review of Last Years Progress</b> .....	<b>2</b>
Autoloader.....	3
Cryogenic Propellant Supply .....	4
Modeling.....	5
155mm Test Bed.....	7
Ship Integration.....	8
<b>Technical Background and CLGG History</b> .....	<b>11</b>
CLGG Physics .....	11
CLGG History.....	13
Previous 45-mm CLGG Design and Test Data.....	14
Propellant Loading.....	15
Combustion and Pressure Control .....	16
Repeatability .....	18
Barrel Erosion .....	19
Performance and Scaling .....	20
Older Test Data Summary .....	21
References.....	21
<b>Bibliography</b> .....	<b>21</b>

## **Appendix A – Cryogenic Propellant Feed System**

## **Appendix B – Computational Fluid Dynamics**

## **Appendix C – Finite Element Analysis**

## **Appendix D – Shipboard Integration Studies**

## **Appendix E – Executive Summary of Independent Ship Integration, Comparison and Safety Analysis**

## **Technical Information**

### **Abstract**

The Combustion Light Gas Gun or CLGG has been investigated for over ten years. During this time the research has shown that the technology provides a minimum of 30% more muzzle energy than advanced solid propellant guns which translates to significant advantages in range and/or throw weight. For the Navy Barrage round fired from a 155mm bore CLGG, the predicted range is up to 200 nm, sufficient to provide effective amphibious and in-shore fire support without endangering capital assets. In addition, the CLGG provides:

- The ability to “manufacture” propellant as needed on board ship
- The ability to remotely discharge propellant in damage control situations
- The ability to automatically adjust the propellant charge as needed

This year’s work built on last years effort by continuing to address remaining issues associated with successful system demonstration such as cryogenic propellant handling, multi-shot demonstration, modeling, and proof of principal at 155mm scale.

### **Response to ONR Objectives**

ONR and the Navy have a long-standing need for long-range (100 plus nm) shore support. This need has spawned ongoing programs such as the Extended Range Guided Munitions (ERGM) program. In these and similar programs the approach is to gun launch, what is in effect, a missile consisting of an artillery warhead and guidance package attached to a large solid propellant rocket motor. This approach provides, in theory, long range (~60 nm) shore support. In practice the approach has been plagued by technical problems, some associated with the effects of high acceleration loads on the massive rocket motor. Even if these problems are solved, the costs associated with this approach appear to be enormous. For example, most credible cost estimates for ERGM are in the range of \$50,000 per round. Assuming a shipboard complement of 1000 rounds, the cost of outfitting one ship with a supply of rounds is 50 million dollars. A single 100 round “fire for effect” mission would expend 5 million dollars worth of munitions. At this price, 5 Tomahawk cruise missiles could be used and would deliver more effective payload on target.

In addition, since the ERGM will be launched with conventional solid propellants at modest velocity, relying on its rocket to provide range, it will be slow to reach its target. This leaves ground forces without timely supporting fires.

The solution to these problems is to launch non-rocket assisted guided projectiles on ballistic profiles at high velocities. Such rounds, such as the Navy’s Barrage Round are in the concept stage and need further development efforts. In addition, what has been lacking until now is a viable and available gun technology capable of launching large projectiles at significantly increased velocities. This capability will transfer the burden of

providing increased range from the projectile to the gun. In other words, a few advanced guns will be able to launch thousands of relatively inexpensive projectiles to the desired ranges in a timely fashion. The Combustion Light Gas Gun is an advanced gun technology that will provide an affordable near term solution to the Navy’s long-range fire support needs. An example of the CLGG’s potential can be seen in Table 1 which shows predicted performance for CLGG based launchers as a function of tube length.

**Table 1 - CLGG performance**

<b>Tube Length (calibers)</b>	<b>Launch Velocity (m/s)</b>	<b>Muzzle Energy (MJ)</b>	<b>Range (nm)</b>
<b>54</b>	<b>1890</b>	<b>33</b>	<b>120</b>
<b>70</b>	<b>2037</b>	<b>38</b>	<b>141</b>
<b>70</b>	<b>2500</b>	<b>58</b>	<b>217</b>
Baseline round is 155mm “low cost” configuration, launch mass – 18.48 kg, flight mass – 15 kg, First two ranges based on demonstrated performance, Last range based on optimized conditions			

**Summary**

The primary goal of this project remains demonstrating and resolving remaining issues associated with fielding a weapon system based on CLGG technology. This year’s effort revolved around efforts to safely use cryogenic propellant as a viable means to store gaseous propellant before use as well as the subsystems (i.e. projectile, igniter, and auto-loader) required for rapid fire operation. In addition the hardware for full scale (155mm) demonstration of CLGG technology was largely completed. Modeling of the combustion process (CFD) continues to support and validate the experimental effort. Finite element modeling is playing a larger role in the development effort largely associated this year with 155mm hardware development. Ship integration efforts continued to address propellant production and storage systems in potential navy platforms and with advanced technology systems currently under development.

The CLGG approach to providing high velocity projectile launch represents a break with traditional solid propellant technology which is as dramatic as using an all electric gun.

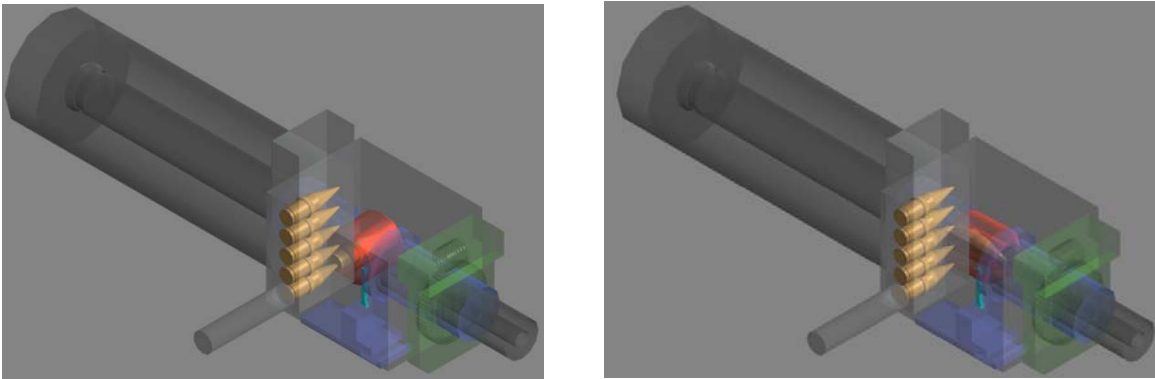
**Review of Last Years Progress**

The bulk of last years technical effort can be broken down into five primary areas, 45-mm autoloader, cryogenic propellant supply, modeling, 155mm gun design and build, and ship integration. A summary of these efforts appears below.

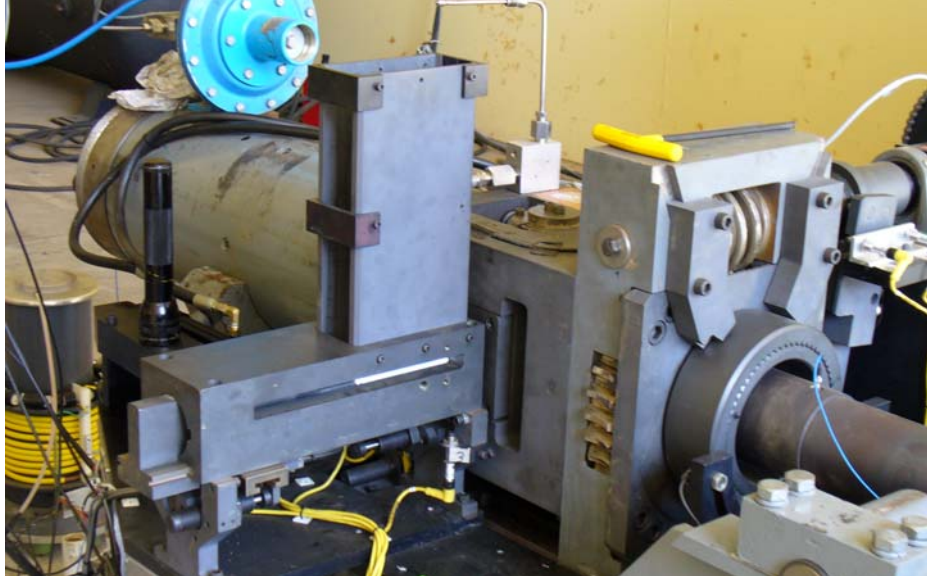
## Autoloader

The autoloader concept for the 45mm CLGG is based on a forward loaded cartridge concept. While there are many ways to engineer an autoloader this design integrates well with the CLGG. The autoloader incorporates a rotating chamber mounted between the forward end of the gun chamber and the barrel. The projectiles are loaded in a cartridge and stacked in a clip designed to gravity feed the cartridges to the rotating chamber. After a cartridge is inserted into the chamber it is rotated 90 degrees to align the cartridge parallel with the barrel. The barrel is then clamped down on the chamber and cartridge to form a pressure tight seal. After firing the chamber rotates back 90 degrees, the spent cartridge is ejected, a new cartridge is loaded into the chamber and the process repeats itself.

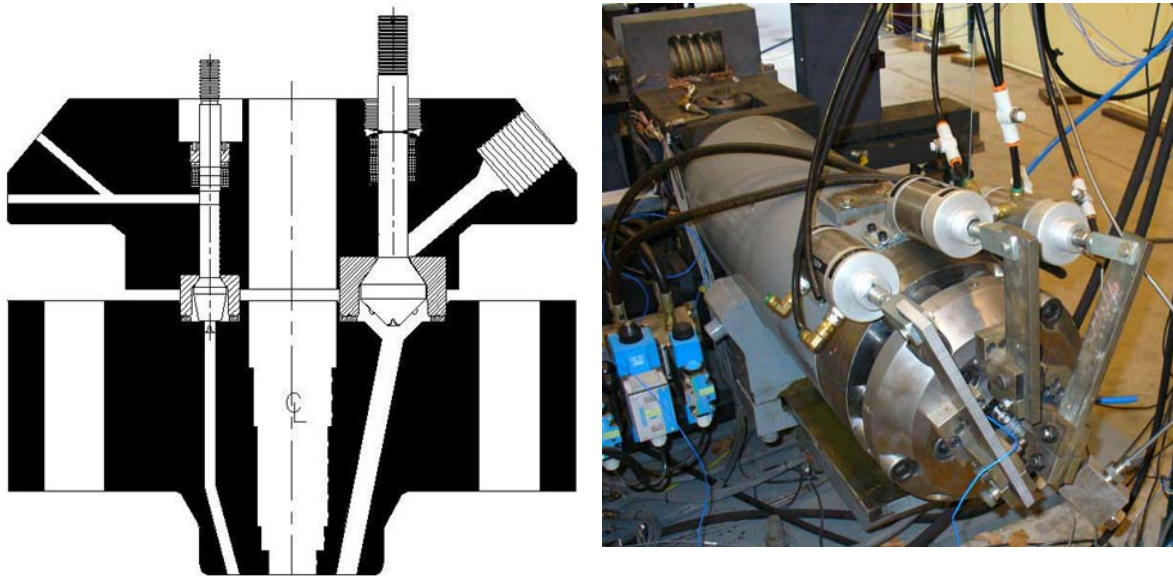
Since the CLGG is a bulk loaded with propellant through injectors, requiring no traditional rear opening breech, this autoloader design dovetails well with the CLGG approach. Also the cartridge concept allows considerable flexibility in projectile design used (i.e., different projectiles could be loaded into the same cartridges for varying mission scenarios. Finally, this design allows the gun to be loaded at almost in firing elevation. Over the last year this design has been extensively tested including an auto sequence of five rounds fired sequentially under computer control. In addition, the system has been modified to accept the “popit” breech designed to allow feeding of cryogenic temperature fluids rapidly into the system. A pictorial view of the autoloader is shown in Figure 1. The actual hardware is shown in Figure 2. Details of the popit breech design are shown in Figure 3.



**Figure 1 - 45mm autoloader design. Left view shows load position, right view shows fire position. For clarity cartridge around projectile is not shown.**



**Figure 2 – 45mm autoloader during testing**

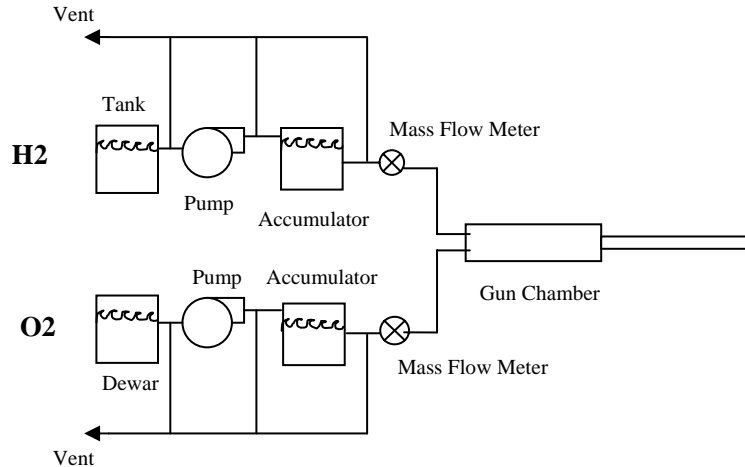


**Figure 3 – Left, cross section of “Popit” breech design. Valves act like automotive valves allowing entry of cold gases and then seating to seal chamber during shot. Right, “popit” hardware installed on gun with pneumatic lifters installed on circumference of chamber.**

### **Cryogenic Propellant Supply**

In order to rapidly fire the CLGG the hydrogen and oxygen propellants are being delivered to the CLGG in a liquid or near liquid state (cold dense gas). In addition cryogenic storage is a very compact method to store the propellants for later use. The major components of such a system are shown schematically in Figure 4. Early last year





**Figure 4 - Schematic of cryogenic propellant storage and feed system**

the cryogenic feed system was completely tested using inert cryogenics (Nitrogen) in a gun firing bay next to the 45mm CLGG gun bay. The system was then disassembled and moved to the 45mm CLGG gun bay for mating with the 45mm. Currently the system is fully operational again and being tested with “live” propellants (liquid hydrogen and oxygen). The system will then be mated to the Popit breech and cryogenic feed firings will commence. Various components of the system in their final positions are shown in Figure 5. A complete report on the cryogenic system is given in Appendix A.

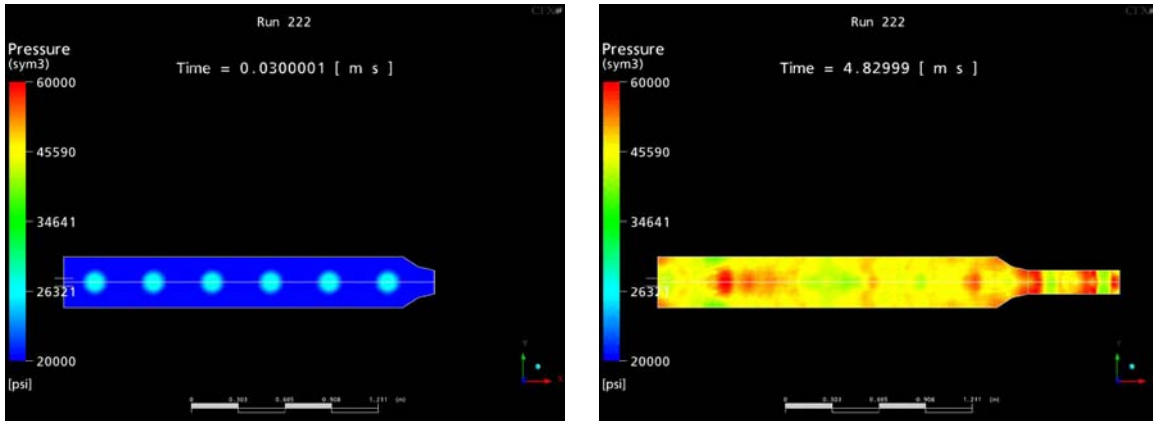


**Figure 5 – (Left), 45mm CLGG with cryogenic feed system installed. Note that this system is oversized to feed the 155mm CLGG also. Right view shows closer view of accumulators (foreground) and pumps (background).**

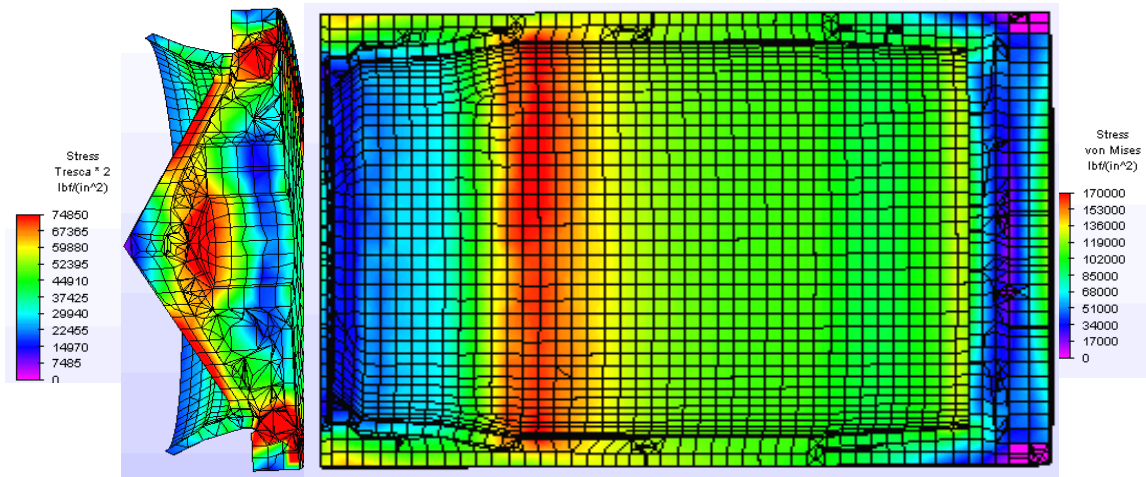
### **Modeling**

Computational Fluid Dynamics (CFD) modeling of the CLGG continues. There are three main thrusts of this effort. The first is to understand the effects of various parameters on CLGG performance such as chemistry, ignition, geometry, temperature, etc. These calculations are often coupled with experiments in the 45mm CLGG for validation purposes. The second primary role of the modeling effort is to predict scaling

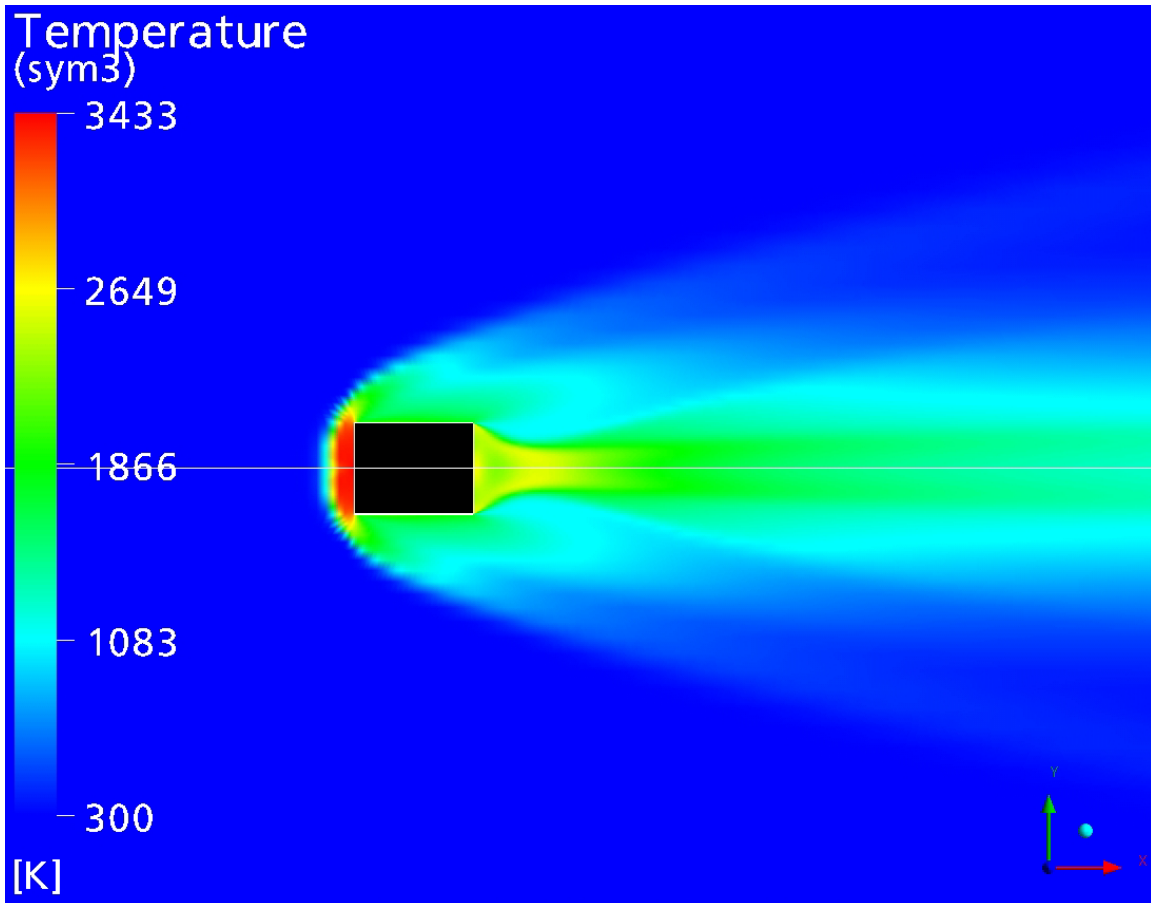
effects when moving to the 155mm version of the CLGG. The third and newest role of the CFD effort is to assess in-flight conditions for hypersonic projectiles for use in the 45 and 155mm CLGG systems. In addition to CFD Finite Element (stress analysis) codes are routinely run to assess key component integrity. This year active analysis of aeroballistics is also being performed. A sample of these calculations is given in Figures 6 through 8. A more detailed look at the modeling effort is shown in Appendix B and C.



**Figure 6 – Sequence of frames from CFD simulation of combustion in the 155mm**



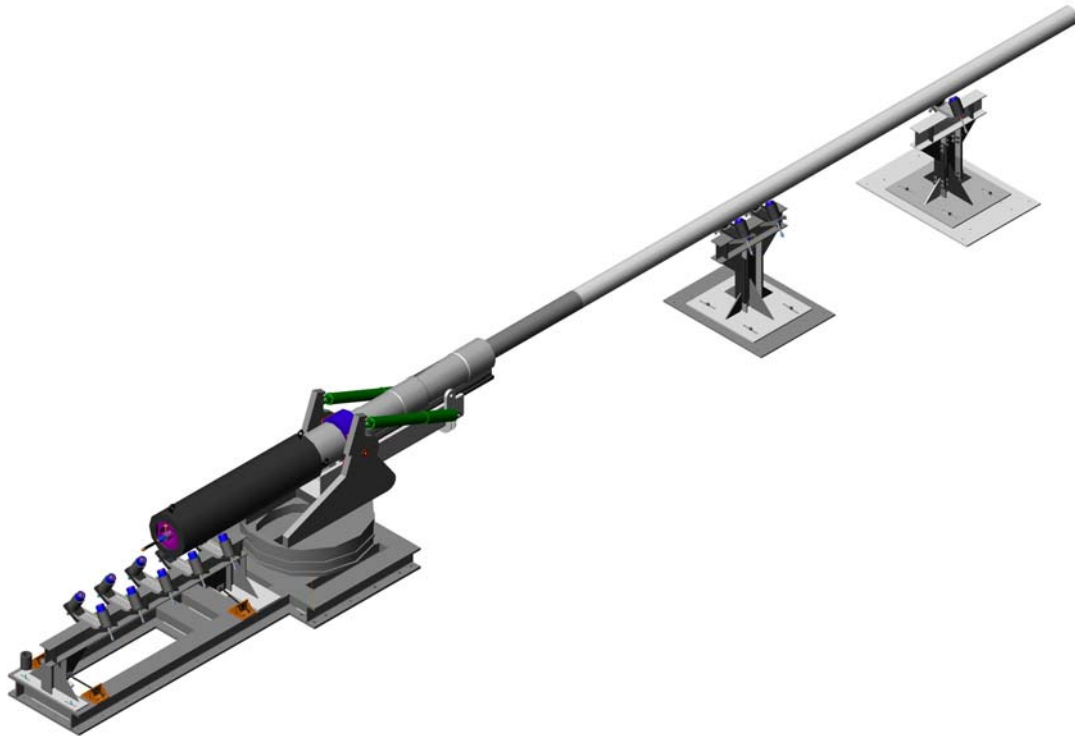
**Figure 7 – Finite element stress model of 155mm test “slug” projectile under load in tube during firing**



**Figure 8 – Temperature profile around slug projectile in flight at 2500 m/s (Mach 7.5).**

### **155mm Test Bed**

After over 8 months of construction delays beyond the control of UTRON, the 155mm CLGG tube has been delivered and set up at the UTRON test site. Currently the gun tube is being fitted to the mount and recoil system. The cryogenic feed system in the adjoining test bay (Figure 5) will be used to fill the 155mm system. Due to the aforementioned delays, test firings with the 155mm system will take place early in 2007. A 3D cad rendering of the assembled system appears in Figure 9. Photos of the tube, mount, and recoil appear in Figures 10.



**Figure 9 – 3D Cad rendering of the 155mm CLGG gun system**

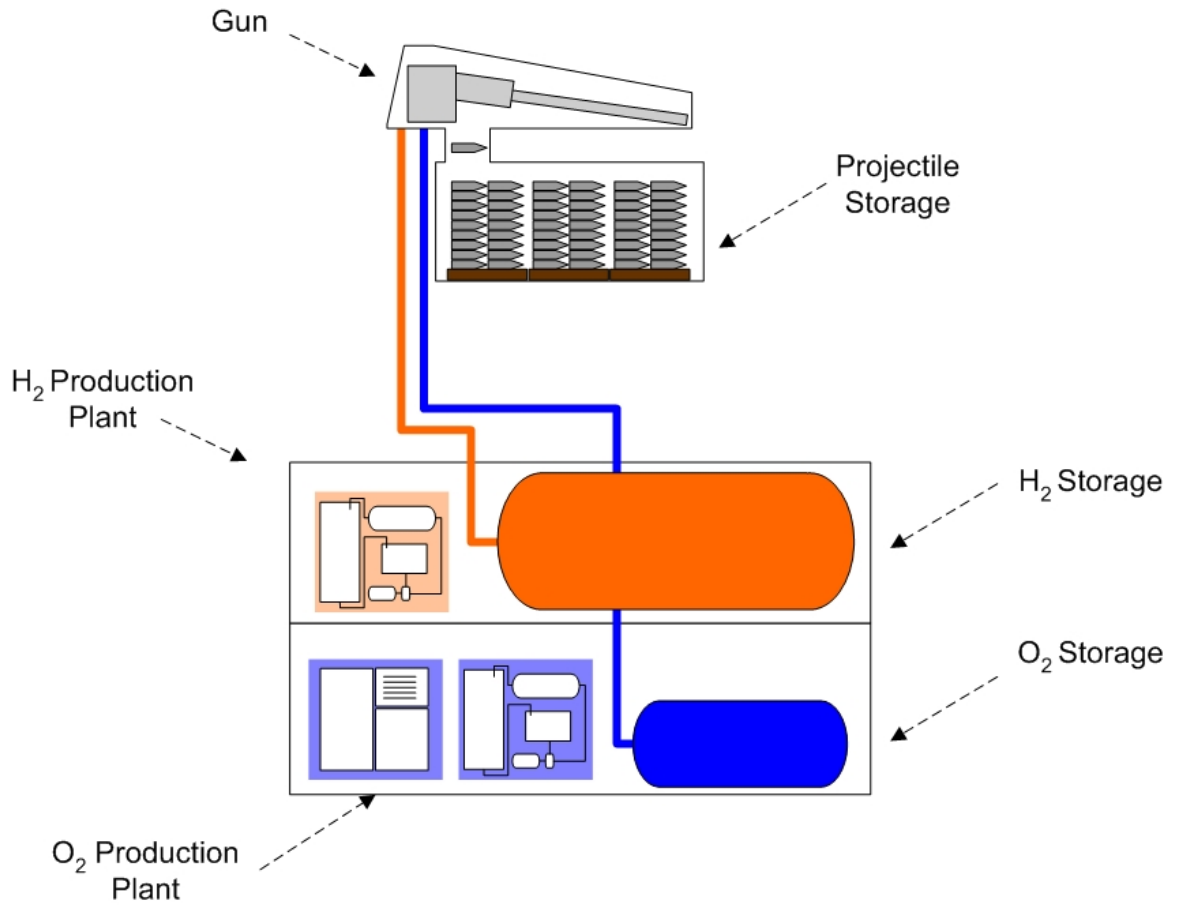


**Figure 10 – Left - 155mm Tube from Muzzle, Right – Rear view showing chamber (unassembled)**

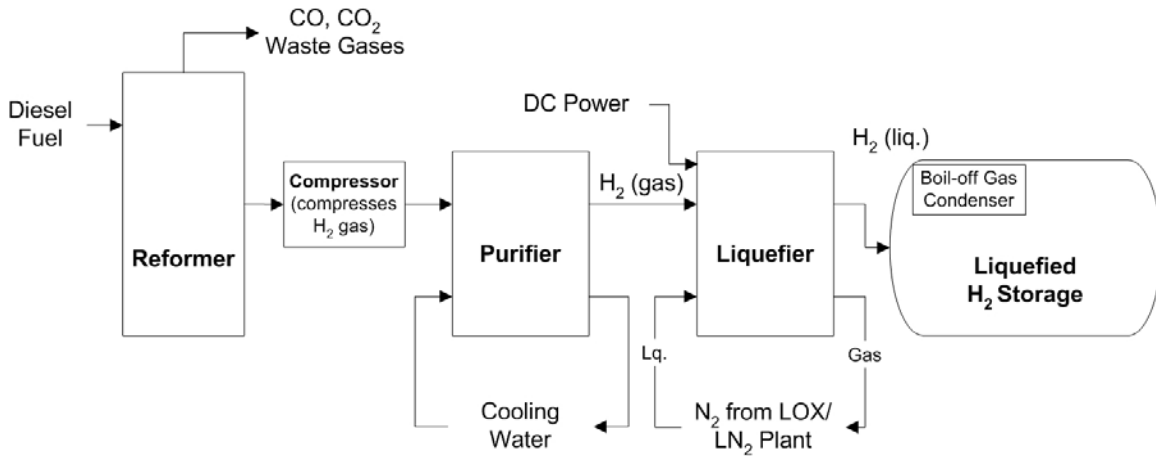
### **Ship Integration**

This task began to look at the options for storing, producing, and safely utilizing CLGG propellants (hydrogen and oxygen) in a shipboard environment. In brief the analysis show that all the equipment to produce and store enough hydrogen and oxygen for a 650 round mission is available “off the shelf” and will fit within the allotted space for gun systems within the DDX class of destroyers. Currently other ship platforms are also being considered. An ongoing Cooperative Research and Development Agreement (CRADA) with the NAVSEA Machinery Group in Philadelphia is also looking advanced

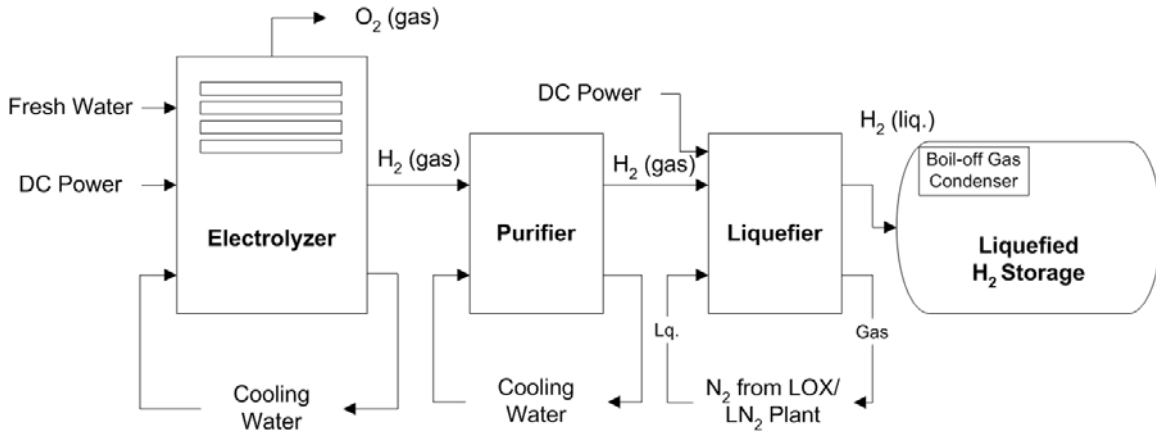
and emerging concepts for hydrogen and oxygen production storage which will continue. In addition in cooperation with MPR associates a safety and firefighting analysis of the CLGG propellant production and storage facility has been completed and with a few minor caveats finds the hazards associated with such a system to be no greater than a solid propellant fed gun system (See Appendix F) A brief look some of these results appears below. A more detailed review is given in Appendix D.



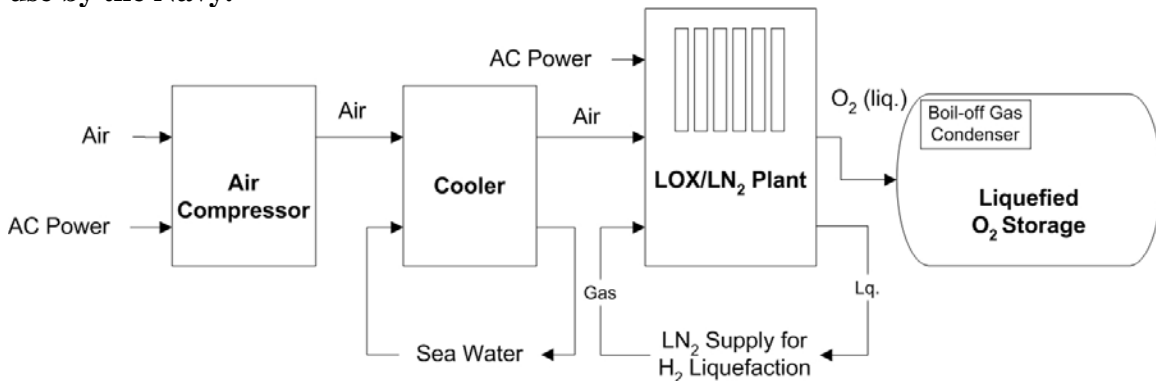
**Figure 11 – Schematic view CLGG propellant storage and production facility for a shipboard weapon.**



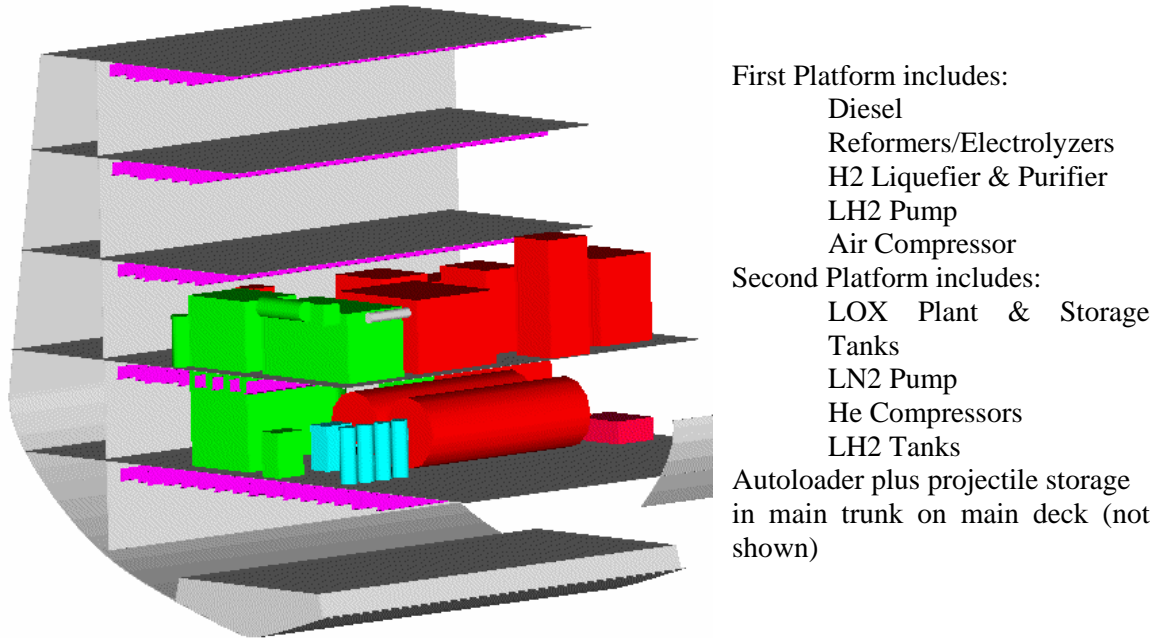
**Figure 12 – Detailed schematic of hydrogen production using a reformer. Reformers are under development by the Navy to support shipboard fuel cells.**



**Figure 13 – Hydrogen production using electrolyzers. Electrolyzers are already in use by the Navy.**



**Figure 14 – Typical commercially available oxygen production plant.**

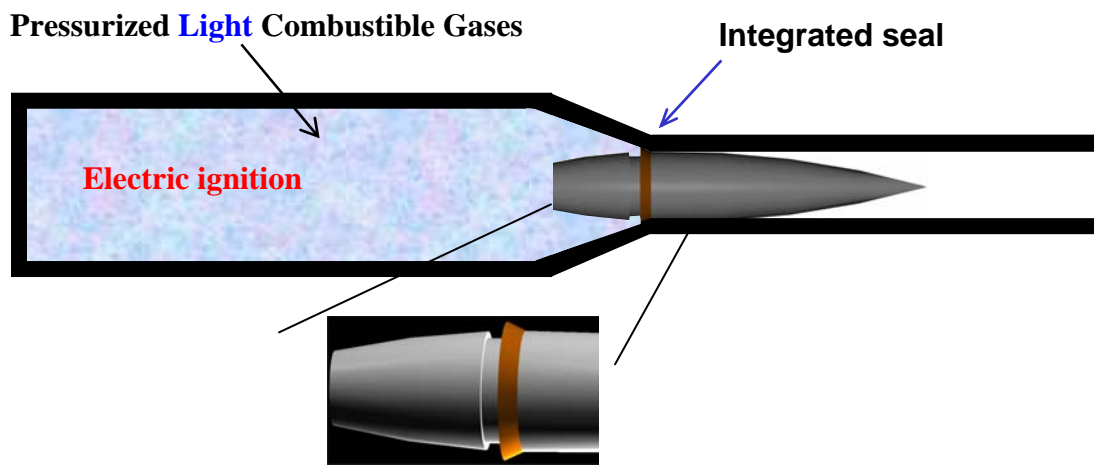


**Figure 15 – Layout of hydrogen and oxygen production and storage inside ship**

## Technical Background and CLGG History

### CLGG Physics

The Combustion Light Gas Gun (CLGG) concept is based on the replacement of solid propellant by low molecular weight, combustible gas mixes. In its simplest configuration, a chamber or cartridge (Figure 16) is sealed with a projectile and filled with a light combustible gaseous propellant mix such as Hydrogen and Oxygen or Methane/Oxygen/Helium at pressures of 4 to 15 kpsi. The mixture is then ignited using a small electrical ignition source. As the combustion process precedes the chamber pressure rises propelling the projectile down bore.



**Figure 16 - CLGG Process**

The physics controlling CLGG operation is elegantly simple. The acceleration of a projectile in a gun is given by:

$$a_p = F_p / m_p \quad (1)$$

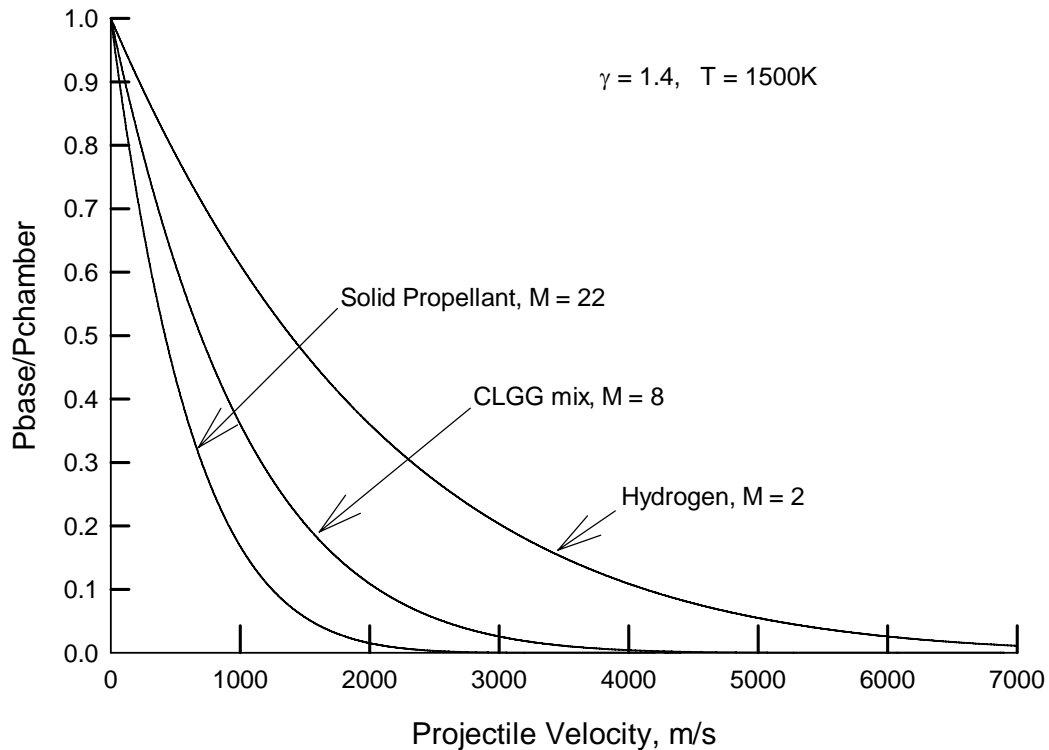
where  $a_p$  = projectile acceleration,  $F_p$  = Force on the projectile and  $m_p$  = projectile mass

An idealized gun can be approximated by the isentropic expansion of a propellant gas given initial pressure ( $p_o$ ) and sound velocity ( $a_o$ ). Since  $F_p$  is a product of the pressure on the projectile base and its base area ( $A_b$ ) and  $a_p$  is the derivative of the velocity, equation 1 above may be rewritten as:

$$m_p \frac{du_p}{dt} = p_{base} A_{base}, \text{ where } p_{base} = p_o \left[ 1 - \frac{u_p^2}{u_{esc}^2} \right]^{\frac{\gamma}{\gamma-1}} \text{ and } u_{esc} = 2 \frac{a_o}{\gamma - 1} \quad (2)$$

where  $u_p$  = projectile velocity,  $u_{esc}$  = “escape velocity” is the maximum velocity for the propellant gas, and  $\gamma$  is the ratio of specific heat for the propellant. Due to non-ideal effects, the performance of an idealized gun suggested by equation (2) is not generally achieved. However, the parameters, which control the performance of any gun, are similar. As can be seen, the pressure transmitted from the combustion chamber to the projectile base is largely controlled by the combustion gas sound speed and ratio of specific heats. The CLGG, by using propellants with low molecular mass (as compared to a solid propellant) and thus much higher sound speed, is able to achieve considerably higher performance. In physical terms the pressures produced in the combustion chamber of the CLGG are transmitted much more efficiently to the projectile base as the projectile accelerates downbore. This effect can be seen when comparing the plots of projectile base pressure versus the pressure in the chamber of the gun as a function of projectile velocity as shown in Figure 17. Note that as the propellant gasses become lighter higher pressures are kept on the base of the projectile as it moves downbore. This translates directly to higher projectile velocity. This is the key to the CLGG’s inherent performance advantage over solid propellant gun technology.





**Figure 17 - Remaining projectile base pressure ( $P_{base}$ ) as a function of gun chamber pressure ( $P_{chamber}$ ) versus projectile velocity for propellants with differing combustion product molecular masses. Note as the propellant mass is reduced performance increases.**

### CLGG History

UTRON'S 45-mm CLGG program expanded on the results of an earlier 16mm CLGG program conducted by GT devices and general dynamics<sup>1</sup> and the even earlier work of Lord<sup>2</sup> in 1960. The 16-mm CLGG work evolved out of the 16-mm Electrothermal Light Gas Gun (ELGG) program in which a chamber pre-filled with high pressure hydrogen gas was arc heated to high pressure, launching 2 gram projectiles up to extreme velocities of 7.2 km/s<sup>3</sup>. Unlike the ELGG the CLGG was designed to provide "high performance" without the need for a bulky power supply. All propulsive energy is supplied from the chemical energy of the propellant gases.

Previous testing with a 16-mm CLGG achieved performance up to 4.2 km/s with hydrogen-oxygen-helium mixtures, and 3.8 km/s with methane-oxygen-helium mixtures<sup>1</sup>. This program demonstrated the performance capabilities of the CLGG and developed practical techniques for chamber pressurization and ignition, but left several questions unanswered, the most important of which was whether CLGG technology could successfully be scaled to larger bore guns. The 45-mm bore CLGG was chosen as an

intermediate size next step, small enough to be affordable, but large enough to credibly address scaling issues.

The primary objective was to build a transportable trailer-mounted 45-mm CLGG and assess its performance in addition to providing additional scaling information for larger bore CLGG launchers. The 45-mm CLGG program began November 25, 1994 with the first test firing occurring on December 4, 1995. An initial series of eight low energy shots were made at UTRON's indoor firing range in Manassas, VA. The gun was then moved to the U.S. Army's Aberdeen Proving Ground in the spring of 1996, where all subsequent tests firings were conducted. A total of 71 test firings have occurred to date, the main results of which appear below following a description of the old 45-mm CLGG.

### Previous 45-mm CLGG Design and Test Data

The 45-mm CLGG test fixture and select specifications are shown in Figure 18. The chamber and barrel float on the mount with recoil taken up by dual shock absorbers. The gun was designed for a maximum operating pressure of 90,000 psi. A photo of the weapon ready for testing at Aberdeen Proving Grounds is shown in Figure 19.

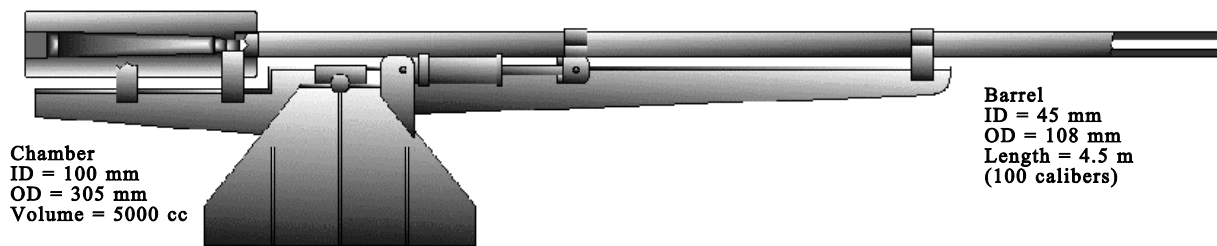


Figure 18 – Schematic of 45mm gas driven gun



Figure 19 - 45-mm CLGG during test firings at Aberdeen Proving Ground.

For simplicity and cost reduction the previous 45-mm CLGG was designed as a single shot gas fed system using a disposable cartridge. Gas was supplied from conventional gas bottles filled with methane, hydrogen, helium, and helium-oxygen mixtures. A two-stage high pressure pumping system using intensifier pumps provides the means of pressurizing the chamber with the propellant mixture.

A small high voltage capacitor bank was used to initiate combustion. Very small amounts of electrical energy are required, but the ignition sources must be located and sequenced properly.

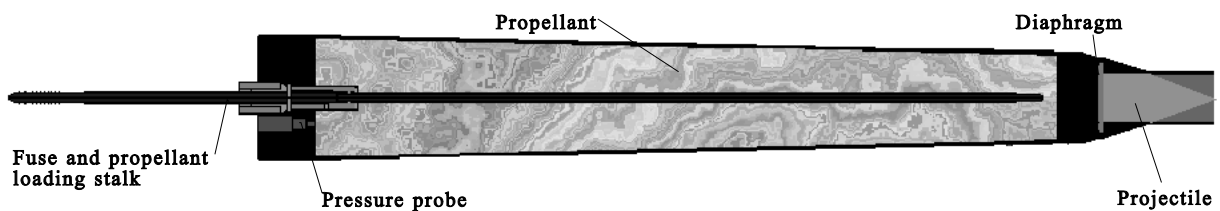
Diagnostics included three pressure probes in the chamber/cartridge and an additional five probes distributed along the barrel. Doppler radar and laser detectors (visible beyond the barrel in Figure 19) determined the projectile velocity.

### Propellant Loading

Propellant gases can be loaded directly into the CLGG chamber as was done in the 16-mm bore gun<sup>1</sup> and in the current 45mm with autoloader or a cartridge can be used as in the initial 45-mm gun. The cartridge, shown in Figure 20, is referred to as a "balloon" cartridge, since the thin-walled structure is designed to contain the propellant gas and peak combustion pressures only when chambered. The cartridge also provided a structure for attaching the fuse/fill device. In addition to igniting the gaseous propellant, the fuse also provides the means by which the gas mixture is admitted into the cartridge, through a series of tiny holes along its length.

Three pressure transducers provide chamber pressure data during the shot. Probe 1 is located at the back end of the cartridge and is directly exposed to the gases. Probes 2 and 3 are conformal, sampling the chamber pressure through the thin wall of the cartridge and are located towards the middle and forward end of the cartridge.

Like solid propellant guns, the combustion process is highly dependent upon the ignition stimulus provided. Proper ignition stimulus is required to ignite the gaseous propellant without causing detrimental pressure waves or other undesirable combustion phenomena. This was done in the 16-mm and 45-mm guns with centerline, multi-point, electrical ignition.



**Figure 20 – 45-mm CLGG cartridge, CLGG propellants are currently bulk loaded**

## Combustion and Pressure Control

The CLGG is both scalable and adaptable to launching a wide range of projectile masses. During the 16-mm testing program there were no indications of undesirable pressure wave activity in the gas mixtures when ignited at propellant fill pressures up to 20 kpsi.

Initial tests on the 45-mm quickly revealed, however, that one significant change was required from earlier 16-mm operation. This was a transition from petaling diaphragms to shearing diaphragms. Previously, a petaling diaphragm sealed the end of the chamber/cartridge. At a pre-determined pressure it petals open into a gap just behind the projectile. While this design works, it is somewhat awkward, and in addition, this gap allows the combustion gases room to suddenly expand prior to projectile acceleration. This sudden expansion causes large pressure waves. Although no damage was done to the hardware, such pressure activity cannot be tolerated.

The solution was to switch to a shear or tear away diaphragm. The projectile is attached directly to the diaphragm, which fails (shears) along a notch at a pre-determined chamber pressure, and the diaphragm then travels with the projectile downbore. This design, when coupled with good ignition practices, essentially eliminates pressure wave activity as will be seen.

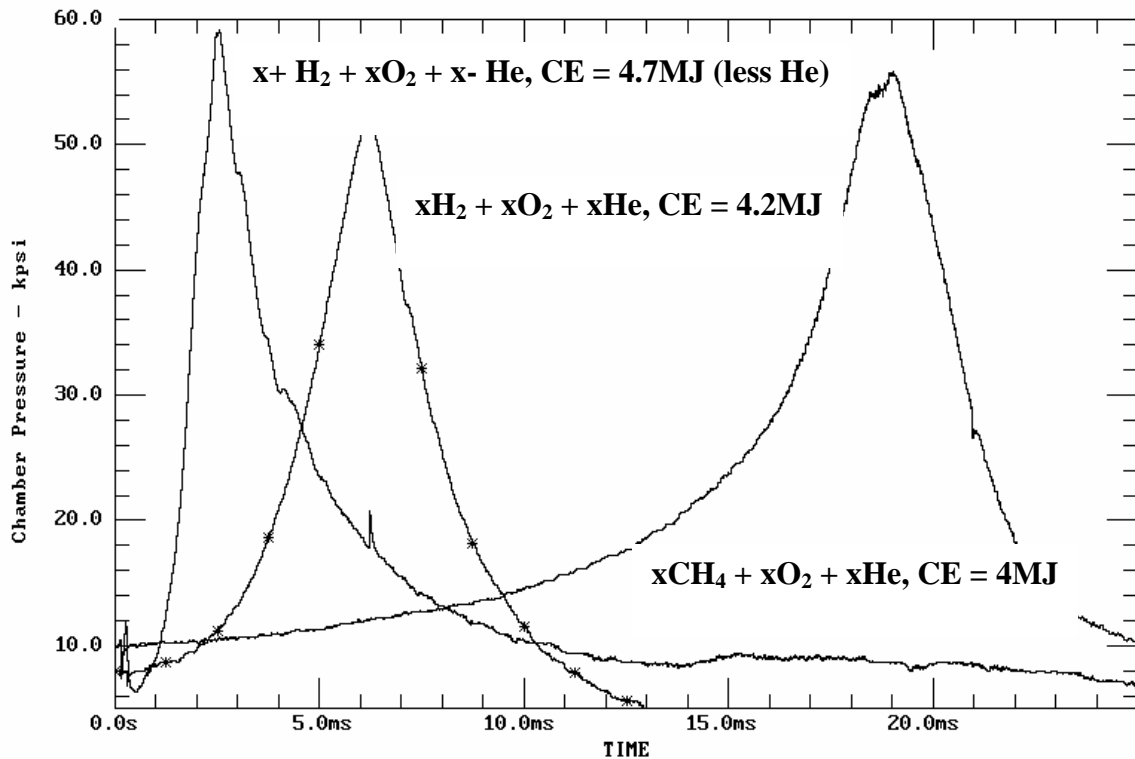
*It should be noted that the shear diaphragm is similar in performance to a traditional copper/nylon obturator band used on conventional projectiles. They both seal gases behind the projectile until a specified load or pressure is achieved at which point the diaphragm/obturator seal fails or flows allowing projectile movement downbore. The only difference is that the CLGG projectile diaphragm/seal/obturator maintains both a short duration static pressure and the brief dynamic load.*

Pressure waves in the propellant gases are mitigated by careful ignition design. Experiments in the 45-mm CLGG have shown that the speed of ignition and the subsequent production of undesirable pressure oscillations can be controlled to a large degree by the amount of energy used in the ignition process and the location of the ignition sites.

The amount of diluent also plays an important role in combustion control and in preventing the formation of pressure waves. A diluent can be either an inert gas such as helium or excess fuel such as methane or hydrogen. It has been shown that if the diluent level is high relative to the amount of free oxygen available, undesirable combustion events (such as pressure waves or gaseous detonations) are simple to avoid<sup>4</sup>.

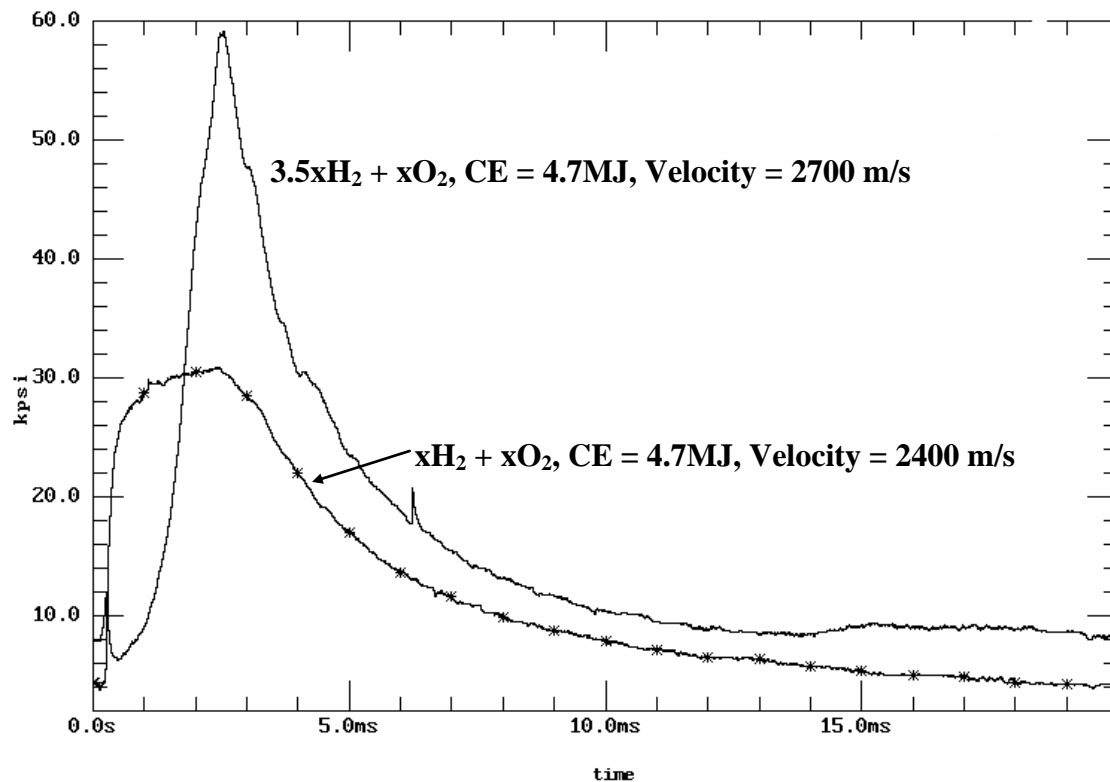
The combination of obturator design, ignition stimulus, and “proper” propellant chemistry allows the CLGG to operate without pressure anomalies even at very high fill pressures. Figure 21 shows three chamber pressure curves for three different propellant mixtures and pressures with similar energies. Note that the pressure rise times can be

controlled by the combination of propellant chemistry and ignition technique. Also note that all the pressure forms display smooth well controlled combustion.



**Figure 21 – CLGG combustion produced pressure forms are controlled by propellant chemistry and ignition stimulus. The pressure curves represent both methane based and hydrogen based propellants. The small “x” represents a molar multiplier. CE is total chemical energy.**

The shape of the pressure produced in the gun chamber can also be controlled by the propellant chemistry and ignition stimuli. An excellent example of this ability is given in Figure 22.

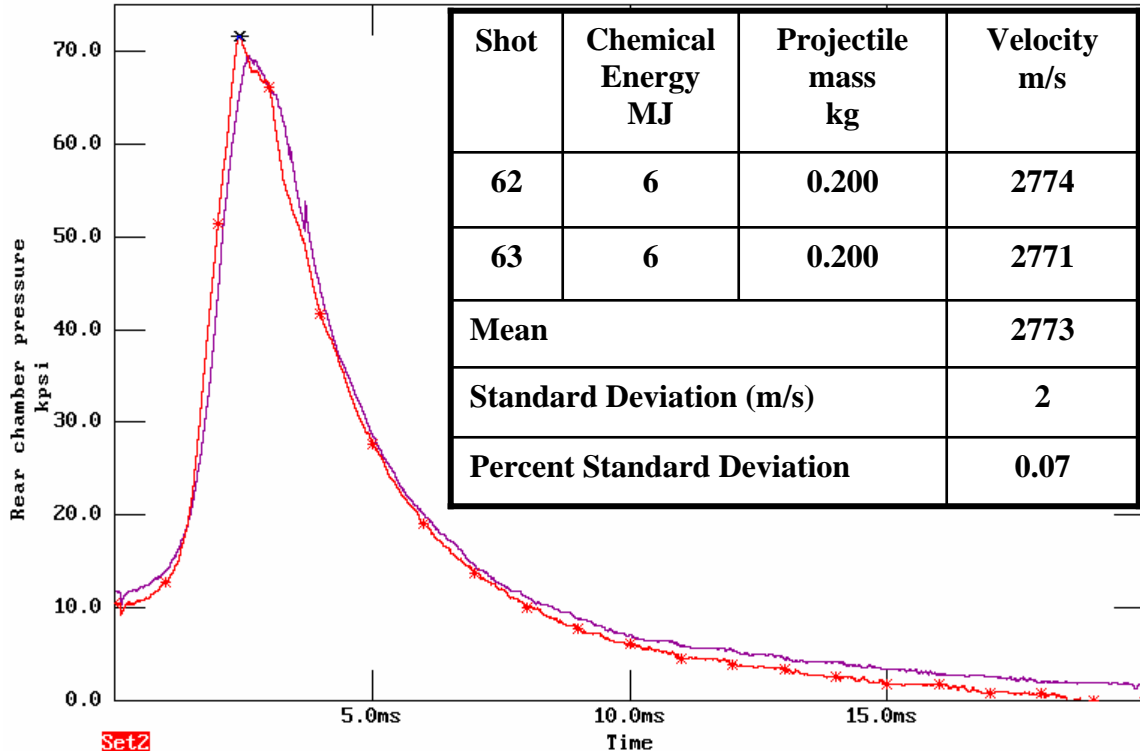


**Figure 22 – Comparison of two chamber pressure curves using different propellant chemistries. Note that the lower level pressure curve represents a nearly ideal ballistic pressure profile (quick rise, flat top). While both propellant chemistries contain the same chemical energy the lower curve reduces the gun chamber pressure by 50 percent while reducing the projectile velocity by only 11 percent.**

Since the CLGG controls the chamber pressure profile primarily with chemistry changes (coupled with proper ignition), it is quite simple to change the entire ballistic profile on a shot-to-shot basis if desired. This property is in stark contrast with the much more complicated fixed and coupled geometry/chemistry effects of solid propellants.

Repeatability

Although few tests have been conducted under controlled repeatable conditions to date in the CLGG, the few that have been indicate very good repeatability both in the combustion/pressure control and in projectile velocity repeatability. An example is shown in Figure 23.



**Figure 23 – Example of CLGG pressure and velocity repeatability.**

### Barrel Erosion

The more energetic nature of advanced solid propellants invariably produces higher flame temperatures. In fact these higher flame temperatures increase the sound speed of the combustion products, which partly accounts for the increased performance. CLGG propellants on the other hand, are lighter and have higher sound speeds to begin with, without the need to burn at excessively high temperatures. As the flame temperature of a propellant increases, the useful life of the gun tube drops dramatically. Comparisons of advanced solid propellant flame temperatures to those typically produced by the CLGG are shown in Table 4.

**Table 4 – Comparison of advanced solid and CLGG propellant flame temperatures**

Propellant	Description	Flame Temperature °K
EX99	Advanced solid	2980
$(\text{CH}_4 + 2\text{O}_2) + x\text{He}$	Typical CLGG propellant	2700
$(2\text{H}_2 + \text{O}_2) + x\text{H}_2$		2460


Performance and Scaling

The left side of Table 5 presents a sample of experimental results for the 45-mm CLGG launching a variety of projectile masses. The right side of Table 6 presents what these results would scale to at several different bore sizes of interest.

An example of the extreme performance capabilities of the CLGG is illustrated in the case of the 1.1 kg projectile. This projectile would scale to 45 kg or 100 pounds if fired in a 155-mm bore system of 100 calibers length. Even if one corrects the velocity back to a more reasonable 70-caliber length gun tube the launch velocity would be over 1500 m/s. Currently fielded solid propellant based weapons of this caliber firing a 100 pound projectile achieve only 830 m/s.

Thus the CLGG would provide nearly twice the launch velocity, and over three times the muzzle energy.

**Table 5 – Experimental and Scaled results for the CLGG**

45-mm Experiments <sup>1,2,3</sup>			Scales to <sup>4</sup>		
Launch mass - kg	Velocity m/s		Bore size mm	Launch mass -kg	Velocity m/s
0.200	2810	→	76	1.00	2750
0.544	2100	→	120	7.85	2350
1.100	1700	→	155	45	1700
3.365	878	→	155	138	878
Notes: <sup>1</sup> – Demonstrated values at 100 calibers travel, Velocity reduction at 70 calibers is 8-9 percent <sup>2</sup> – CLGG results are not optimized <sup>3</sup> – Nominal chamber pressure is 70 kpsi or less <sup>4</sup> – Scaling using IBHVG2 ballistic codes and d <sup>3</sup> methods Projectiles shown with increasing mass from left to right (0.2 to 3.365 kg)					



## Older Test Data Summary

CLGG technology has been successfully demonstrated at 16 and 45-mm bore size and shows every indication of the ability to successfully scale to larger bore sizes. The CLGG has shown greatly improved performance, tailor-able pressure profiles, repeatability, and low barrel erosion capability. Although work remains, the CLGG system represents a breakthrough in providing a practical high performance gun.

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- <sup>1</sup> D.A. Tidman, D.W. Massey, and F.D. Witherspoon, F.W. Robbins, A.L. Brandt, "Compact Light Gas Gun Firings with High Pressure Gaseous and Solid Energetic Materials - Experiments and Analysis", 31st JANNAF Combustion Subcommittee Meeting, Sunnyvale, CA, 17-21 Oct, 1994.
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- "Ramac II, A System Analysis of Ram Acceleration for Naval Applications", December 2000.
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## **Appendix A - Cryogenic Propellant Feed System**

# Table of Contents

TABLE OF CONTENTS.....	1
TABLE OF FIGURES.....	2
INTRODUCTION .....	3
OBJECTIVES.....	3
SAFETY.....	3
SAFETY.....	4
HISTORY .....	4
CURRENT SYSTEM DESIGN .....	6
DESIGN DETAILS .....	7
TESTING .....	10
STATUS .....	11
CONCLUSION .....	11
REFERENCES .....	12
MYTH #2 FROM “TWENTY HYDROGEN MYTHS” BY AMORY B. LOVINS.....	12

## Table of Figures

Figure 1: 45 mm CLGG.....	3
Figure 2: Liquid CO <sub>2</sub> at IHOP.....	5
Figure 3: Accumulator concept.....	5
Figure 4: Simplified system design.....	7
Figure 5: LH2 tank.....	7
Figure 6: LH2 tank.....	7
Figure 7: LOX supply line .....	8
Figure 8: LH2 supply line.....	8
Figure 9: GN2 supply.....	8
Figure 10: GN2 Supply.....	8
Figure 11: Pumps to accumulator .....	9
Figure 12: Pumps .....	9
Figure 13: Accumulators.....	9
Figure 14: Regulator and mass flow meter.....	9
Figure 15: Test chamber .....	10
Figure 16: Poppet valve .....	10

## Introduction

For the 45mm bore CLGG (see Figure 1) Utron is creating a cryogenic-high-pressure-propellant-feed system, where the result is to inject LOX and GH<sub>2</sub> into the gun chamber. The cryogenic propellant feed system has been designed, drafted, assembled, and is being tested to accomplish the secondary goals of being able to fire the gun every 10 seconds and have liquid storage of the oxygen and hydrogen. This document will discuss the history of the project, the current system level design, the design details, and testing of the system.



*Figure 1: 45 mm CLGG*

## Objectives

The primary objectives of the high-pressure-propellant-feed-system are:

- two seconds to fill the combustion chamber
- liquid propellant storage
- projectile mass = .52 kg
- projectile velocity = 1700 km/s

To achieve the primary objectives, there are consequential objectives, which are:

- proving that a gun can operate at cryogenic conditions where the chamber, ignition system, and barrel will survive numerous firings
- sufficient supply line flow area
- leak testing of all plumbing and tanks
- mass flow rate control
- confirmation of 100% liquid in the pump's sump
- system automation
- intrinsic and extrinsic safety

## Safety

Many people when first hearing about the project are concerned about the safety of personnel working with oxygen and hydrogen. They are particularly concerned about the flammability of hydrogen. Although hydrogen is a fire hazard, it is not to the level of gasoline or acetylene [5]. Explaining the flammability risk of hydrogen is a lengthy matter and beyond the scope of this document. “Twenty Hydrogen Myths” by Amory B. Lovins, which discusses the flammability risk of hydrogen is given at the end of this report.

Liquid oxygen and hydrogen hazards are asphyxiation, extreme cold, and fire. Each of these risks can be mitigated by following proper design guidelines and procedures. To mitigate risk, Utron Inc. has done the following:

- The system is compliant with NFPA (National Fire Protection Agency) guidelines [6] [7], OSHA law [1], and Air Products safety guidelines [2].
- There are alarms with oxygen and hydrogen sensors in each room near the testing area.
- Operators wear safety glasses, steel toe boots, and pants at all times. For some operations; gloves, earplugs, and face shields are worn.
- Every piece of equipment is O2 cleaned per CGA 4.1 [4].
- Before testing, all employees in Ashton, WV are notified, some entryways are locked, and entryways to the test area are posted with “keep out, test in progress”.

## History

Several key decisions were made during the design process:

- what propellants to use?
- what propellant storage method?
- what combustion chamber injection method?
- what phase should the propellants be at ignition?
- what chamber injection rate should be used?
- how much mass of propellant to use?

### **Propellant selection:**

Hydrogen and oxygen were chosen as propellants because of their superior heat of reaction and low molecular weight exhaust mass.

### **Storage method selection:**

Cryogenic liquid storage of the propellants is the best storage method because of the significant space savings. Liquid storage allows for:

- 851 times less volume than hydrogen gas at ambient conditions
- 860 times less volume than oxygen gas at ambient conditions
- 6 times less volume than hydrogen gas in a cylinder at 2200 psi
- 5 times less volume than oxygen gas in a cylinder at 2200 psi

Cryogenic liquid storage has become very common in commercial industries, for example; LOX dewars for fish stocking aeration and beverage CO<sub>2</sub>. Figure 3 shows a liquid CO<sub>2</sub> dewar at IHOP in Barboursville, WV for carbonated beverages.



Figure 2: Liquid CO<sub>2</sub> at IHOP

Utron Inc. will purchase LH<sub>2</sub> and LOX at typical commercial conditions, 40 psi at -420 °F for LH<sub>2</sub>, and 230 psi at -330 °F for LOX.

#### Chamber injection method:

Extensive effort went into deciding the injection method. The methods of using direct liquid injection (CTS pump), a high pressure reservoir between the pump and combustion chamber, and gas storage with passive heat exchanger cooling were examined. The high pressure reservoir between the pump and the combustion chamber was chosen because of the following benefits:

- flow smoothing/steadiness
- consistent supply from accumulator to chamber
- ability to use a smaller, less excessive pump
- modularization of pump and test chamber

Figure 3 shows the accumulator concept.

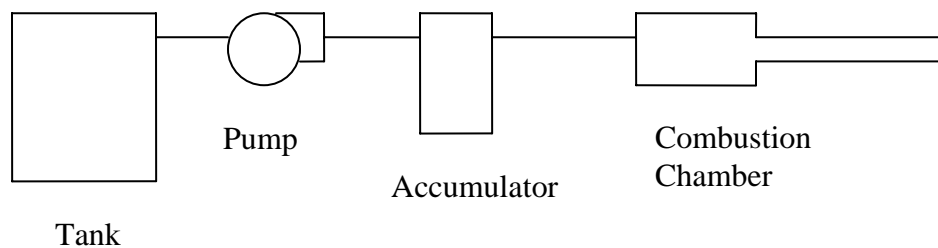


Figure 3: Accumulator concept

#### Phase selection:

Several choices for what phase the propellants would be at combustion were available. The options are GOX + GH<sub>2</sub>, LOX + LH<sub>2</sub>, LOX + GH<sub>2</sub>, or GOX + LH<sub>2</sub> at ignition. LH<sub>2</sub> + GOX or LOX is not possible, because LH<sub>2</sub> at any temperature will freeze oxygen and LH<sub>2</sub> is thermally sensitive in that it is only about 15 °F from the liquid saturation temperature (15 °F away from becoming a gas). GOX + GH<sub>2</sub> at near ambient conditions has the problem of not being sufficiently dense, unless it is at a very high pressure. LOX + GH<sub>2</sub> has a mixing problem.



To solve all of these issues, the pumps will pump 100% liquid, the oxygen accumulator will store oxygen as liquid and hydrogen as gas, both at  $-319\text{ }^{\circ}\text{F}$  [8] [3]. The  $-319\text{ }^{\circ}\text{F}$  is achieved by cooling the accumulators with LN2. The LOX and GH2 flow into the combustion chamber and there is sufficient conduction from the metal of the supply lines that oxygen phase changes to gas. The result at ignition is GOX + GH2 at  $-135\text{ }^{\circ}\text{F}$ .

### **Mass of Propellants:**

Testing with the current ambient-temperature-gas-propellant system has shown that the stoichiometric mixture of  $(2)\text{ H}_2 + (1)\text{ O}_2 \rightarrow (2)\text{ H}_2\text{O}$  burns hot and ablates the inside of the combustion chamber and barrel. A rich mixture of  $(8)\text{ H}_2 + (1)\text{ O}_2 \rightarrow (2)\text{ H}_2\text{O} + (6)\text{ H}_2$  is sufficiently cooler. This 8:1 ratio will be continued for the cryogenic-propellant-feed system.

## **Current System Design**

The cryogenic-propellant-feed system is being tested to accomplish the secondary goals of being able to fire the gun every 10 seconds and have liquid storage of the oxygen and hydrogen.

This system stores LH2 in a Prentex 500 gallon fixed tank and LOX in Air Gas dewars. It obeys NFPA guidelines and OSHA law. PHPK vacuum-jacketed tubing is used for the LH2 supply line to the pump and Swagelok tubing insulated with cellular glass is used for the LOX supply line to the pump. The Cryostar pumps fill an 18 liter LOX accumulator and an 18 liter GH2 accumulator, built by Vulcan and Prentex. The accumulators are filled to 8000 psi and are LN2 cooled to maintain long-term storage. After the accumulator, the LOX or GH2 is reduced to 5000 psi and flows through a mass flow meter by Micromotion and Utron Inc.'s poppet valve to fill the gun chamber. The gun chamber is filled from the accumulator in 2 seconds. Figure 4 shows the simplified system design.

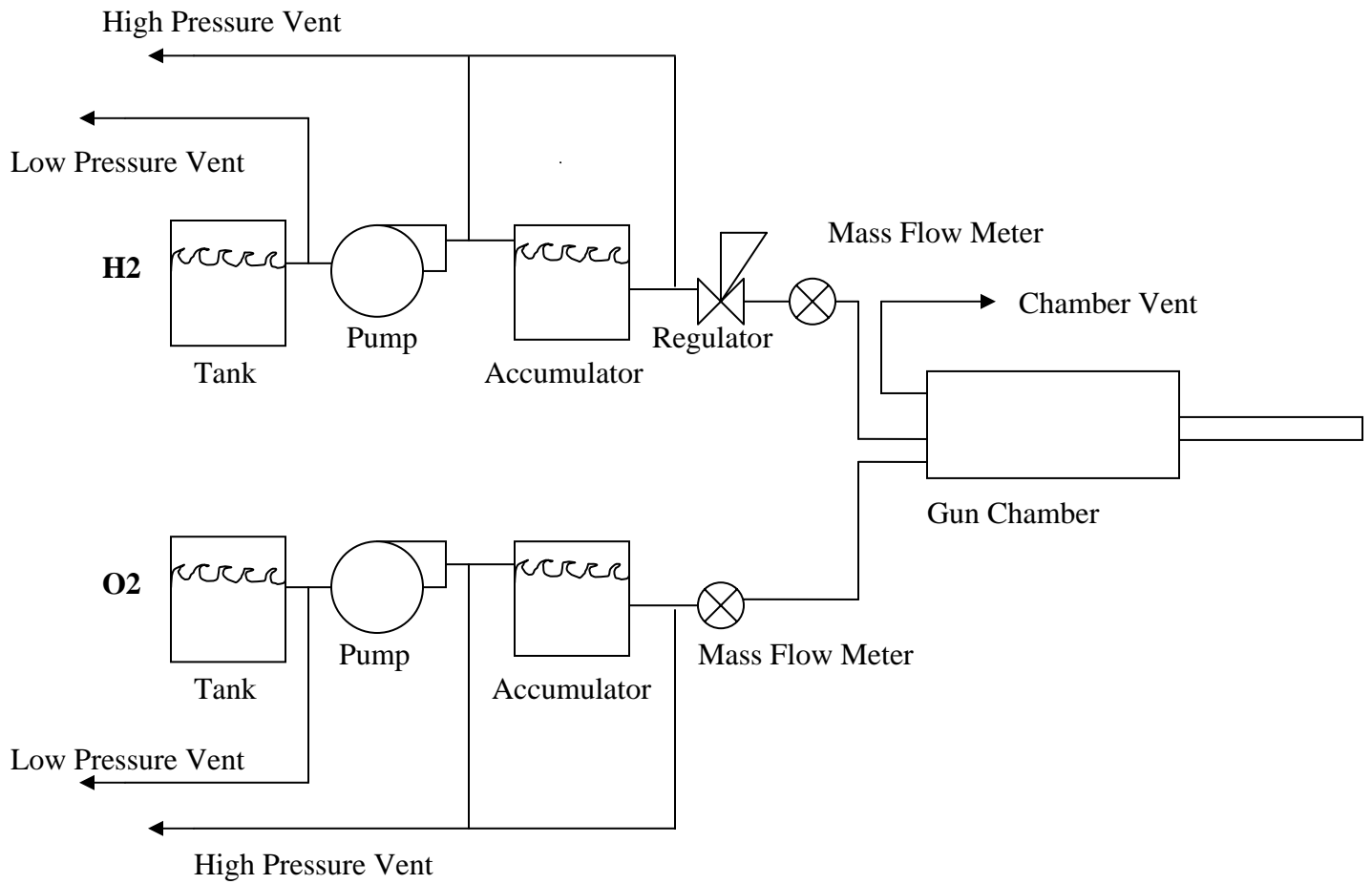


Figure 4: Simplified system design

## Design Details



Figure 5: LH<sub>2</sub> tank



Figure 6: LH<sub>2</sub> tank

The 500 gallon LH2 tank, 2" OD low pressure vent, and 1.25" OD high pressure vent on the north side of the gun bays can be seen in Figures 5 and 6.



*Figure 7: LOX supply line*

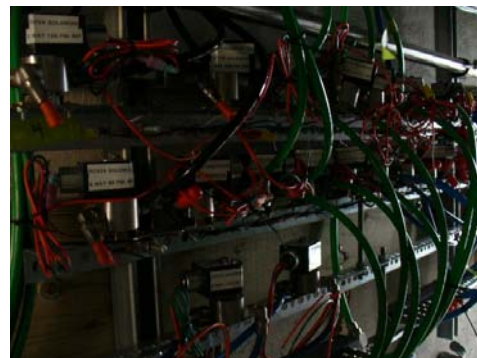


*Figure 8: LH2 supply line*

The 1.25" OD oxygen supply line, 1.25" OD low pressure vent, and 1.25" OD high pressure vent can be seen in Figure 7. Figure 8 shows the vacuum-jacketed LH2 supply line, GH2 low-pressure vent, and GH2 high-pressure vent passing through the 45 mm gun bay. In Figure 8, the vertical drop of the vacuum-jacketed LH2 supply line is to provide LH2 to the cryogenic-propellant-feed system when it is moved to the 45 mm gun bay and attached to the current 45 mm CLGG.



*Figure 9: GN2 supply*



*Figure 10: GN2 Supply*

Figure 9 shows the GN2 supply that is used to actuate all pneumatic valves (at 30 psi, 90 psi, and 250 psi) and provide purging. For the system to be intrinsically safe, all the supply valves are normally closed and all the vent valves are normally open. In the event of power failure or disruption of the nitrogen supply the supply line valves will close and the vents are open. Figure 10 shows the solenoid bank that controls the nitrogen supply to each pneumatic valve.



Figure 11: Pumps to accumulator



Figure 12: Pumps

Figure 11 is an overall view showing the pumps, accumulators, equipment cart (mass flow meters and regulator), and test chamber. Figure 12 shows the reciprocating pumps, one for LOX, and one for LH2. During the operation of the pumps, it is critical that there is 100% liquid in the pump's sump.



Figure 13: Accumulators



Figure 14: Regulator and mass flow meter

Figure 13 shows the accumulators. Both accumulators can hold up to 8000 psi and have an outer jacket that is LN2 cooled. That jacket is open to the atmosphere and is vented through a fourth vent. The hydrogen accumulator stores GH2 at 8000 psi at -319 °F that is reduced to 5000 psi by the pressure-reducing regulator before it passes through the hydrogen mass flow meter and into the test chamber. The oxygen accumulator stores LOX at 6000 psi at -319 °F that then passes through the oxygen mass flow meter and into the test chamber. Figure 14 shows the mass flow meters and pressure-reducing regulator.



Figure 15: Test chamber

Figure 16: Poppet valve

Figure 15 shows the test chamber, which is being used for Test 2A, the flexible line that allows for the CLGG's recoil, and the vacuum pump. Figure 16 shows the final valve that is mounted on the gun chamber and is designed to survive the 80,000 psi combustion in the CLGG.

## Testing

Various testing sequences are being conducted. Individual component testing, leak testing, and system testing are necessary. The system is being tested in two parts, Test 2A and Test 2B. Test 2A first proves the system with LN2. Test 2A is continued with oxygen or hydrogen, not both. They are never mixed. Test 2B loads hydrogen and oxygen into the gun chamber where they mix and combustion occurs.

### **Preparatory Testing:**

Each component has been individually tested. Leak testing is complete, but will periodically be repeated because the system will be cold shocked during cryogenic testing.

### **System Testing:**

Test 2A involves separate mass control of LOX and GH2. This test cryogenically tests all of the system components, except for the gun's stinger and projectile. Test 2A begins with substituting LN2 for LH2 and LOX and has the following milestones:

- getting liquid to the pump
- starting the pump and filling the accumulator
- taking the pump and accumulator to full capacity
- starting the mass flow meter
- mastering the mass flow meter

This will be done first for the hydrogen supply, then the oxygen supply. Once the preceding steps are accomplished, the same will be done using LH2, then LOX. At the completion of Test 2A, Test 2B will begin.

Test 2B involves mixing oxygen and hydrogen, initiating combustion, and firing the 45 mm CLGG. For this test, the pump, accumulators, mass flow meters, and poppet valve will be moved into the 45mm bay and attached to the 45 mm CLGG.

Each sequence of testing is done per the approved SOP and Test Sequence Check List. The Standard Operating Procedure details how each system component works and when and how it will be used. The Test Sequence Check List is a 3 page summary of the SOP and is carried at all times during testing.

## Status

Drafting: Detail, Assembly, and System Drawings (99% complete)

Procurement (100% complete)

Assembly for Test 2A (90% complete):

LH2 Supply (99% complete):

Incomplete: subcooler installation

LOX Supply (90% complete):

Incomplete: 25% of insulation

GN2 Supply (100% complete)

LN2 Supply (100% complete)

Electrical Supply (90% complete):

Incomplete: mass flow meter control

Control System (80% complete):

Incomplete: PLC upgrade

Testing:

Procedural Documentation (90% complete):

Incomplete: final draft of SOP, final draft of Sequence checklist

Leak testing (100% complete)

Component testing (100% complete)

Safety Procedures (95% complete):

Incomplete: oxygen and hydrogen alarm system calibration

Test 2A (10% complete)

Test 2B (0% complete)

## Conclusion

Component and leak testing of the cryogenic propellant feed system has been completed. System testing with LN2 has begun and is going well. The hydrogen and oxygen lines will first be tested with LN2, then with LOX or LH2 in a test chamber. When testing with the test chamber is completed, the hydrogen and oxygen lines will be connected to the current CLGG and enable the goal of firing every ten seconds.

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## Myth #2 from “Twenty Hydrogen Myths” by Amory B. Lovins

Myth #2. Hydrogen is too dangerous, explosive, or “volatile” for common use as a fuel. The hydrogen industry has an enviable safety record spanning more than a half-century. Any fuel is hazardous and needs due care, but hydrogen’s hazards are different and generally more tractable than those of hydrocarbon fuels.<sup>34</sup> It’s extremely buoyant — 14.4 times lighter than air (natural gas is only 1.7 times lighter than air). Hydrogen is four times more diffusive than natural gas or 12 times more than gasoline fumes, so leaking hydrogen rapidly disperses up and away from its source.<sup>35</sup> If ignited, hydrogen burns rapidly with a nonluminous flame that can’t readily scorch you at a distance, emitting only one-tenth the radiant heat of a hydrocarbon fire and burning 7% cooler than gasoline. Although firefighters dislike hydrogen’s clear flame because they need a viewing device to see it in daylight, victims generally aren’t burned unless they’re actually in the flame, nor are they choked by smoke. Hydrogen mixtures in air are hard to explode, requiring a constrained volume of elongated shape. In high-school chemistry experiments, hydrogen detonates with a “pop” when lit in a test tube, but if it were in free air rather than a long cylindrical enclosure, it wouldn’t detonate at all. Explosion requires at least twice as rich a mixture of hydrogen as of natural gas, though hydrogen’s explosive potential continues to a fourfold higher upper limit. Hydrogen does ignite easily, needing 14 times less energy than natural gas, but that’s of dubious relevance because even natural gas can be ignited by a static-

electricity spark.<sup>36</sup> Unlike natural gas, however, leaking hydrogen encountering an ignition source is far likelier to burn than to explode, even inside a building, because it burns at concentrations far below its lower explosive limit. Ignition also requires a fourfold higher minimum concentration of hydrogen than of gasoline vapor. In short, in the vast majority of cases, leaking hydrogen, if lit, will burn but not explode. And in the rare cases where it might explode, its theoretical explosive power per unit volume of gas is 22 times weaker than that of gasoline vapor. It is not, as has been claimed, “essentially a liquid or gaseous form of dynamite.” Contrary to a popular misunderstanding, these safety attributes actually helped save 62 lives in the 1937 Hindenburg disaster. An investigation by NASA scientist Dr. Addison Bain found<sup>38</sup> that the disaster would have been essentially unchanged even if the dirigible were lifted not by hydrogen but by nonflammable helium, and that probably nobody aboard was killed by a hydrogen fire. (There was no explosion.) The 35% who died were killed by jumping out, or by the burning diesel oil, canopy, and debris (the cloth canopy was coated with what nowadays would be called rocket fuel). The other 65% survived, riding the flaming dirigible to earth as the clear hydrogen flames swirled harmlessly above them. This would hardly be the case if an aircraft with only liquid hydrocarbons caught fire while aloft. **It emphasizes that hydrogen is generally at least as safe as natural gas or LPG, and is arguably inherently safer than gasoline,**<sup>39</sup> although the character of their risks is not identical. For example, leaking hydrogen gas will accumulate near the ceiling of an airtight garage, while gasoline fumes or propane will accumulate near the floor — a greater risk to people because they’re typically near the floor, not the roof. Standing in a carpet of fire is far more dangerous than standing below a nearly non-luminous clear flame that goes upwards. Lingering perceptions that hydrogen is unusually dangerous are likely to be dispelled by the kinds of compelling videotaped demonstrations now becoming available, such as a comparison of a hydrogen fire with a gasoline fire. First, a hydrogen leak was created, assuming a very unlikely triple failure of redundant protective devices (industry norms for hydrogen leak detection and safety interlocks are convincingly effective). **The tested leak, deliberately caused at the highest-pressure location, discharged the entire 1.54-kg hydrogen inventory of the fuel-cell car in ~100 s, but the resulting vertical flame plume raised the car’s interior temperature by at most 1–2 F° (0.6–1.1 C°), and its outside temperature nearest the flame by no more than a car experiences sitting in the sun. The passenger compartment was unharmed. But then in the second test, a 2.5- fold-lower-energy leak from a 1.6-mm (1/16") hole in a gasoline fuel line gutted the car’s interior and would have killed anyone trapped inside.**<sup>40</sup> **Because the hydrogen-leak test didn’t damage the car, both tests were conducted successively using the same car.**<sup>41</sup> Finally, of course, there is no connection whatever between ordinary hydrogen gas, whose chemical reactions make it useful as a fuel, and the special isotopes whose thermonuclear reactions power hydrogen bombs. A hydrogen bomb can’t be made with ordinary hydrogen, nor can the conditions that trigger nuclear fusion in a hydrogen bomb occur in a hydrogen accident; they’re achieved, with difficulty, only by using an atomic bomb.



## **Appendix B – Computational Fluid Dynamics**

# CFD program for the CLGG

## 1 – CFD Codes

The first CFD company in the US is Fluent (Lebanon, NH). The Fluent code can handle combustion and high speeds, and has good pre and post-processing capability, but the combustion part works with ideal gases only. The next release of Fluent (in 2006) is supposed to include real gas capability.

CFD-Research (Huntsville, AL) and Aerosoft (Richmond, VA) both have very good chemistry capabilities, but also only for ideal gases.

CHEMKIN (San Diego, CA) is a well known Chemistry code, which can be combined with a fluid code, but suffers from the same restriction to ideal gas. All these programs are unusable for our case, because at pressures of several thousand atmospheres, the ideal gas assumption breaks down.

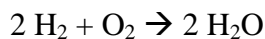
We found only one CFD code which allows real gas combustion, CFX from Ansys (Pittsburgh, PA). Ansys just announced in February 2006 that they bought Fluent.

## 2 – The CFX code

CFX, developed in the UK and Canada, was bought by Ansys. It has very good pre-processing capabilities, i.e. grid generation, and excellent post-processing. We receive very good support from two Engineers working with us. The code solves the equations for mass, momentum and energy, and one advection-diffusion equation for each species, including effects of chemical reactions. It includes a certain number of combustion models, a few of which can be used for our gun calculations. We are mainly interested in the following:

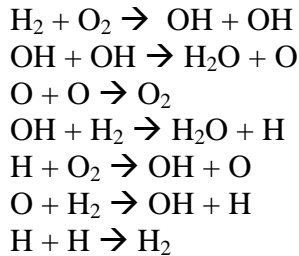
- The Finite Rate Chemistry Model
- The Premixed Model
- The Eddy Dissipation Model (also called Eddy Breakup Model)

The Finite Rate Chemistry model solves for the chemical reaction in the chemical time-scale, less than  $10^{-7}$  sec and is more costly. One can simplify the chemistry to one single global reaction, e.g.

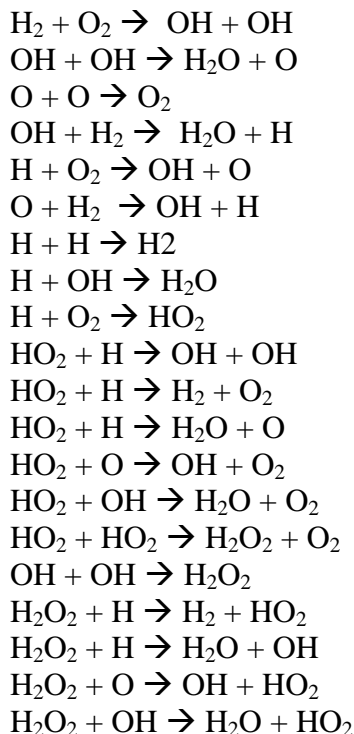


A more complex model involves the eight most important reactions for hydrogen-

oxygen:



Finally, the complete list of reaction is the following:



We have only used the single reaction and the 8 reactions cases in our tests up to now. The Stiff Chemistry option does a special numerical treatment to take into account the large difference in reaction rates between slow reactions ( $10^7 \text{ mol m}^{-3} \text{ sec}^{-1}$ ) and fast reactions ( $10^9 \text{ mol m}^{-3} \text{ sec}^{-1}$  or more).

The Eddy Dissipation Model assumes that initially, the chemical species are not well mixed, and that the turbulence generated by combustion controls the mixing. The mixing time-scale is the relevant one, and is much larger than the reaction time-scale.

The reactions are therefore assumed to occur instantaneously wherever there is mixing (“mixed is burnt”). This model is appropriate when the fluids are injected separately and ignition occurs soon after. It has the advantage of being less costly than the chemistry models, since the turbulence time scale (tens of microseconds) is large respect to the chemical reactions time-scale. A typical calculation will take 12 to 24 hours on a workstation.

The premixed model does not use the reaction rates. It only solves one scalar equation for the “Reaction Progress”, which has value 0 for fresh gases and 1 for burned gases. The species mass fractions are then deduced from the local values of the reaction progress. This model is also less costly than chemistry models and does not require as small a time step.

The finite rate chemistry model is the most accurate. But due to the very small time step needed and therefore its high cost, we use it mainly to calibrate the simpler models and to do control runs for the most important cases.

In CFX, the user can impose his own equation of state. We choose to use the Peng-Robinson equation,

$$P = \frac{RT}{V - b} - \frac{a}{V(V + b) + b(V - b)}$$

with the coefficients  $a$  and  $b$  depending on temperature and density and given by known formulae. This equation has been shown to be well adapted to very high pressure cases.

An alternative, more general, equation would be the virial equation of state,

$$P = \frac{ZRT}{V}$$

with the compressibility factor  $Z$  given by

$$Z = 1 + a_1 \rho + a_2 \rho^2 + a_3 \rho^3 + \dots$$

where  $\rho = 1/V$  is the density. This requires access to good data about the “virial coefficients”  $a_1, a_2, a_3, \dots$  which depend on the gas mixture.

### 3 – Tests of the Eddy Dissipation Model (EDM)

In order to evaluate the accuracy of the Eddy Dissipation Model, we have reproduced an experiment with an old UTRON 45 mm gun for which there is extensive measurement data. Figure 1 shows the geometry of the gun chamber, with the location of the five ignitors and the three probes. The geometry is axisymmetric, and the calculation uses this approximation. The initial condition is shown in figure 1 for Temperature. We did not simulate the ignition process but started from an assumed initial condition with some energy deposited around the ignition points. The projectile is allowed to start moving when the pressure at its base reaches 25000 psi. The time step is  $10^{-5}$  sec and the computation grid includes about 40000 points.

Figure 2 shows the pressure versus time at the three probe positions from the experiment at the top and the corresponding data from the calculation at the bottom. One can see that this simple model catches the right time-scale for the pressure buildup and the peak pressure. However, there are significant differences. The numerical curves display oscillations due to pressure waves which are absent from the experimental ones. Also, the experimental results show a time lag between the pressure at the three probes while the three numerical curves are much closer to each other.

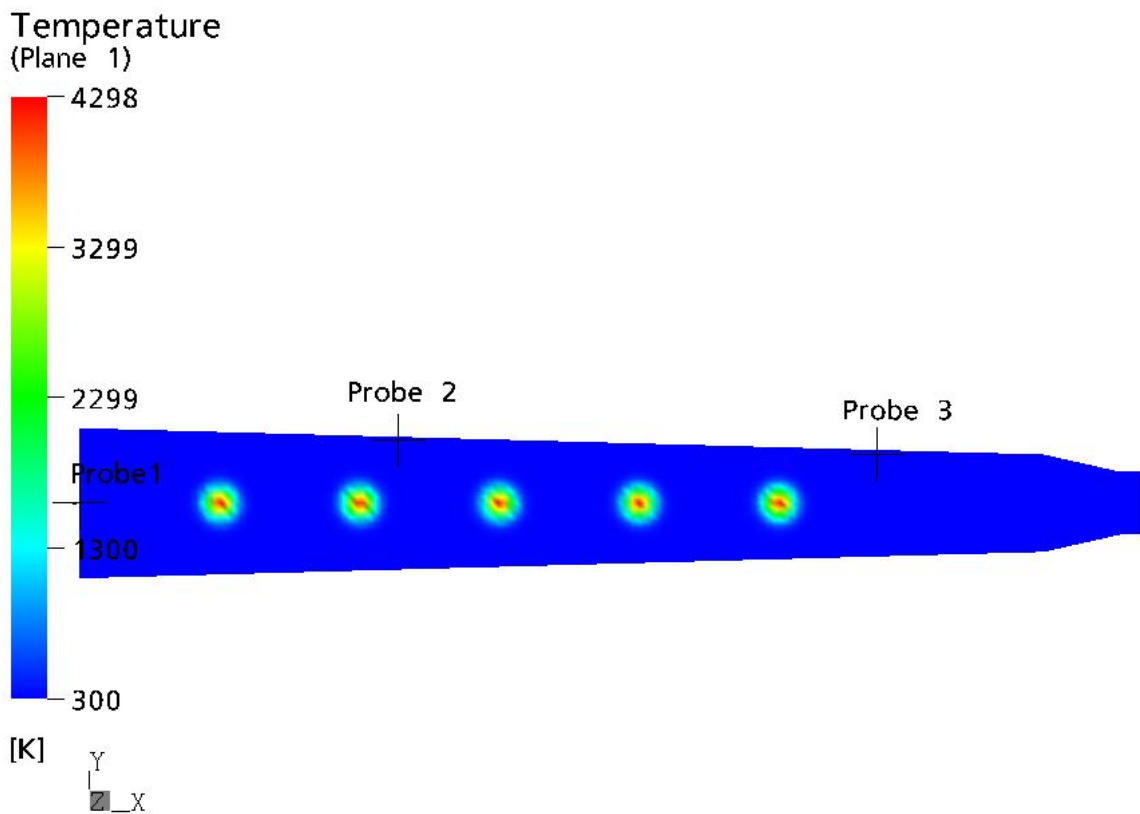


Figure 1: Initial temperature plot of the chamber, showing the five ignition points and the position of the three probes.

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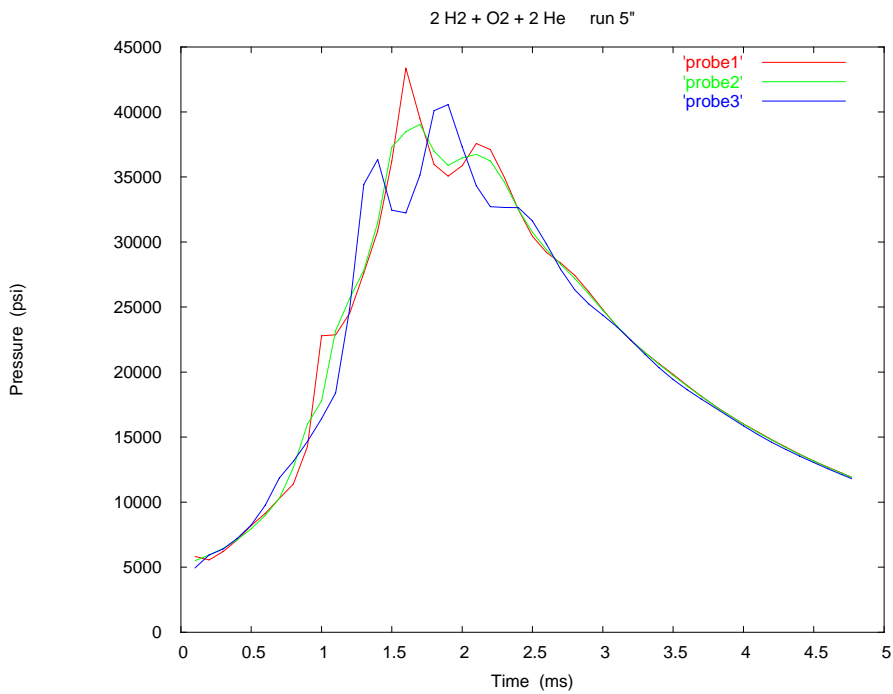
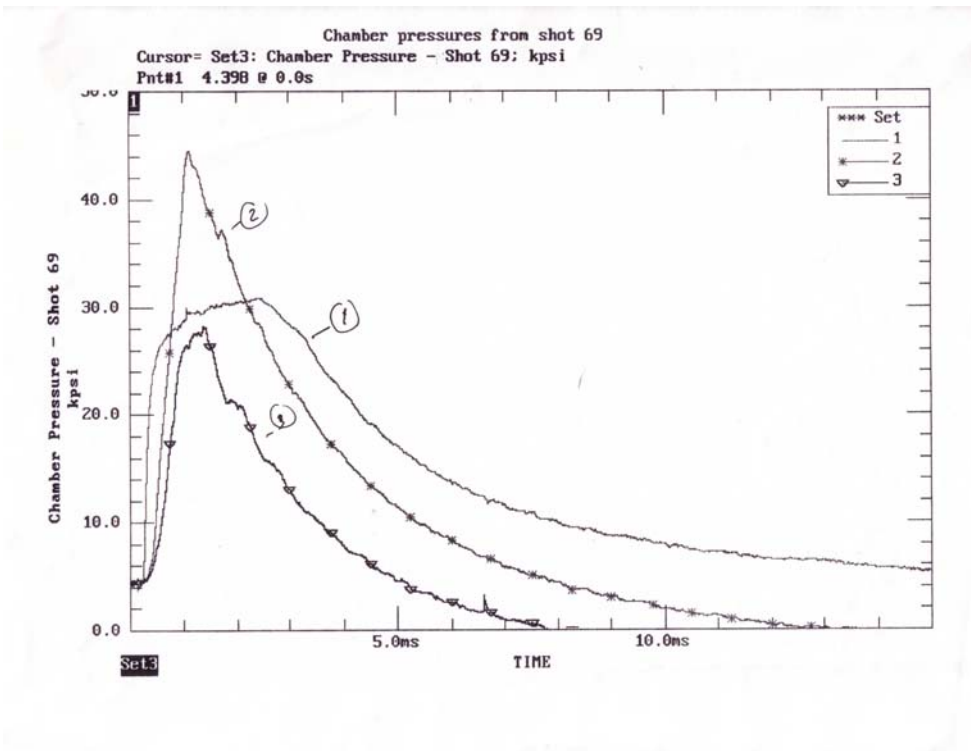


Figure 2: pressure versus time at the three probe positions indicated on fig.1. Experimental values (top) and computed values (bottom).

Finally, we have redone the Eddy Dissipation calculation presented above with a full three dimensional grid instead of an axisymmetric one. Figure 3 shows a comparison of the pressure at probe 3 for the two calculations. One can see that there are differences but they are within the uncertainties of this type of calculation.

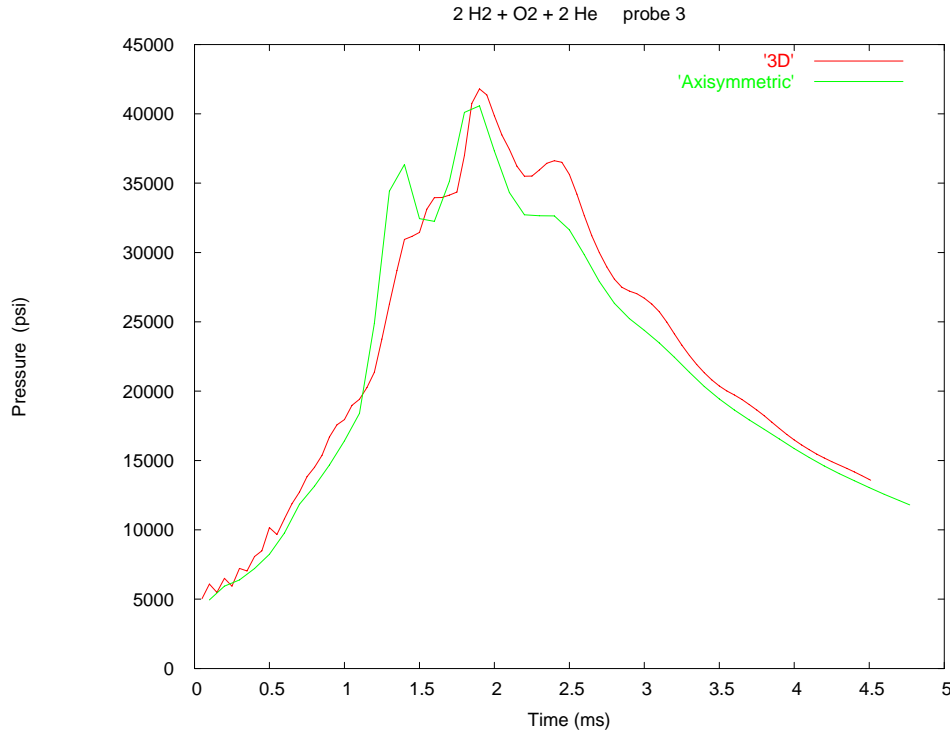


Figure 3. Comparison of the pressure at probe 3 for the Eddy Dissipation Model with a full 3D grid (red curve) and an axisymmetric grid (green curve).

We have redone the same calculation as above using the Finite Rate Chemistry model, in the simple case of one global reaction  $2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O}$ . This is a crude model, since the variation of reaction rates with temperature is different for different reactions, and the assumption of one single reaction with no corresponding backward reaction is not accurate. The reaction rate is taken to be that of the slowest reaction,  $2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{OH}$ . The time step used in the calculation is  $5 \times 10^{-7}$  sec, much smaller than with the previous model, and the calculation takes a week on our two-processor workstation.

Fig. 4 shows a comparison of the pressure versus time for the two models at the position of probe 2. The initial conditions were the same except for the Temperature at the ignition points, which was 10000K for the Chemistry run and 4000K for the EDM model. One can see that despite the important difference in the assumptions made by each model, there are similarities in the curves. The EDM curve is much smoother than the FRCM one. This is partly the result of the much larger time step used in the former,  $10^{-5}$  sec, and the resulting averaging effect. The most important difference is that the Single Reaction Model predicts a maximum pressure higher than the EDM value.



Fig. 5 shows a comparison of the volume averaged temperature predicted by the EDM and FRCM models. The second model predicts a higher maximum temperature, but the curves are very close.

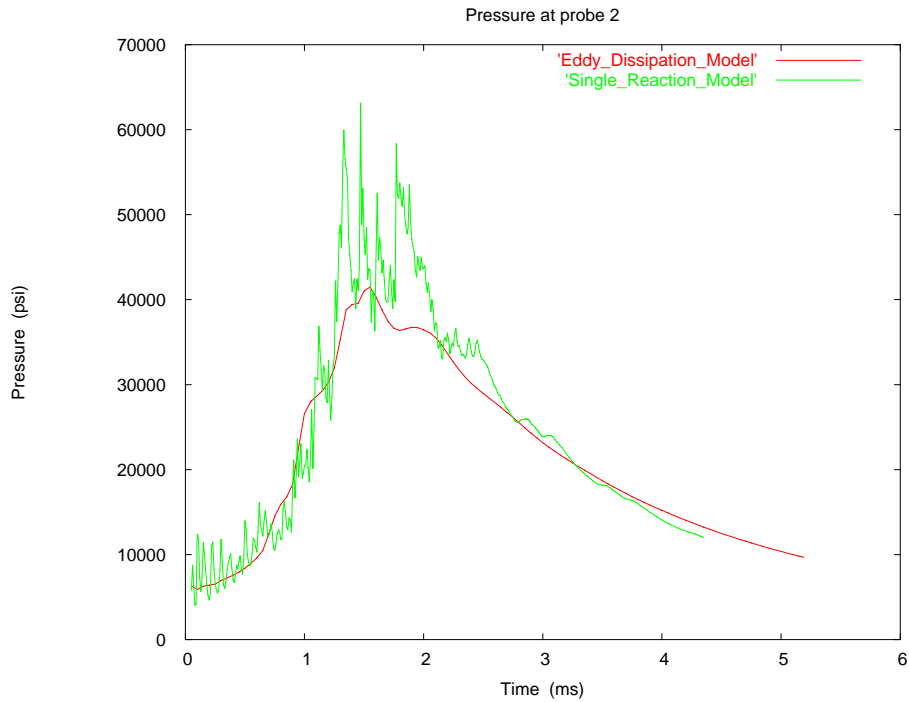


Figure 4. Comparison of the pressure at probe 2 from the Eddy Dissipation Model (red curve) and the Single Reaction Chemistry model (green curve).

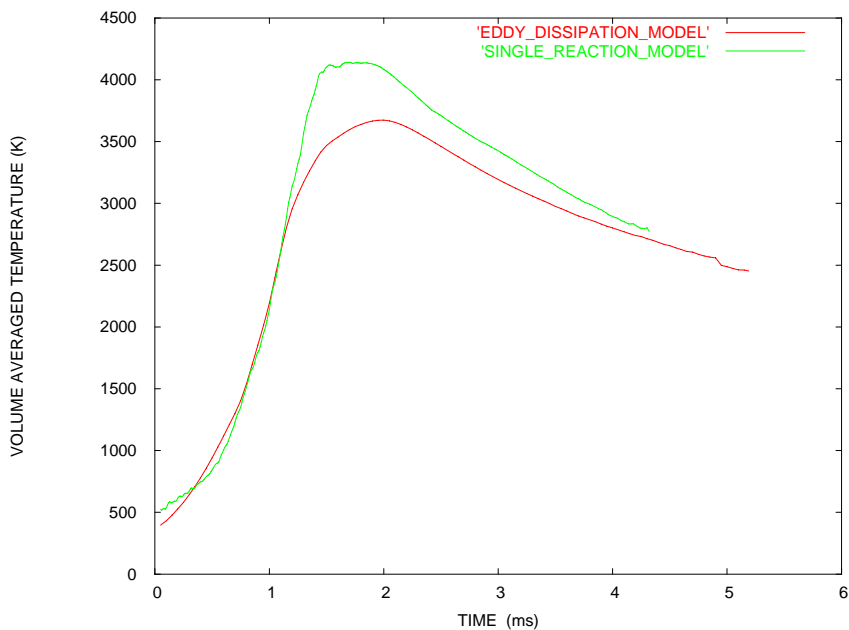


Figure 5. Comparison of the volume averaged Temperature predicted by the Eddy Dissipation Model (red curve) and the Single Reaction Chemistry model (green curve).

## 4 – Tests of the Premixed Model

We have done several computations using the Global Chemistry Model and the premixed model with the same initial condition, using axisymmetric grids. An O<sub>2</sub>-H<sub>2</sub> mixture is heated at several points on the chamber axis for a fraction of a millisecond to start the reactions, using the Global Chemistry model. The two parallel calculations are then started from the resulting condition. Figure 6 shows the pressure curves obtained for the 45 mm UTRON gun with a total chemical energy of 7 MJ and a projectile mass of 0.52 kg. The velocity obtained was 2400 m/s. The agreement is moderately good.

Another comparison is shown in figure 7 for a model of the 155 mm UTRON gun. The volume of the chamber and the projectile mass are 40 times larger than in the case of the 45 mm gun, respectively 200 litres and 21 kg. The agreement is fairly good. Note that the chemistry calculation curve displays some peaks. These are due to pressure waves traveling in the chamber and barrel. These peaks are invisible in the premixed model curve. This is not surprising since the time-step used in the second case is 10<sup>-5</sup> s while in the chemistry case it was 10<sup>-7</sup> s. The pressure waves are filtered out in the premixed calculation, due to the large time-step used.

Figure 8 shows the projectile acceleration from the same calculations of the 155 mm gun. Again, the pressure waves are clearly visible in the chemistry calculation, but absent in the premixed one. Obviously, the premixed model is less accurate than the chemistry model, and misses some phenomena. But given the fact that it is 100 times faster, it is extremely useful as a first exploration tool. Important results can be later confirmed by chemistry calculations.

The 8 reactions chemistry model was used in some tests and compares well with the Global single reaction model. The time step is at most 10<sup>-8</sup> s, and makes the calculation very expensive. No computation was done yet with the complete set of reactions. We are waiting for the coupling of CHEMKIN with CFX .

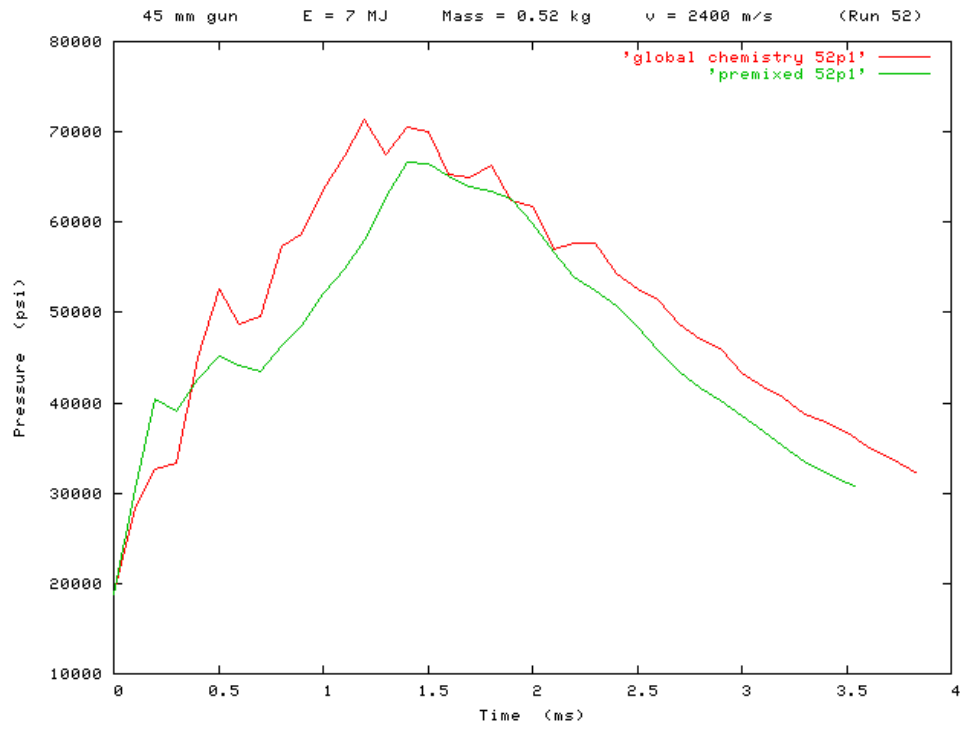


Figure 6: Pressure versus time at probe 1 (back of the chamber) in the 45 mm gun computed with the Global Chemistry model (red) and the premixed model (green). The total chemical energy was 7 MJ and the projectile mass 0.52 kg.

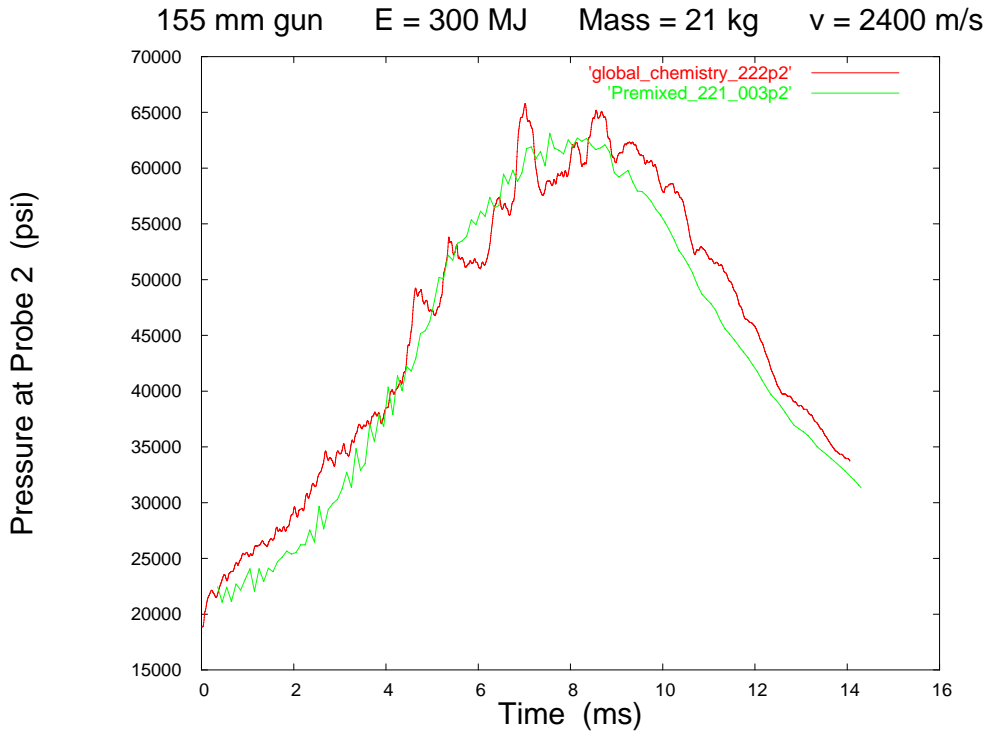


Figure 7: Pressure versus time at probe (forward top of the chamber) in a model of the 155 mm gun computed with the Global Chemistry (red) and the premixed model (green). The total chemical energy was 300 MJ and the projectile mass 21 kg.

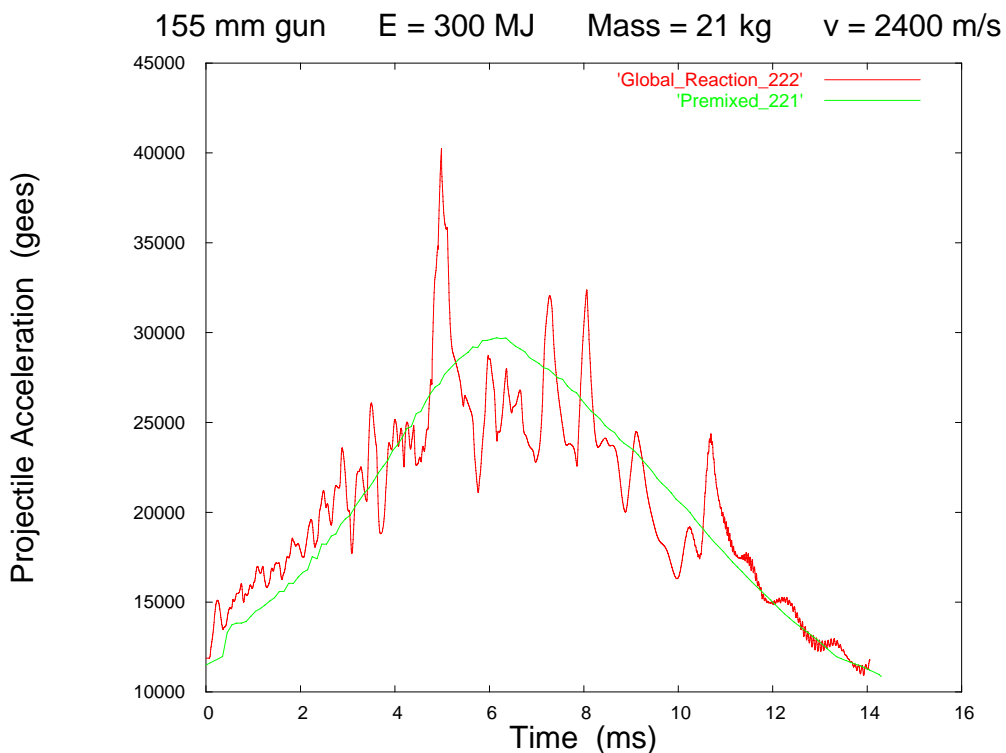


Figure 8: Projectile acceleration versus time from the same calculation as in figure 7, with the Global Chemistry model (red) and premixed model (green).

## 5 – Comparison between computation and experimental results

We have tried to reproduce the results of an experimental shot of the 45 mm UTRON gun, with a total chemical energy of 3 MJ and a projectile mass of 0.52 kg. The comparison of experimental and computed pressure curves is shown in figure 9. The experimental data was filtered for the comparison, and the computation curve was shifted to approximately match the time of maximum pressure. Indeed, we do not expect to compute this time accurately because the ignition process is not modeled in detail, and replaced by simply heating the gas along the chamber axis. Despite the filtering, the experimental curve still presents some peaks due to pressure waves, which are barely visible in the computed curves. Note that the premixed model was used in this test.

The resulting projectile velocities were 1700 m/s in the experiment and 1800 in the calculation. The efficiency is 0.25 and 0.28 respectively.

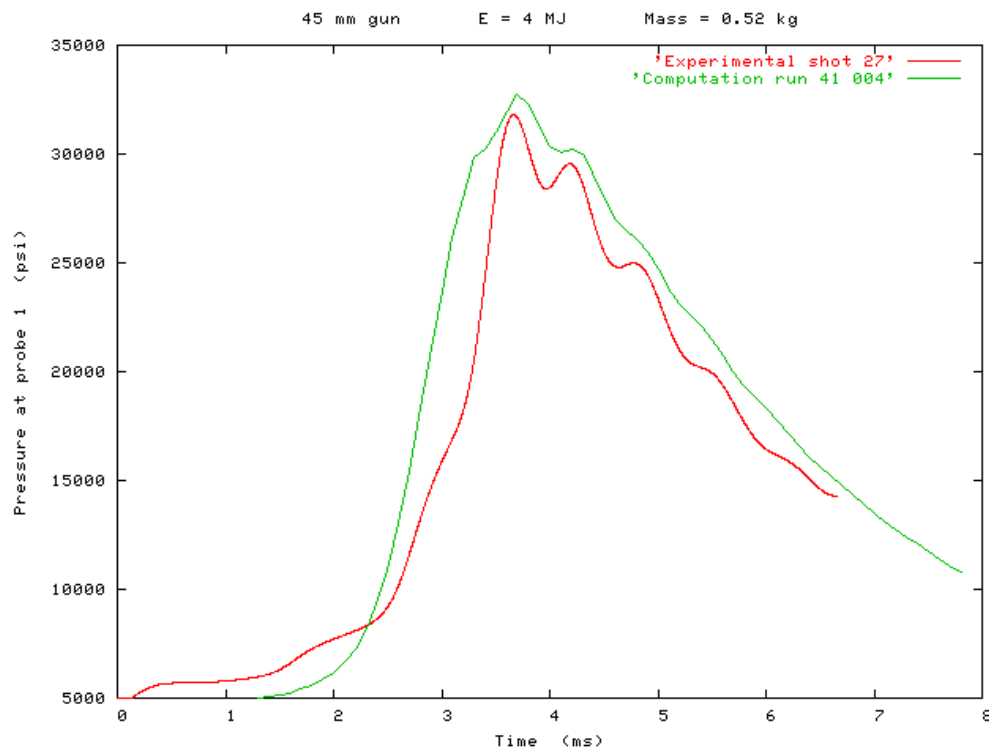


Figure 9: Pressure versus time at probe 1 (back of the chamber) in the 45 mm gun from experiment (red curve) and Premixed model computation (green curve). The Chemical energy was 3 MJ and the projectile mass 0.52 kg.

## 6 - Temperature at the wall of the gun chamber

We have used the Global Chemistry model to study the temperature at the wall in the chamber for the 45 mm gun. The program allows modeling of solid parts with heat transfer taken into account. The metal is assumed to be steel. A very fine boundary layer grid was used both on the gas side and the metal side of the interface. The first grid point was at 50 microns of the wall. Figure 10 shows a vertical cut of the gun shortly after the projectile release. A detail of the region of the end of the chamber an entry of the barrel is shown in figure 11. A thin white line, barely visible, shows the position of the wall. One can see the gas turbulent boundary layer in contact with the wall, and at roughly the same temperature. The temperature of the wall in this zone is of the order of 1600 K, which is very close to the melting temperature of steel. In the rest of the chamber, the temperature at the wall is much lower, below 1000 K.

Our interpretation is that the very strong turbulence that is produced behind the projectile blows out the viscous boundary layer and lets hotter gas in contact with the wall. The conclusion is that in that part of the gun, a different material must be used.

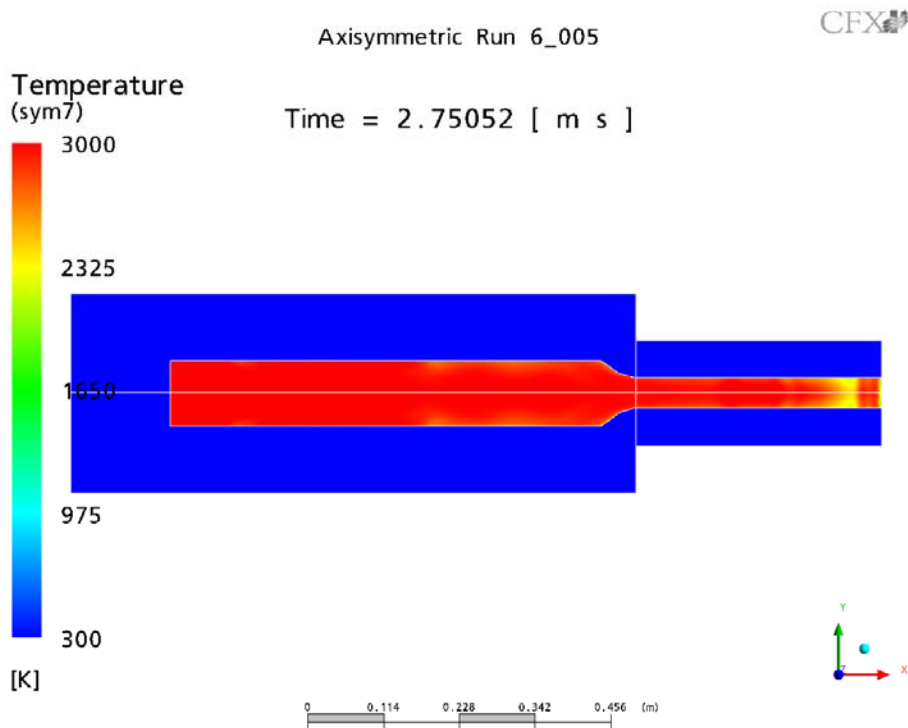


Figure 10: Temperature of the gas and metal in a simulation of the 54 mm gun soon after the projectile release.

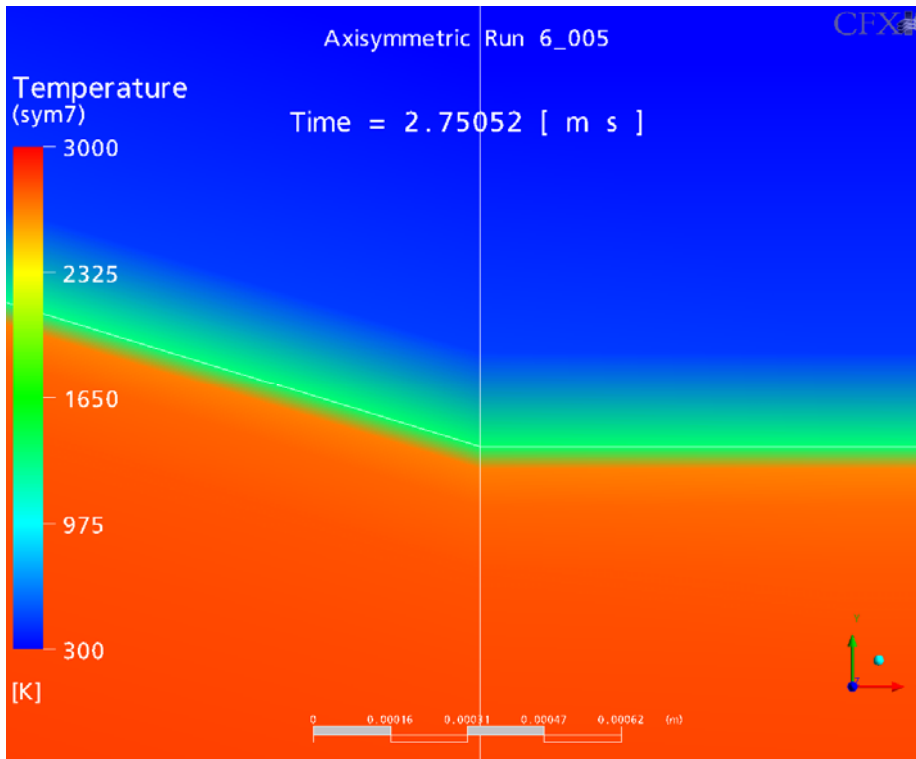


Figure 11: Detail of previous figure at the entry of the barrel. The white line shows the position of the wall. One can see the gas boundary layer.

## 7 - Effect of the chemistry

We have repeated the previous calculation while varying the initial amount of hydrogen. The composition was chosen to be  $n \text{ H}_2 + \text{O}_2$  taking the values 6,8, 10, 12. The maximum temperature at the wall is displayed in figure 12 as a function of  $n$ , for two values of the chemical energy, 6 and 7 MJ. The effect of  $n$  on the temperature is quite pronounced, and for low  $n$ , as said above, the temperature approaches the melting temperature of steel.

The effect on the pressure and on the projectile velocity was within the uncertainties. It seems that, due to real gas effects, the variation in temperature is compensated by a variation of the compressibility factor when the density is increased.

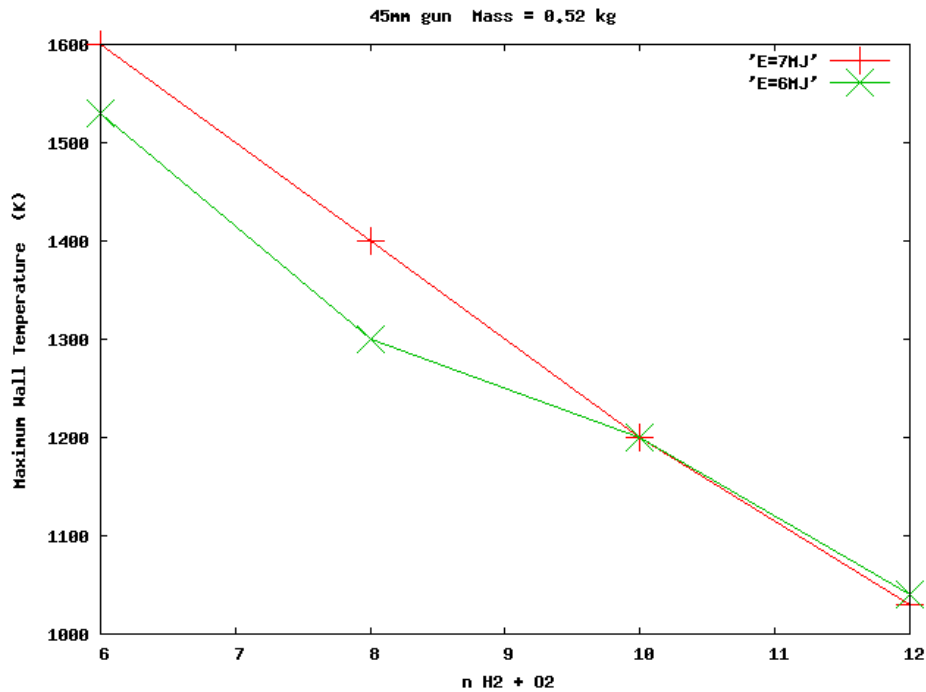


Figure 12: Variation of the maximum wall temperature in the 45 mm gun with the amount of hydrogen n (the composition is n H<sub>2</sub> + O<sub>2</sub>) for two values of the chemical energy, 6 MJ (green curve) and 7 MJ (red curve).

## 8 - Effect of the chamber volume

We have done a series of calculations with different chamber volumes, all other parameters being the same, for the 45 mm gun. The results are displayed in figure 13. As expected, decreasing the volume increases the efficiency of the gun, but at the cost of higher chamber pressure.



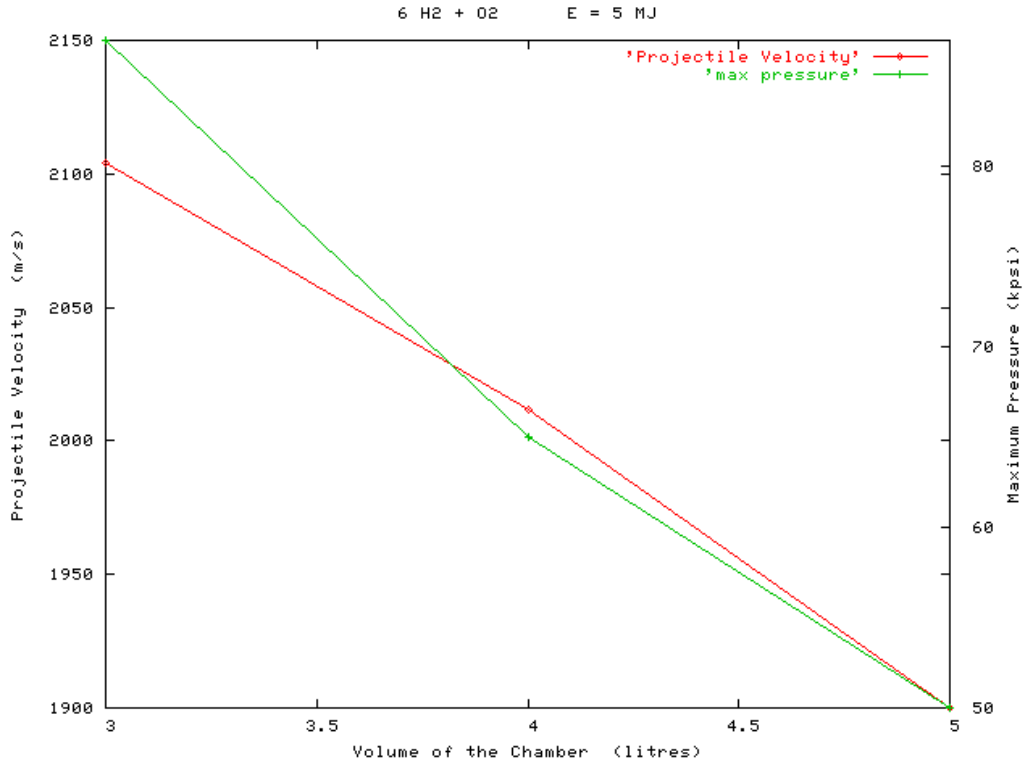


Figure 13: variation of the projectile velocity (red curve) versus the chamber volume, for the 45 mm gun, with 5 MJ chemical energy. Also shown is the maximum chamber pressure (green curve).

## 9 – Effect of the projectile mass

To study the effect of the projectile mass on performance, we have done a series of calculations for the 45 mm gun with masses 0.2, 0.52 and 1 kg. The premixed model was used. The loss of efficiency at lower mass, as seen in the 0.2 kg curve, which becomes horizontal at high energy, is due to the faster acceleration the projectile and the resulting incomplete burning of the fuel.

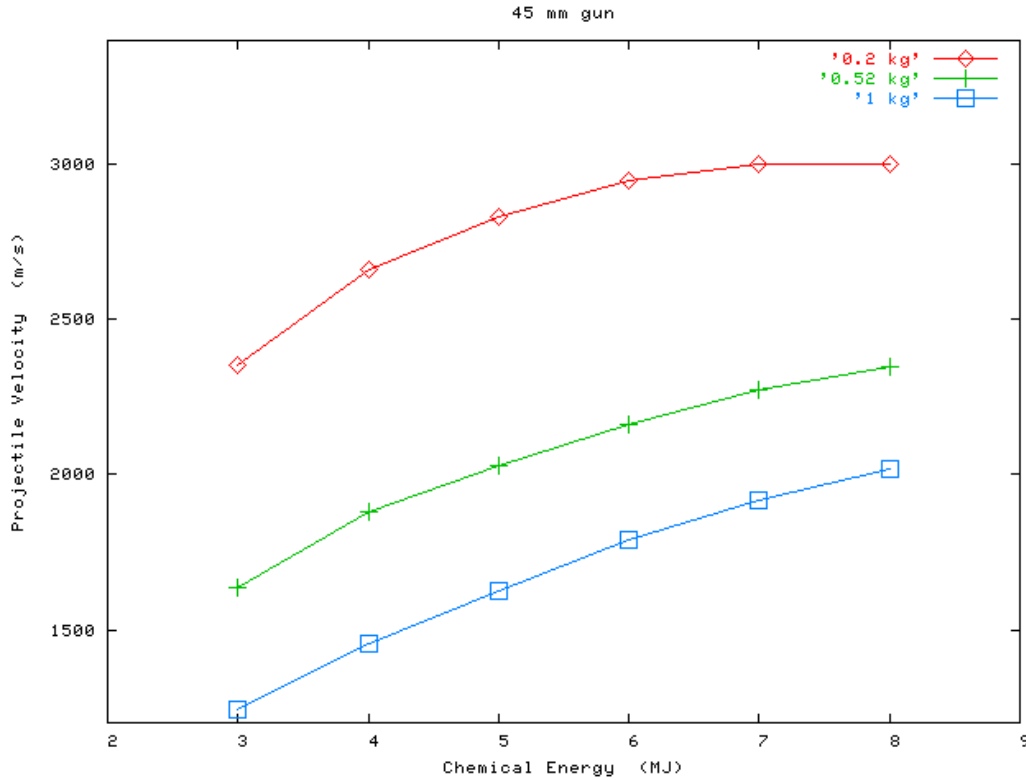


Figure 14: Projectile velocity versus chemical energy for three different projectile masses, 0.2 kg (red), 0.52 kg (green) and 1 kg (blue).

## 10 – Modeling the 155 mm gun

The scaling from the present 45 mm gun to the 155 mm gun under construction is as follows. The pressure, density and temperature are the same, but the volume and the projectile mass are 40 times larger. The volume goes from 5 to 200 liters and the mass from 0.52 to 21 kg. The energies go up by the same factor 40 and the projectile velocity is expected to be the same. We have done several simulations of the 155 gun with a geometry close to the actual one. One calculation is presented here. The chemical energy was 300 MJ for a mixture of hydrogen and oxygen. Figure 15 shows the temperature at the end of the calculation (projectile exit) and the position of seven pressure probes. Figure 16 shows the pressure history at these seven probes. The curves are very similar to experimental curves from the 45 mm gun. This calculation was done using the global reaction chemistry model and the pressure was recorded every 5 microsecond. The data was requested by the gun builder. The projectile velocity was 2400 m/s. Figures 17a to 17e show the pressure in the gun at five different times. One can see the pressure waves propagating in the chamber and barrel.

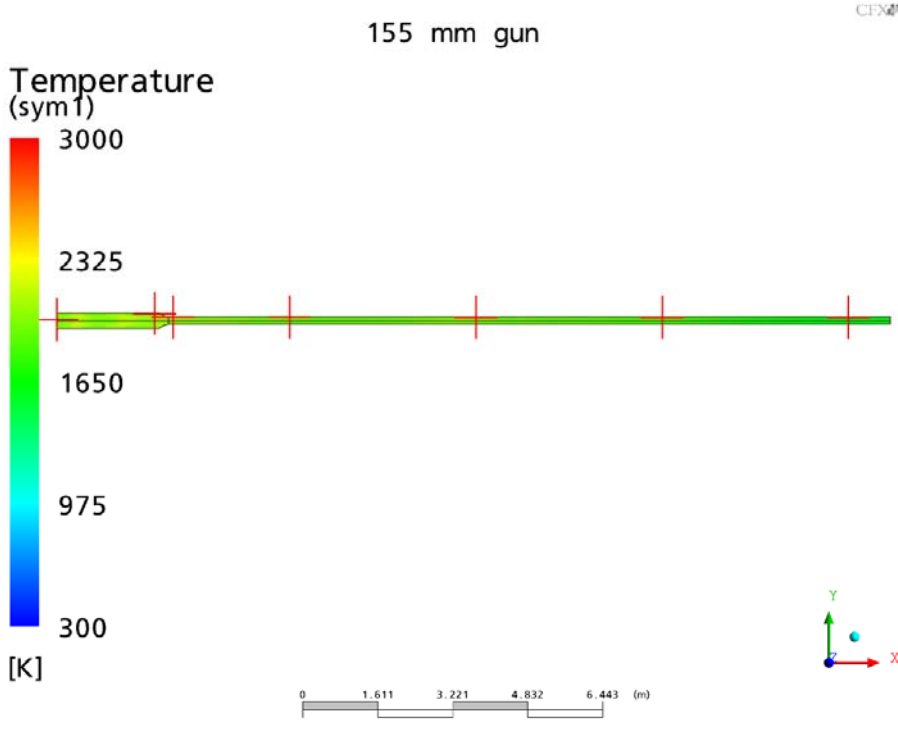


Figure 15: Positions of the seven pressure probes used in our model of the 155 mm gun. Probe 1 is the back of the chamber and probe 7 almost at the barrel exit.

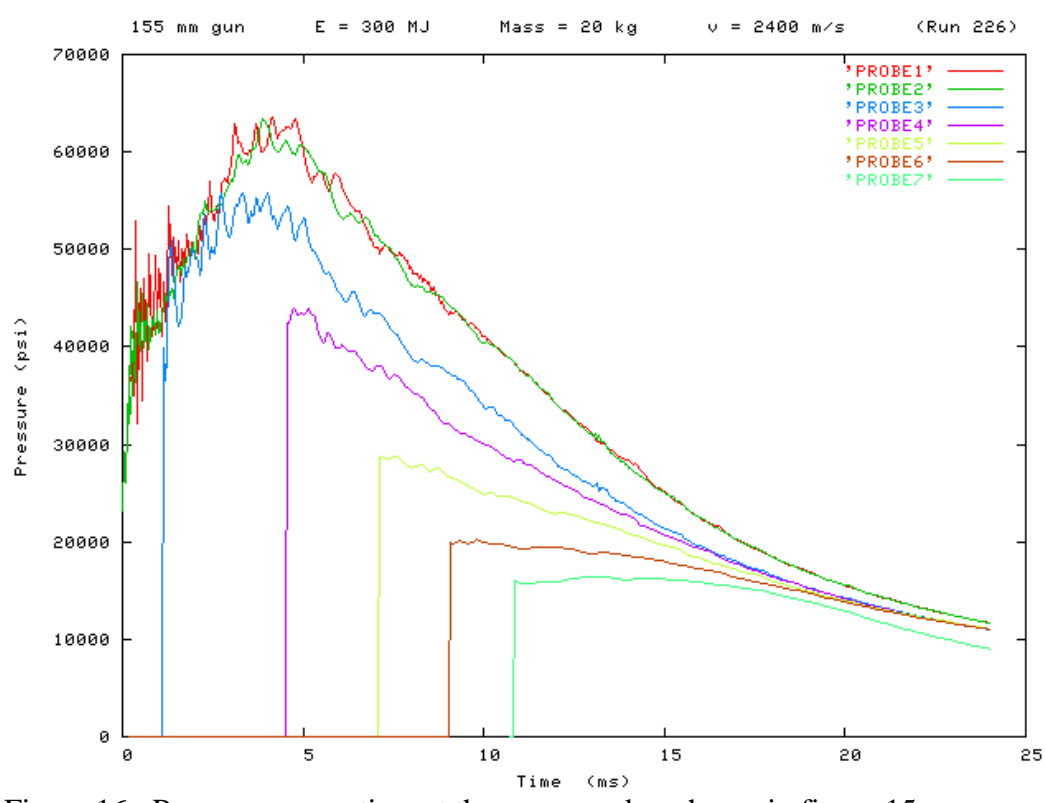


Figure 16: Pressure versus time at the seven probes shown in figure 15.

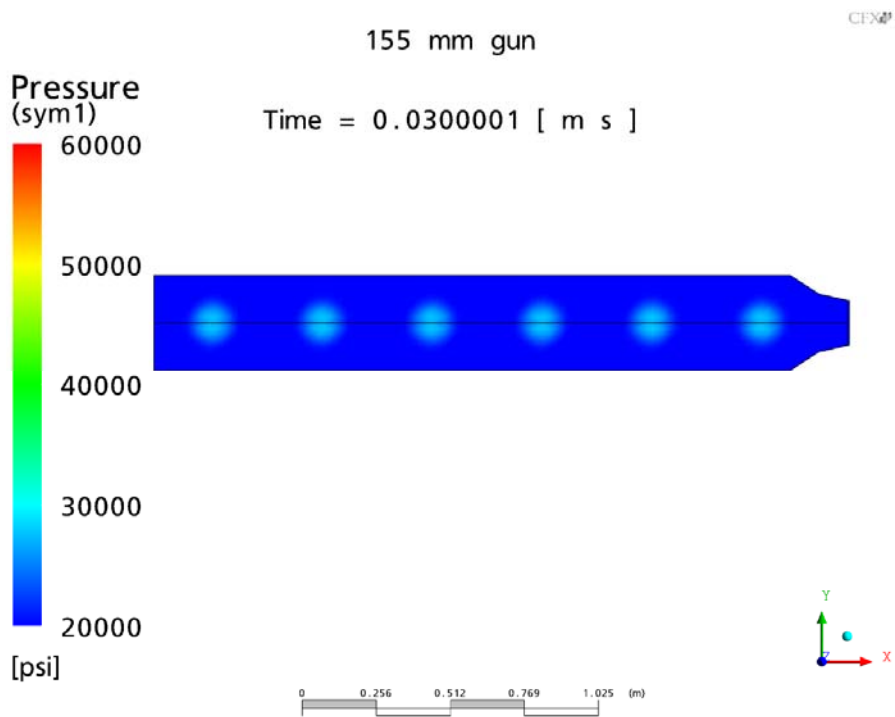


Figure 17a: Pressure at an early time.

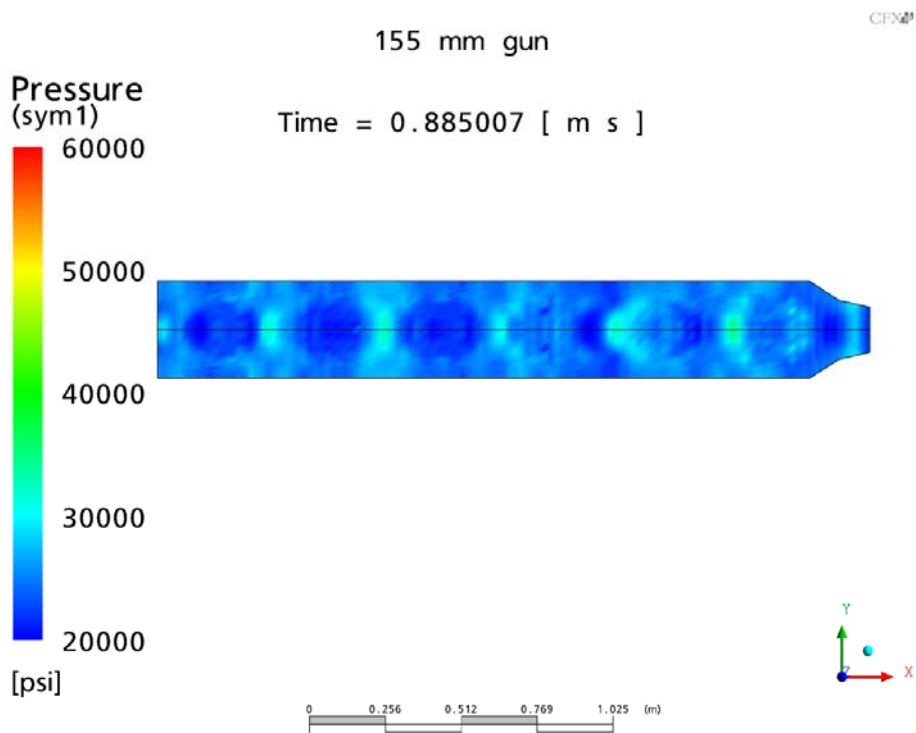


Figure 17b.

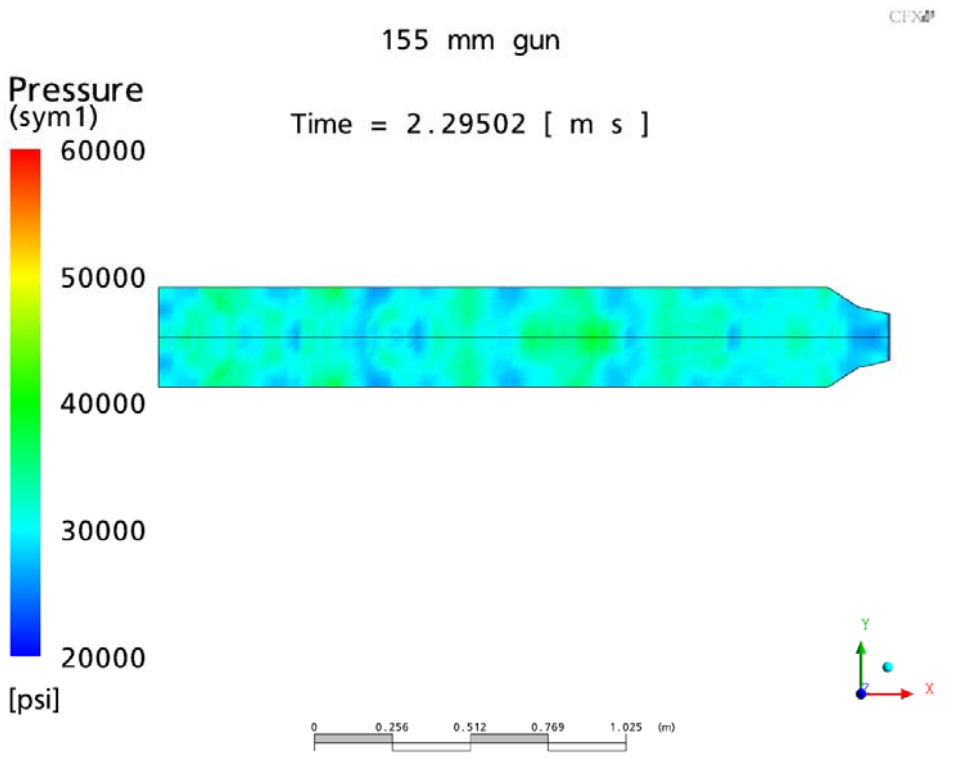


Figure 17c. Pressure at time 2.29 ms.

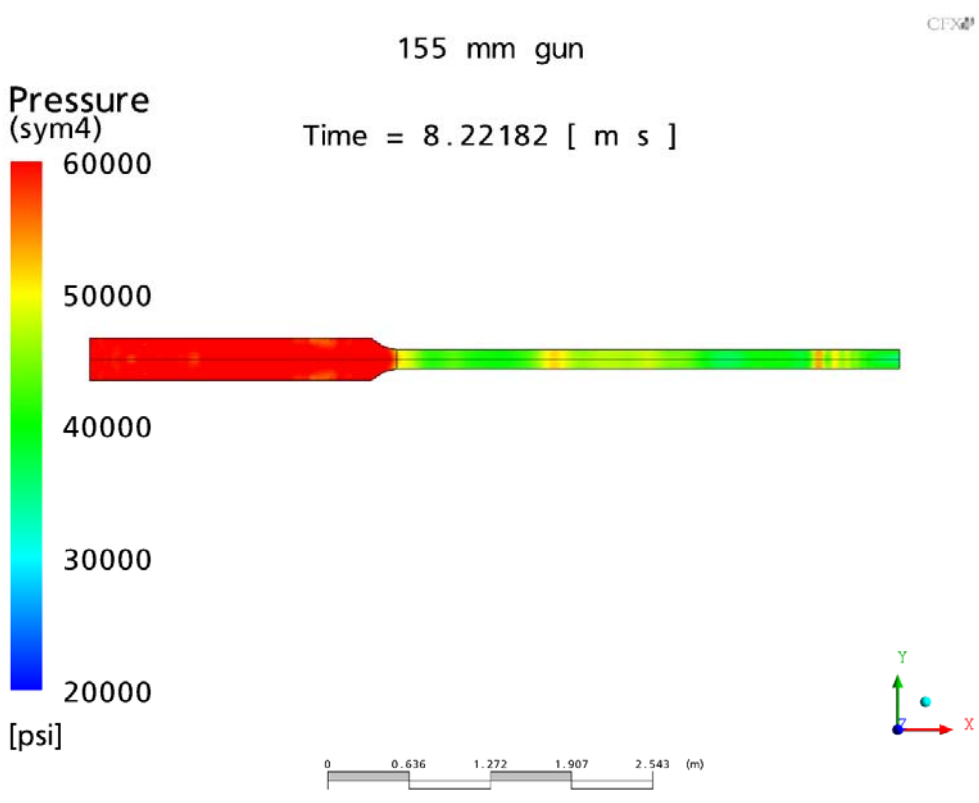


Figure 17d. Pressure at time 8.22 ms.

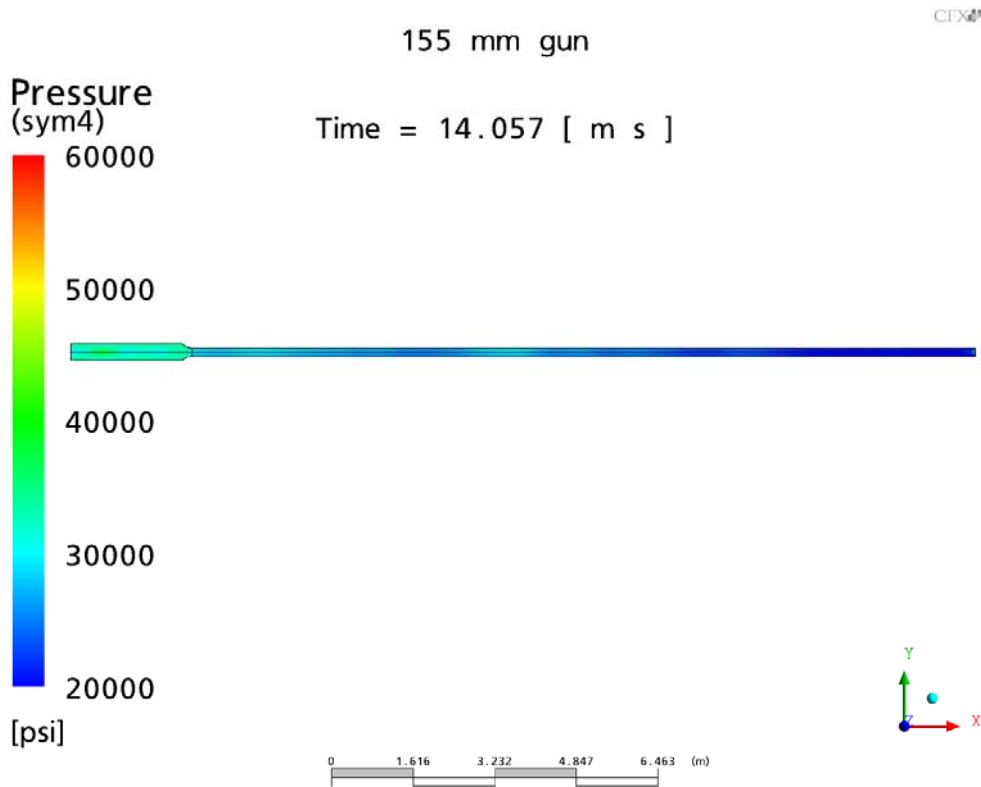


Figure 17e. Pressure at the time of projectile exit.

Figure 18 shows the projectile acceleration, in gees, for the same calculation. The effect of the pressure waves is clearly seen. The green curve was obtained by filtering the data with a low pass filter and gives approximately the maximum effective acceleration. It is assumed that the high pressure transients due to the waves have little effect on the projectile, given their short duration. This remains to be confirmed by tests of the real gun. The maximum effective acceleration is approximately 30,000 gees.

Finally, figure 19 summarizes the predictions of the code concerning the acceleration and maximum chamber pressure required to reach a given velocity and range with the 155 mm gun. These calculations are using the premixed model and the uncertainty is probably of the order of 5%. The results are given both for 100 calibers and 70 calibers. One can see that 2500 m/s and 200 Nautical miles can be reached at 100 calibers with acceptable chamber pressures, but at 70 calibers this requires pressures which are at the upper limit of what the 155 mm gun under construction is designed for.

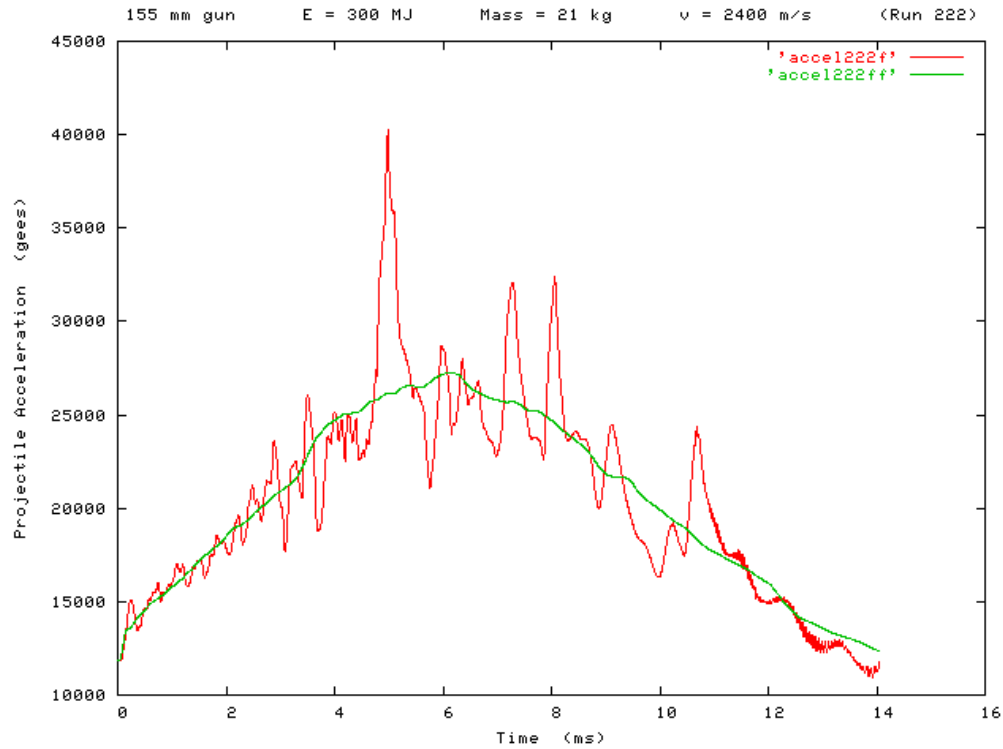


Figure 18. Projectile acceleration versus time (red curve) and its filtered version (green curve) with a low pass filter.

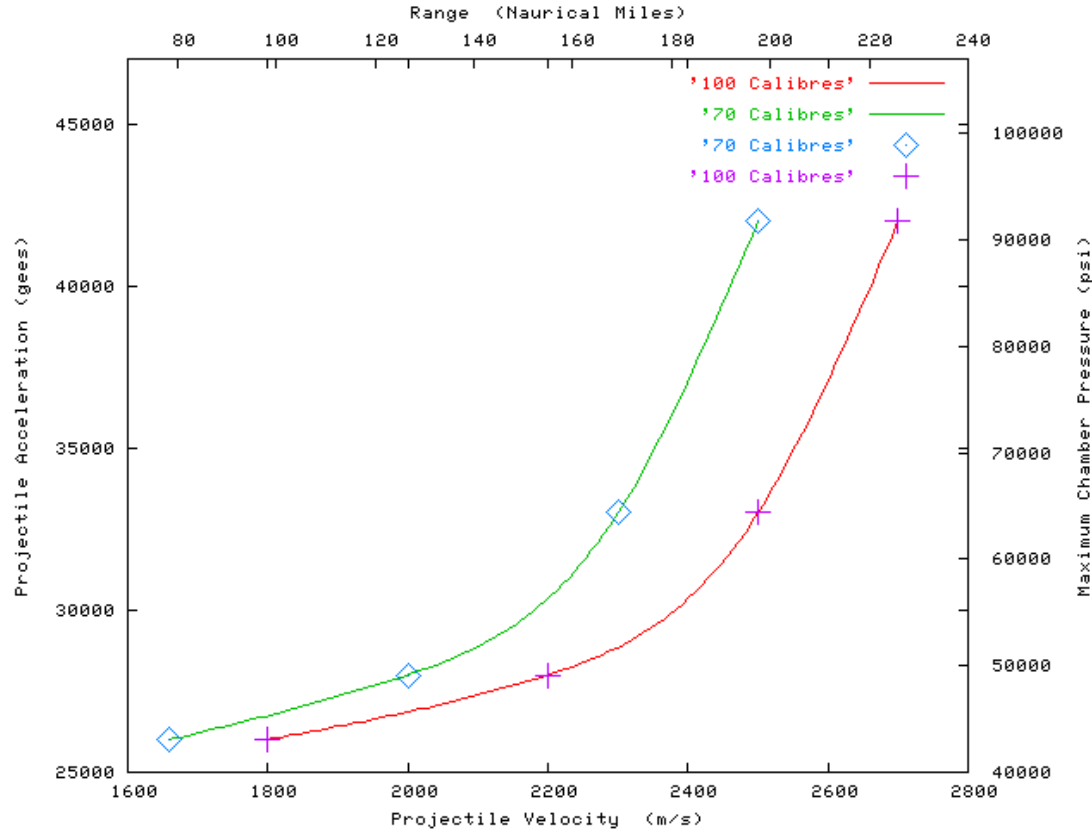


Figure 19: Acceleration, maximum pressure and gun range as a function of projectile velocity for the 155 mm gun. 100 calibres results (red curve) and 70 calibres (green

curve)



## **Appendix C – Finite Element Analysis**

## CLGG45 Projectile FEA

After ignition, the projectile skirt yields at the optimum combustion chamber pressure and folds down into a recess in the projectile to fire the projectile and maximize muzzle velocity. The high pressure driving the projectile also presses the skirt against the gun barrel to dynamically seal and prevent blow-by of combustion gases past the projectile. Figure 1 shows a projectile skirt prior to firing on the left and the skirt folded after firing on the right. Figure 2 contains a picture from a high-speed camera of the projectile in flight with the skirt folded against the body of the projectile. Variable gas seepage can cause pressure variations between the skirt and forcing cone. For a given combustion chamber pressure, these pressure variations can substantially change the skirt stresses that determine the firing point.

However, the geometry of the skirt has a large impact on the severity of firing point inconsistency. The greater outer surface area of the skirt results in a larger collapsing force than the resisting force on the inner surface (because of diameter differences). Different angles of the inner and outer skirt surfaces relative to the axis will also change the balance of the opposing radial forces, as will different lengths of these surfaces. Furthermore, a shorter skirt length reduces the magnitude of these forces and their contribution to skirt stress variations (independent of combustion chamber pressure). Finally, a force imbalance that tends to collapse the skirt has a greater impact on firing point variation than forces that push the skirt against the supporting forcing cone. Present projectiles have relatively short skirt lengths, a slightly shorter outside than inside skirt length and similar skirt angles. Different projectile designs would require adjustment of the inner and outer skirt angles, lengths and diameters in order to keep firing point variations within acceptable limits. Figures 3 – 5 illustrate a potential stress variation of only 3% in a skirt design that uses these methods with FEA optimization and Figure 6 shows the projectile against the forcing cone.



Figure 1 Left - Projectile skirt prior to firing. Right – skirt folded after firing.

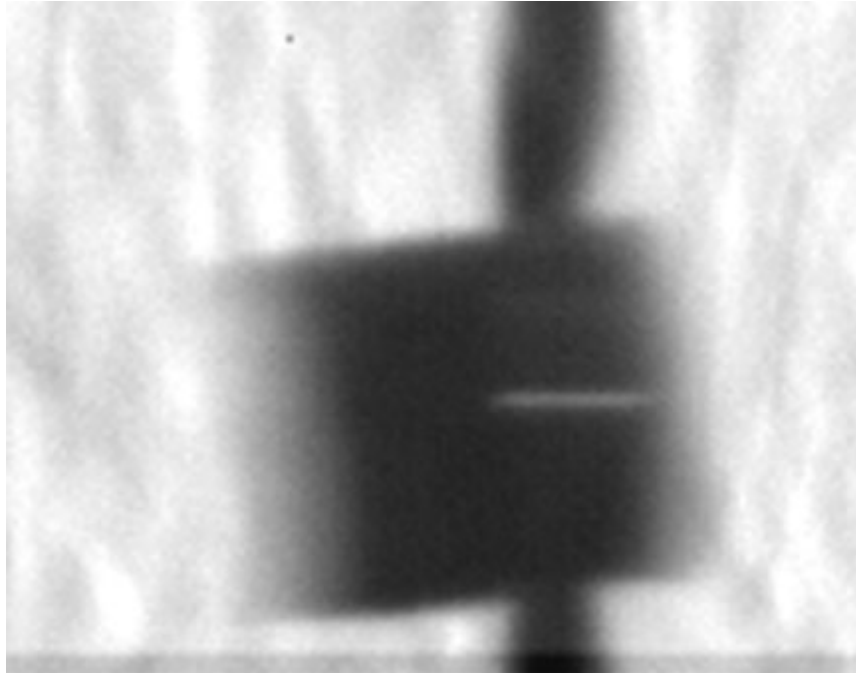
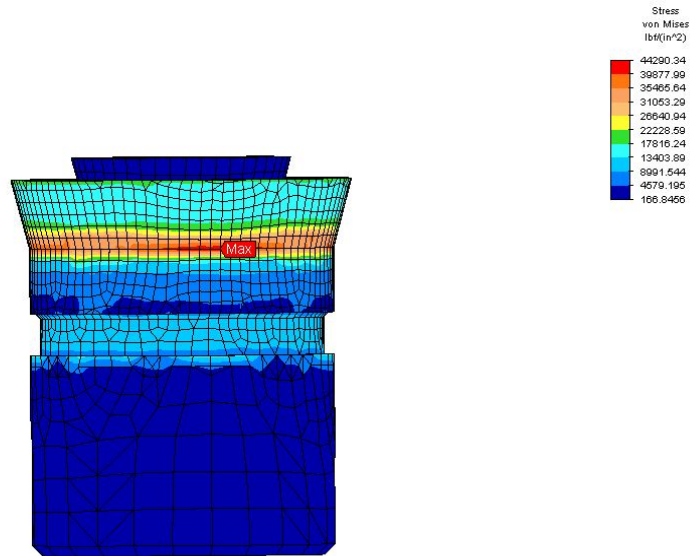


Figure 2 Projectile in flight with skirt folded against body



Load Case: 1 of 1

Maximum Value: 44290.3 lb/(in<sup>2</sup>)

Minimum Value: 166.846 lb/(in<sup>2</sup>)

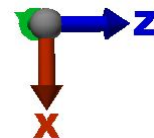
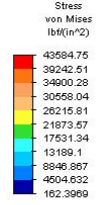
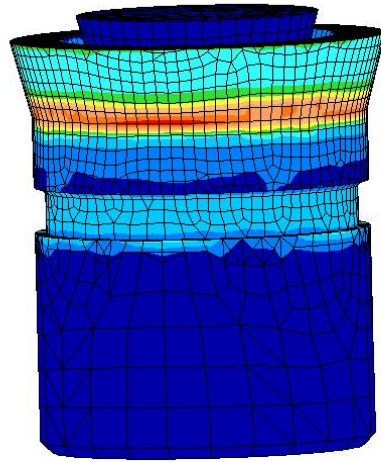


Figure 3 Full pressure between skirt and forcing cone



Load Case: 1 of 1

Maximum Value: 43584.7 lbf/(in<sup>2</sup>)

Minimum Value: 162.397 lbf/(in<sup>2</sup>)

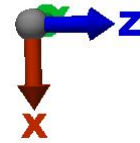
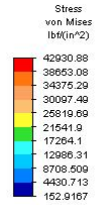
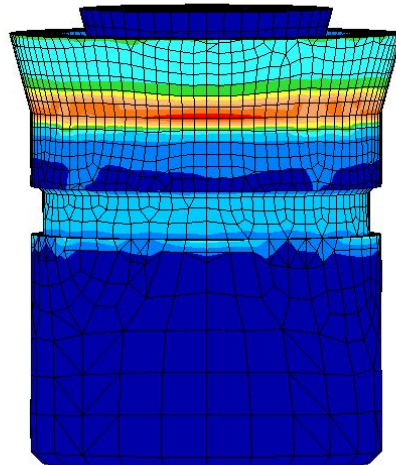


Figure 4 Half pressure between skirt and forcing cone



Load Case: 1 of 1

Maximum Value: 42930.9 lbf/(in<sup>2</sup>)

Minimum Value: 152.917 lbf/(in<sup>2</sup>)

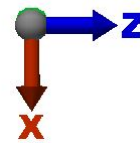


Figure 5 Zero pressure between skirt and forcing cone

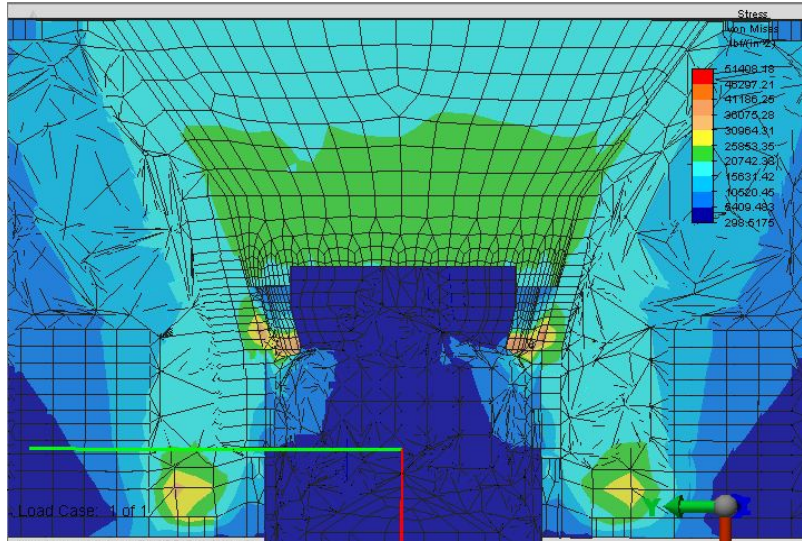


Figure 6 Assembly cross section – half pressure between skirt and forcing cone

Shot13 Simplified P2 Pressure Curve

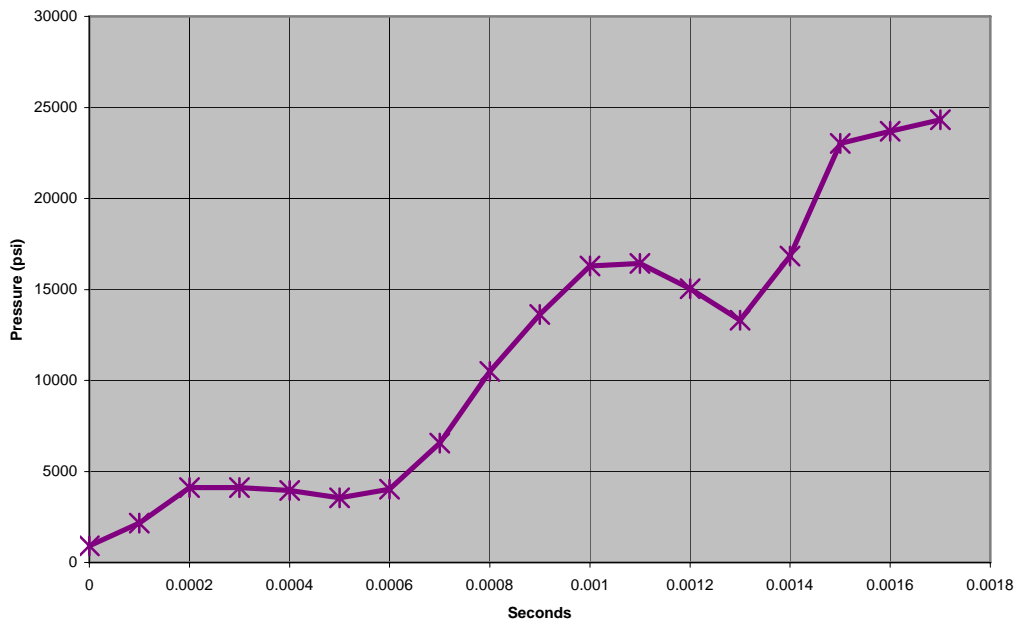


Figure 7 Shot 13 simplified P2 pressure curve used for linear dynamics FEA

The curve in Figure 7 derived from a P2 combustion chamber pressure probe located a few inches from the projectile and has been simplified to obtain reasonable linear dynamics FEA solve times while preserving the curve shape to the point of projectile fold. Days long linear dynamics FEA trials with fast-rise sections of the original data did not produce substantially different stresses. Longer nonlinear FEA runs yielded a firing point at a pressure of about 24000

psi while providing rules of thumb for determining firing points with faster linear dynamics methods.

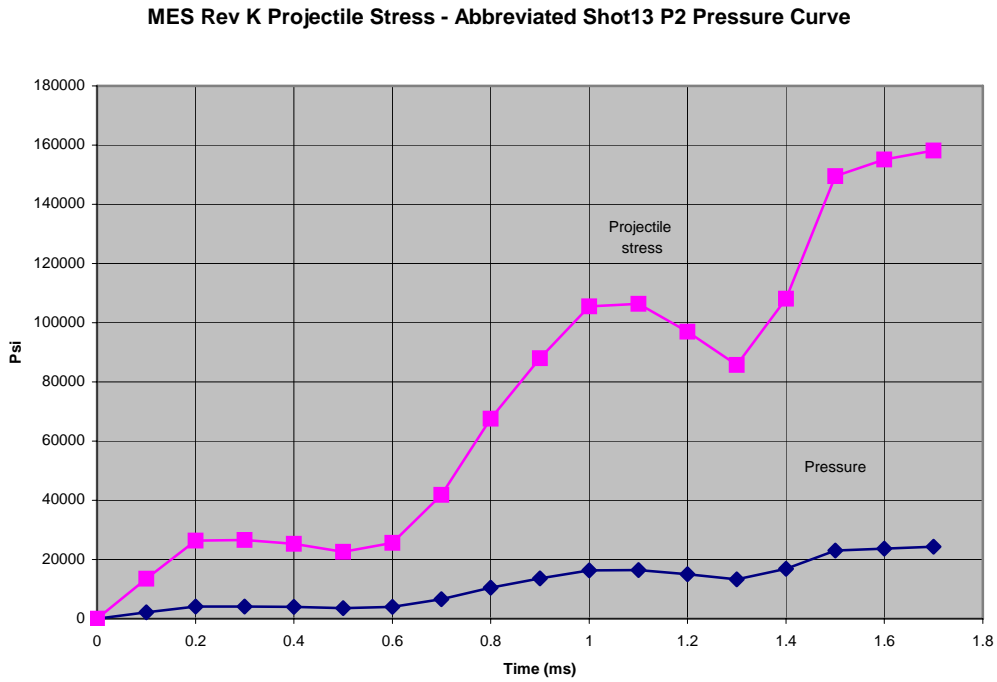


Figure 8 Shot 13 P2 pressure curve vs. linear dynamics FEA projectile folding stress

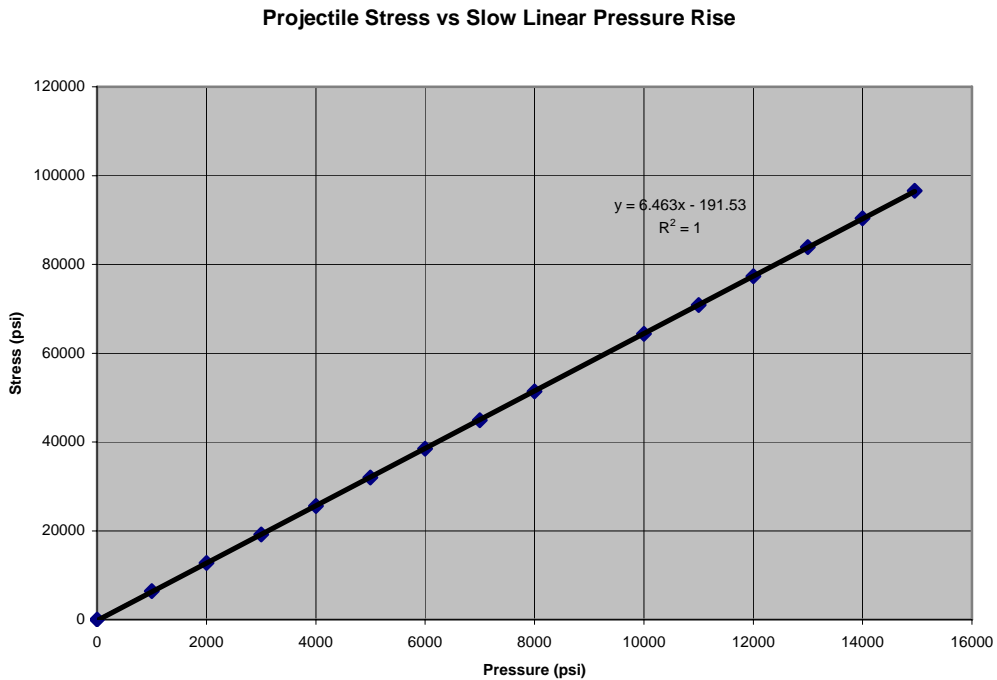


Figure 9 Slow linear rise pressure versus linear dynamics folding projectile stress

Figure 8 shows folding skirt projectile stress variations plotted with the Figure 7 pressure curve. Figure 9 includes the linear curve fit between pressure and linear dynamics FEA projectile stress for a slow pressure rise.

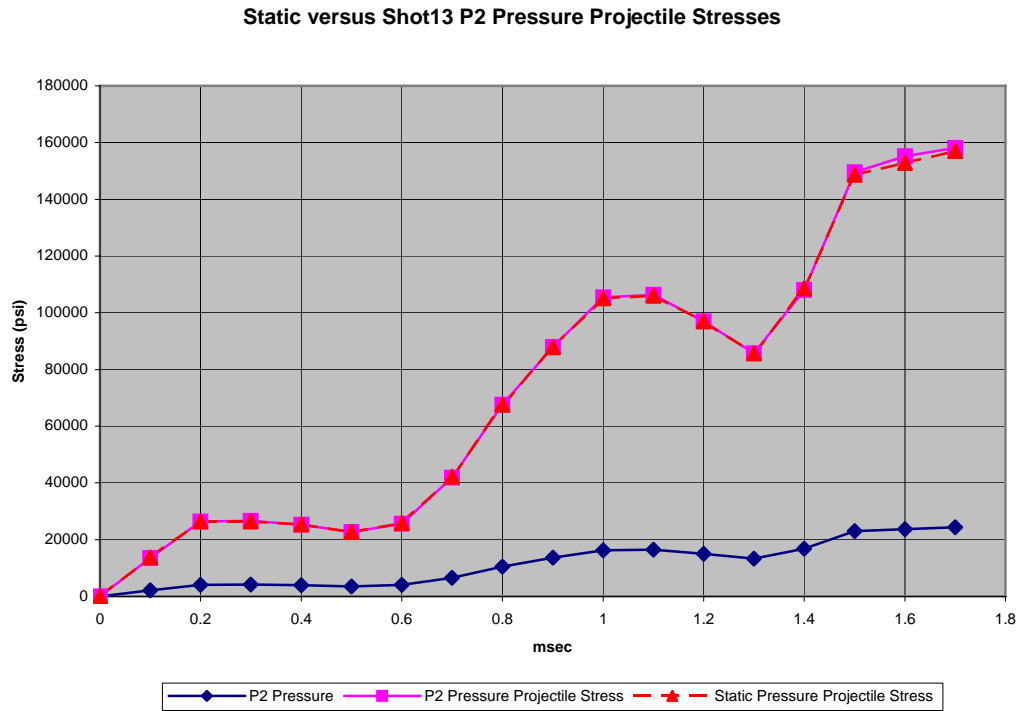


Figure 10 Shot 13 P2 pressure curve versus P2 stress and equivalent static stress

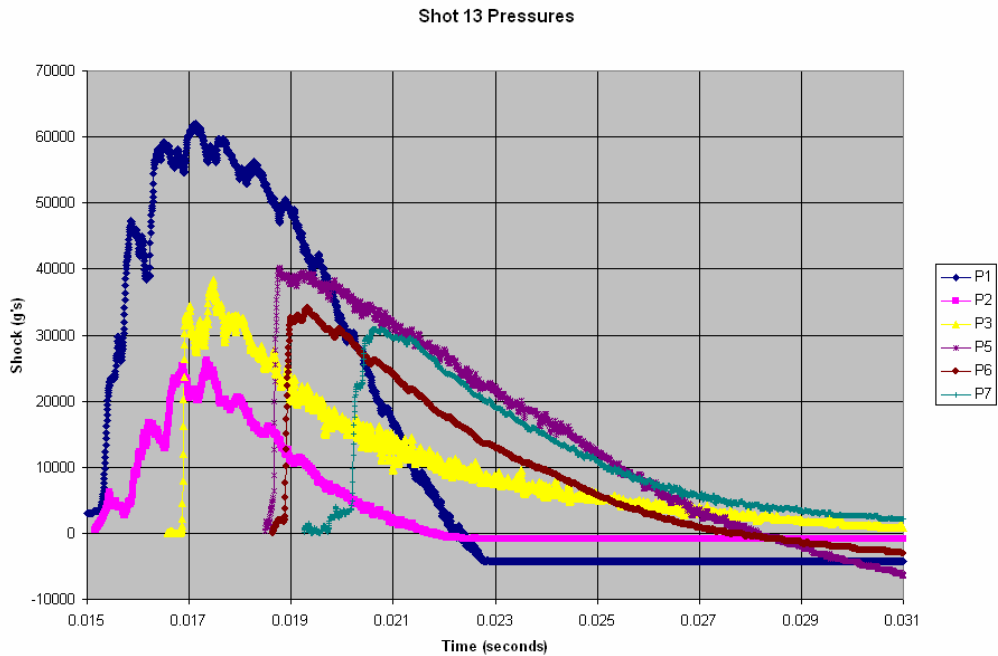


Figure 11 Shot 13 pressures at 0.66 MJ of projectile energy

The static pressure curve (dotted line) in Figure10 represents the linear curve fit stress predictions using the simplified P2 pressure data. The very small deviations between the static and dynamic analytical data indicate that Shot13 dynamic pressure variations do not have a major effect on projectile stresses. Comparisons of projectile firing points to FEA predictions and evaluation of barrel strain gage data support this conclusion. The projectile radar acceleration curve in the barrel (Figure 12) also shows little impact from the pressure curve variations.

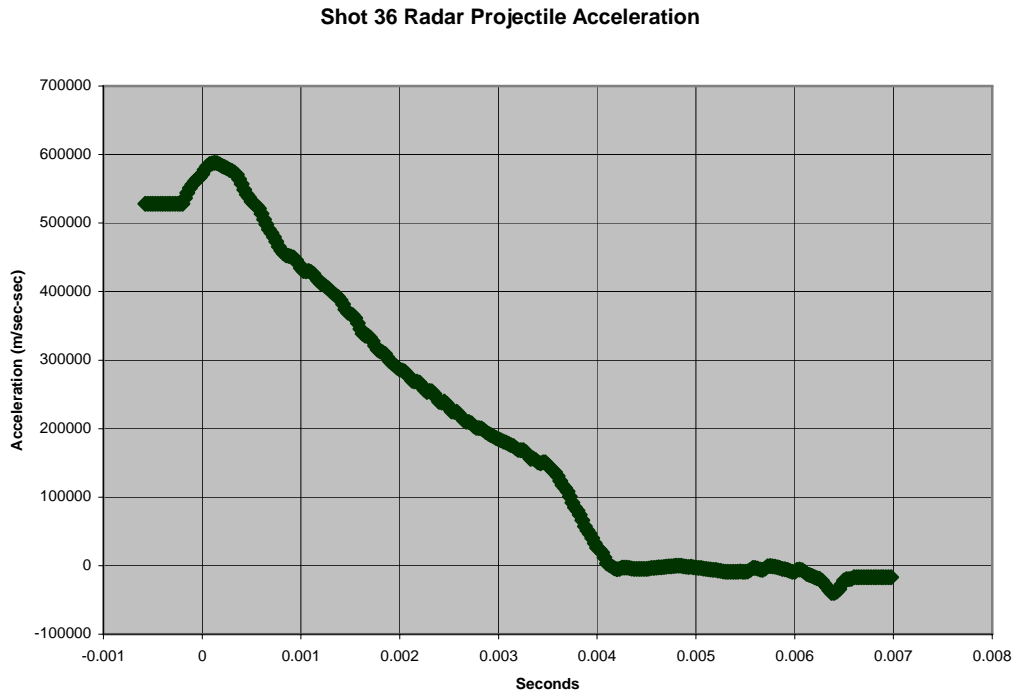


Figure 12 CLGG45 radar projectile acceleration in barrel

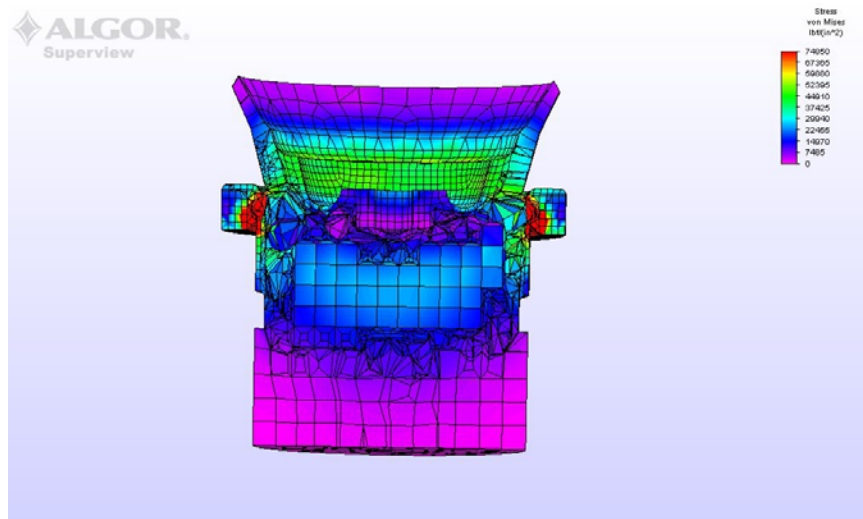


Figure 13 Shear ring projectile cross section at firing point.



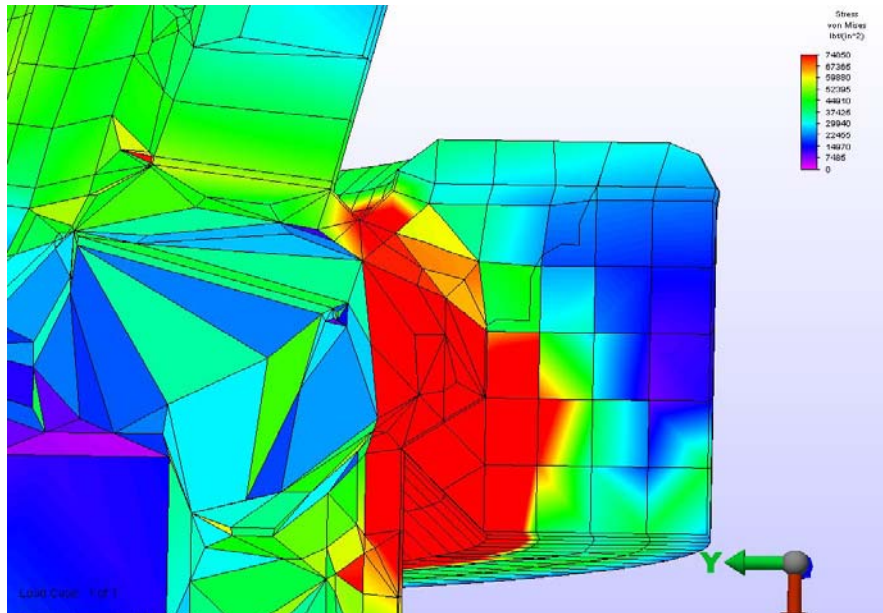


Figure 14 Shear ring cross section at firing point.

Figures 13 and 14 illustrate a shear ring projectile that provides more firing point consistency than the folding skirt projectile but still uses the folding skirt to reduce combustion gas blow-by.

### CLGG 45mm Autoloader FEA

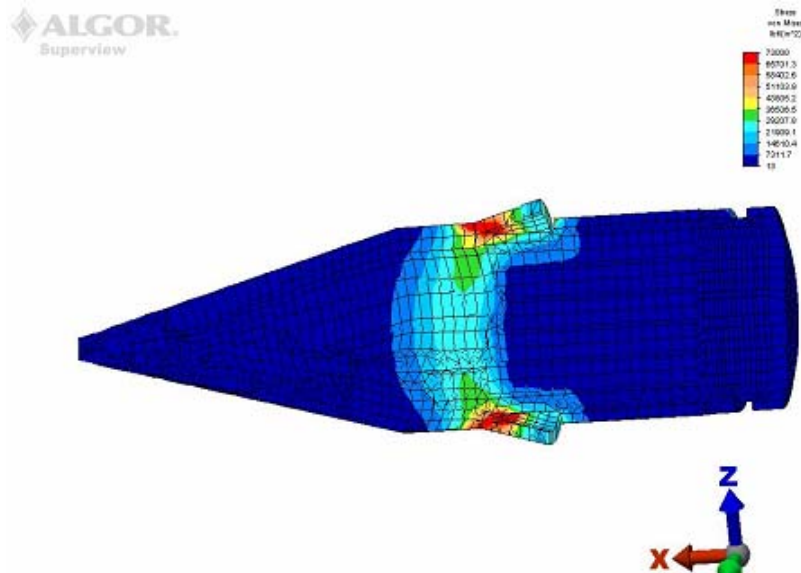


Figure 15 Original autoloader projectile cross section – no leakage between skirt and cartridge

LGOR.  
rview

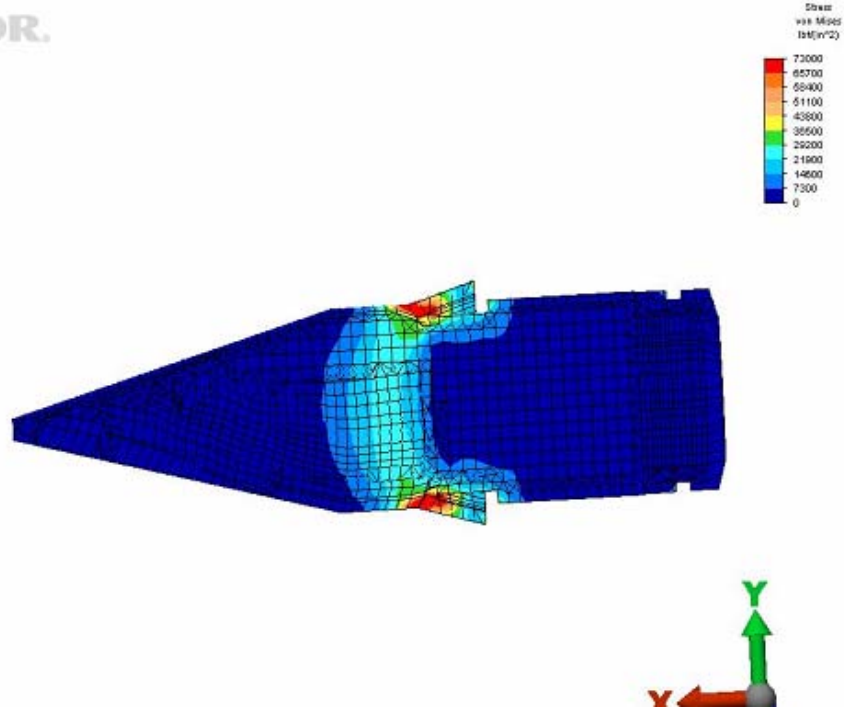


Figure 16 Autoloader projectile cross section – half pressure between skirt and cartridge

DR.

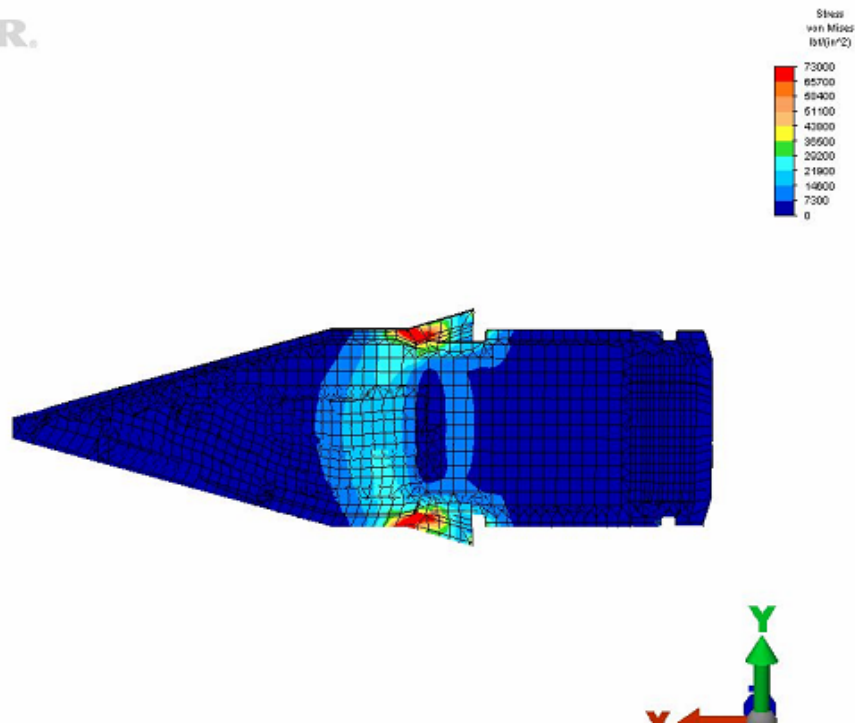


Figure 17 Autoloader projectile cross section – full pressure between skirt and cartridge

The above folding skirt autoloader projectile had a 7.4% lower firing pressure with leakage.

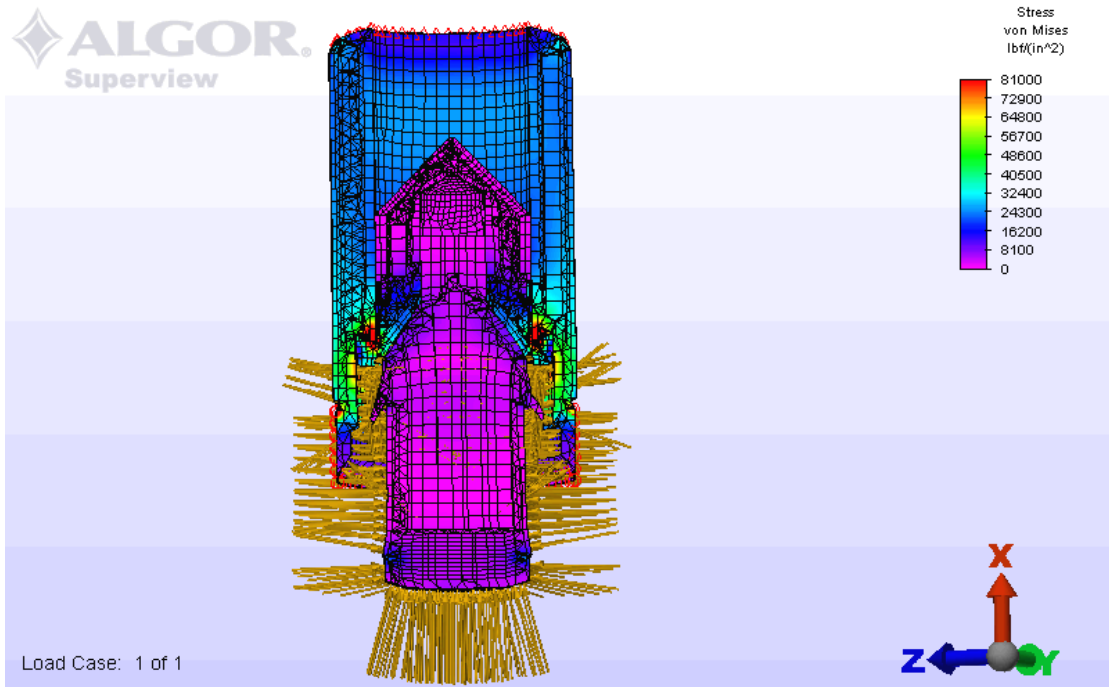


Figure 18 New shear ring autoloader projectile cross section at 21000 psi firing pressure

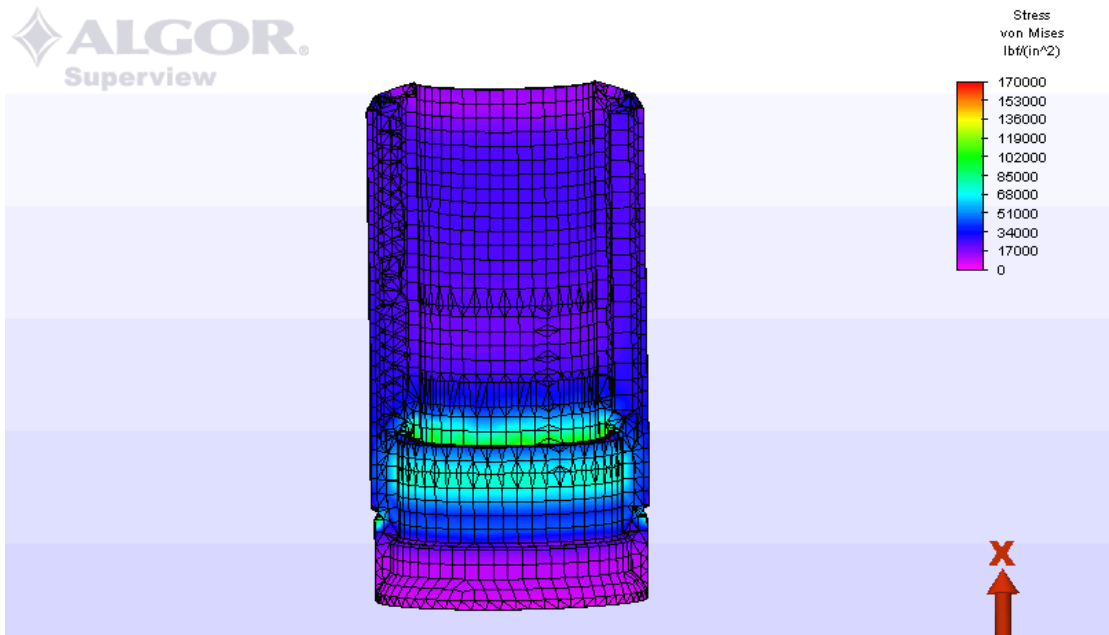


Figure 19 Shear ring autoloader cartridge cross section at 21000 psi firing pressure

Figure 18 shows the shear ring autoloader cartridge-projectile assembly stresses at 21000 psi of combustion chamber pressure. The firing point consistently occurs in the 21000 to 22000 psi pressure range. Figure 19 includes the stress contours for the cartridge, which are well below

yield. The Lexan rear projectile piece in Figure 20 shifts the center of gravity further forward to provide more stability than a one-piece titanium projectile. The design had to be adjusted to prevent the static firing point stresses from breaking this piece in two.

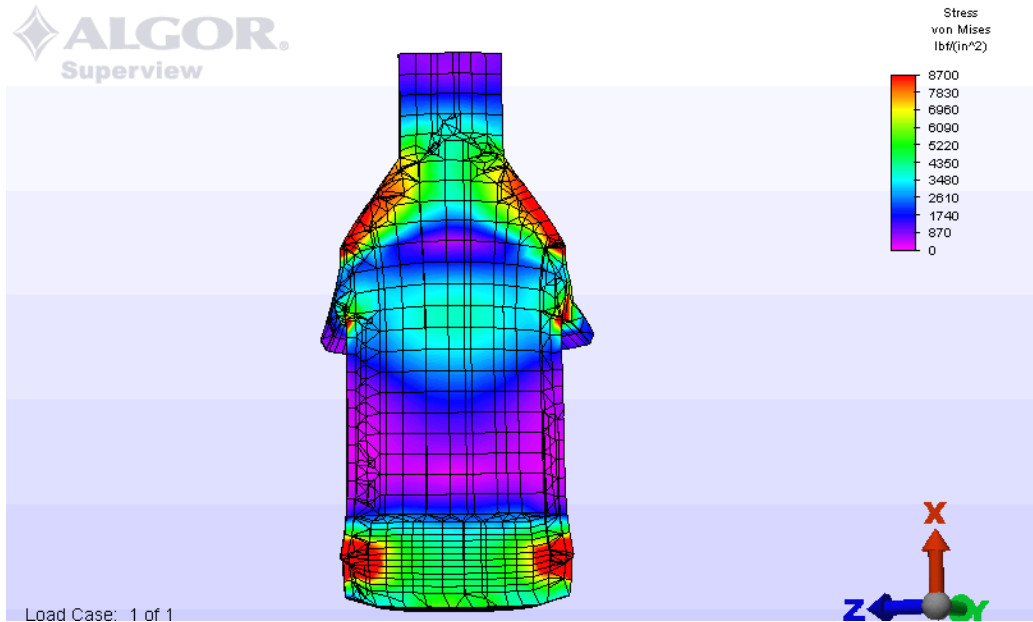


Figure 20 Shear ring autoloader Lexan rear projectile piece cross section at 21000 psi

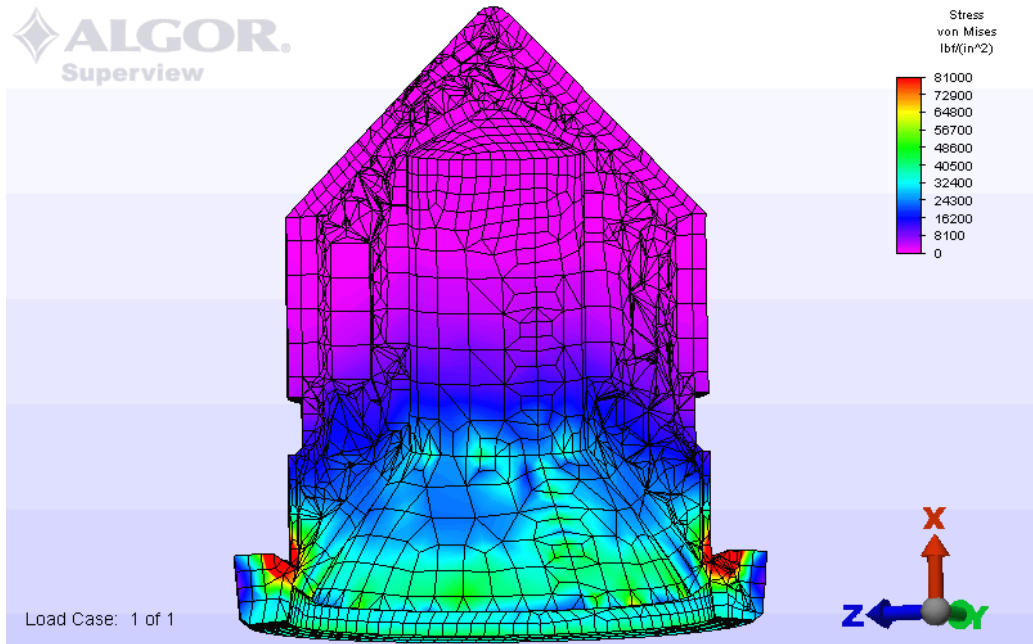


Figure 21 Shear ring autoloader titanium front projectile piece cross section at 21000 psi

Figure 22 shows the stress contours in the titanium shear ring at the firing point. This geometry required FEA optimization to constrain the stresses to a limited area to provide a clean shear

plane for the sealing skirt to pass through, to minimize erosion and debris generation from ragged shear edges and to shear at the correct pressure. An animation reveals a very focused progression of shearing stresses through the shear plane.

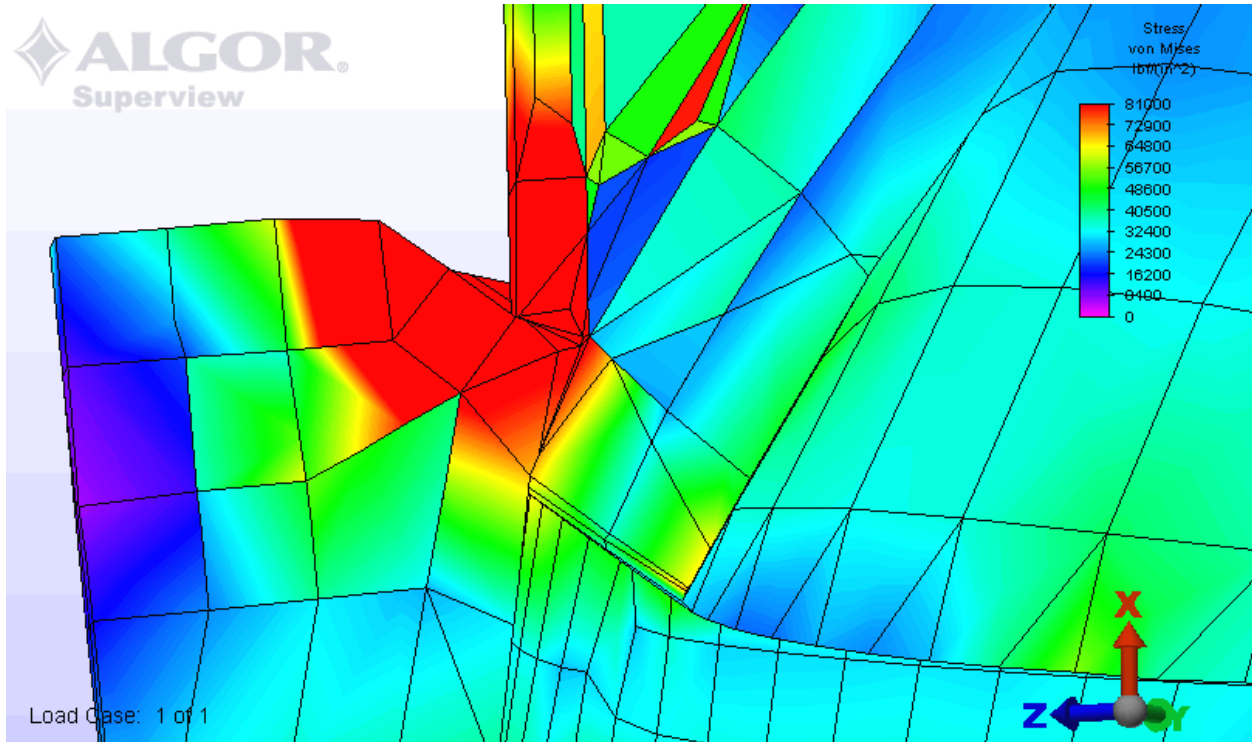


Figure 22 Close view of shear ring stress on autoloader projectile cross section at 21000 psi

The CLGG45 autoloader structural members in Figure 23 that constrain the sealing forces and the gear housing in Figure 24 have stresses below the 48000 psi fatigue limit at 1000 shots.

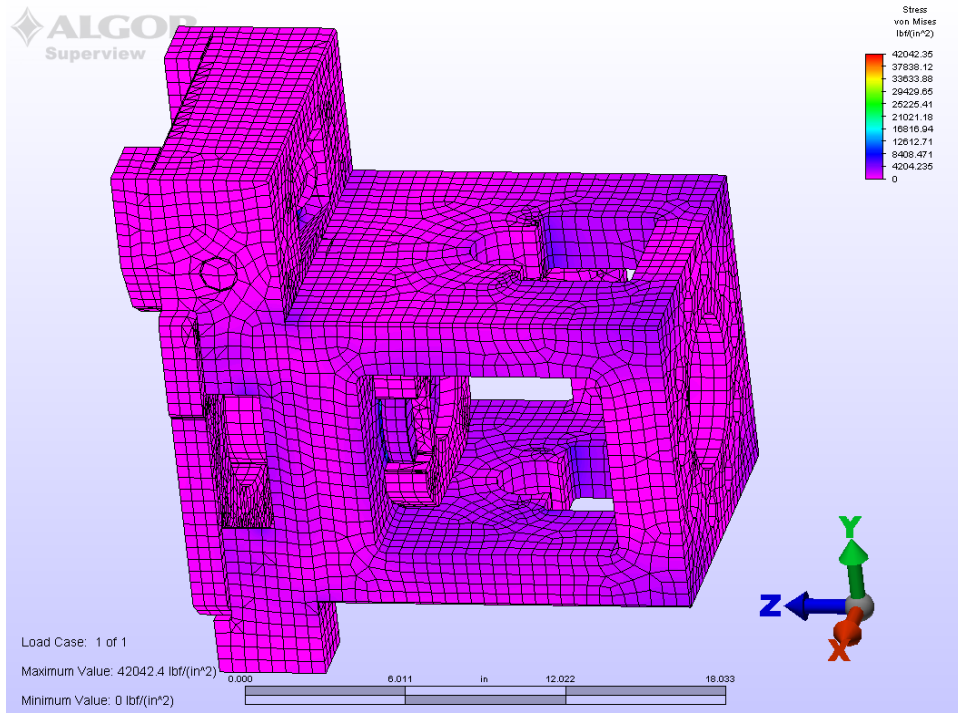


Figure 23 Autoloader stresses at 59000 pounds of sealing force

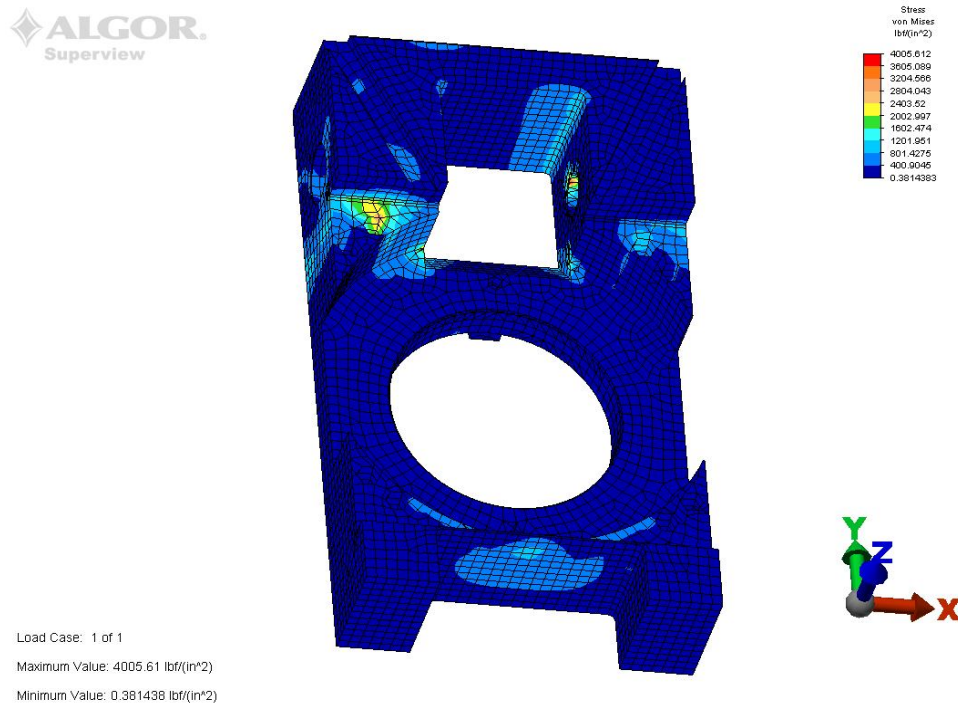


Figure 24 Autoloader gear housing stresses at 59000 pounds of sealing force

Poppet FEA for CLGG45 Cryogenic Injection

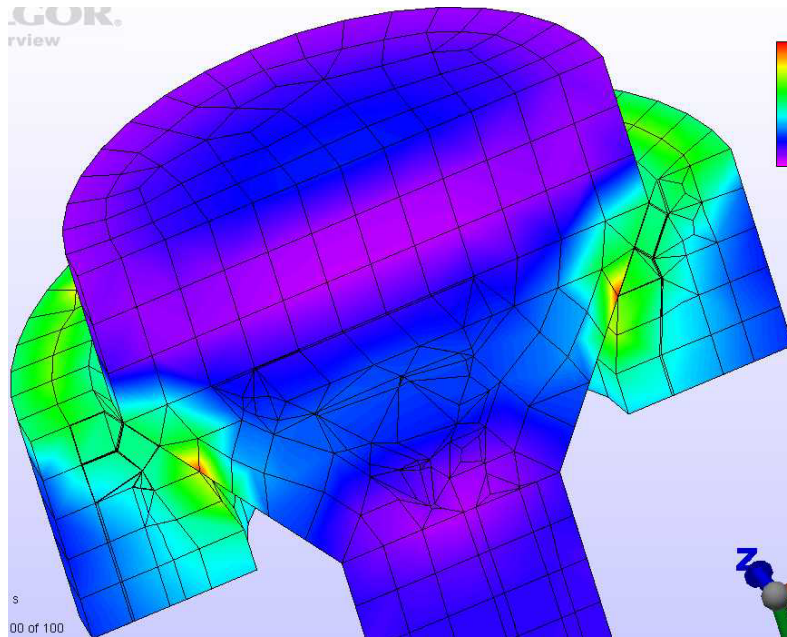


Figure 25 First poppet design cross section at 34,000 psi pressure

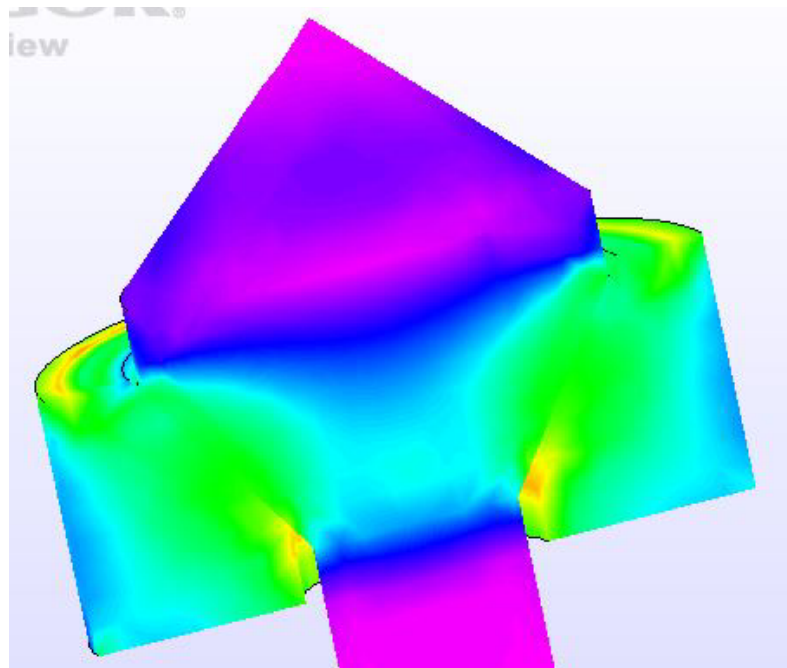


Figure 26 Final poppet design cross section at 80,000 psi pressure

The initial poppet design in Figure 25 had a stress riser on the seat that would have caused a failure at 34,000 psi. Adjustments in the seat angle reduced the stresses but did not correct the uneven stress distribution. The conical top shown in Figure 26 added proportionate stiffness in the areas of highest deflection, minimizing uneven poppet deformation in the seat area and

resulting in a much more even distribution of stresses across the seat. The stress contours in Figures 27 and 28 illustrate that the final poppet design will handle 2.4 times higher pressures than the first poppet design while maintaining similar stress levels.

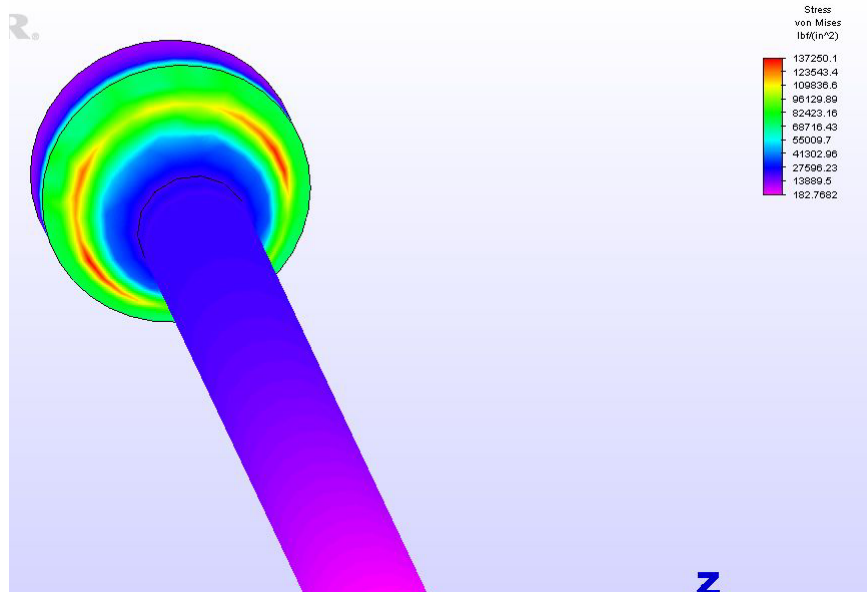


Figure 27 First poppet at 34,000 psi pressure

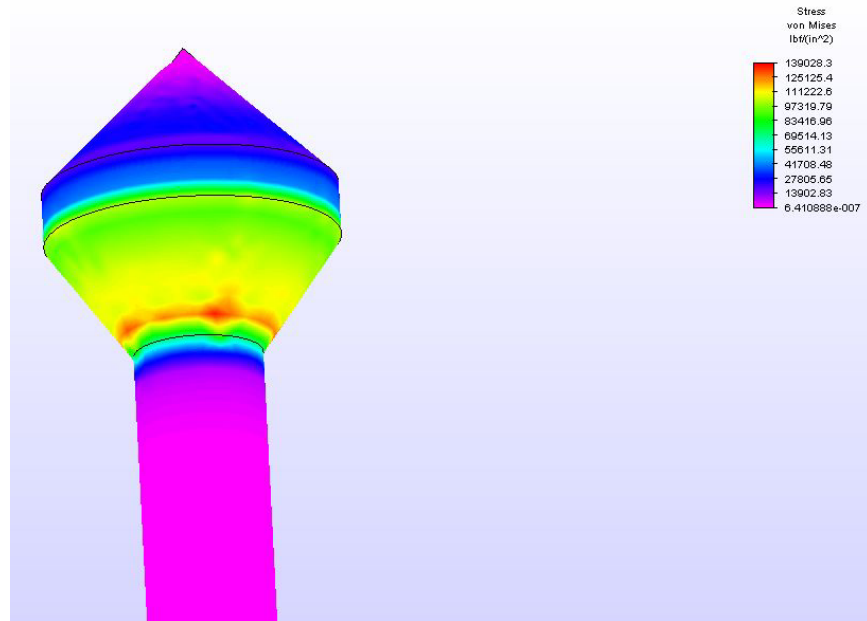


Figure 28 Final poppet at 80,000 psi pressure



Initial linear dynamics FEA on the first poppet applied pressure loads according to the 34000 psi pressure curve in Figure 29 while the final design used the 80000 psi pressure curve in Figure 30. Additional FEA trials on the first poppet with the Figure 30 curve scaled to 34000 psi provided stress versus pressure results almost identical to results for the Figure 29 curve.

**P1 Shot13 Poppet Curve**

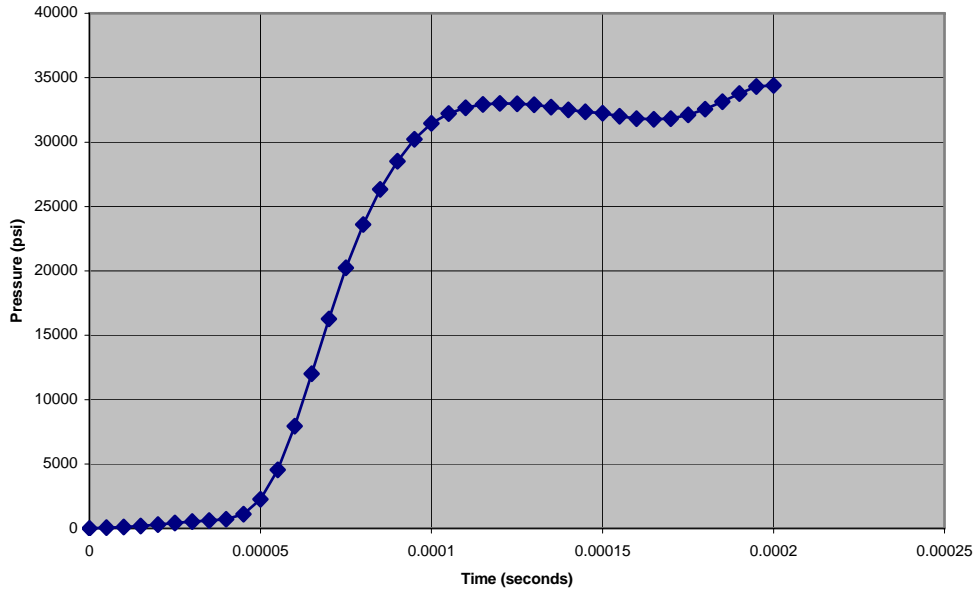


Figure 29 First poppet design combustion pressure curve

**Poppet P1 Pressure Curve - 80000 psi max**

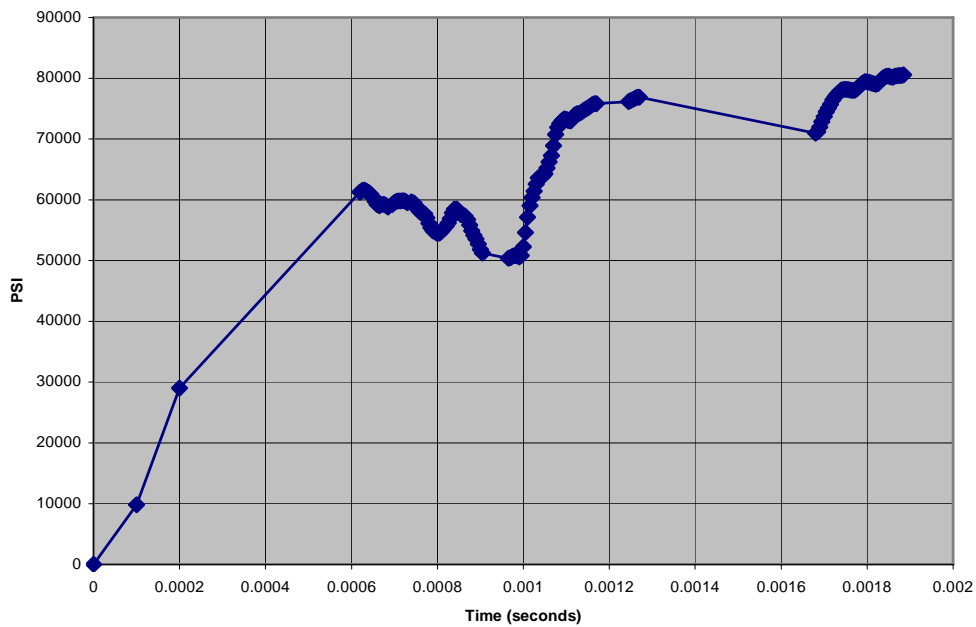


Figure 30 Final poppet design combustion pressure curve

### CLGG155 FEA

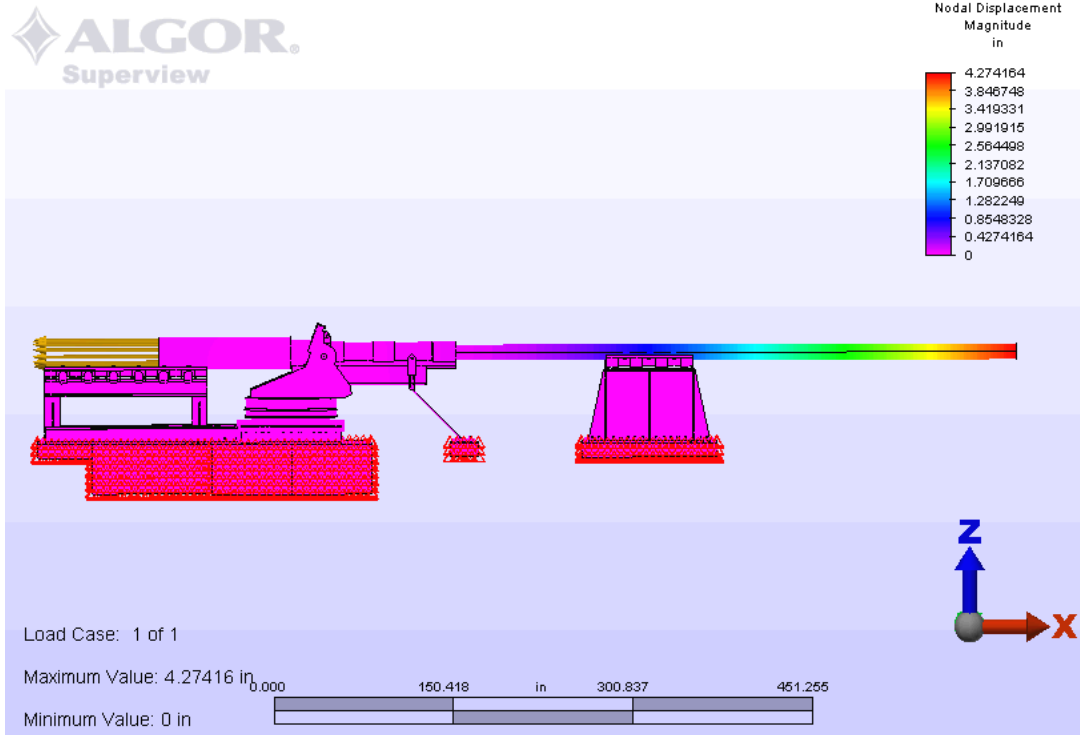


Figure 31 CLGG155 static recoil deflections at 63MJ projectile energy

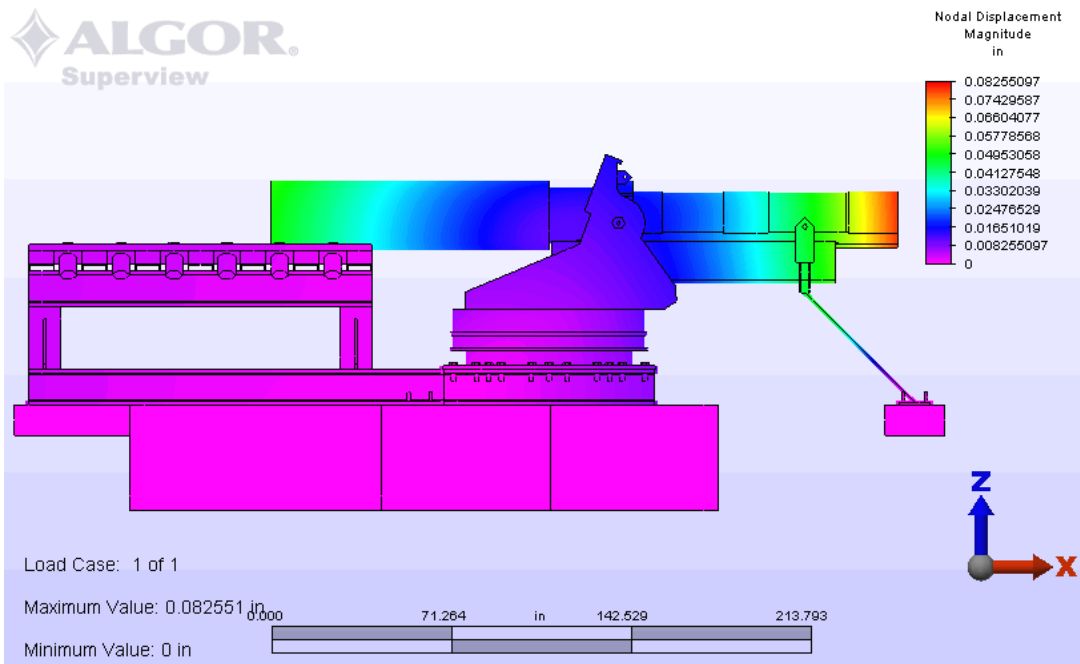


Figure 32 CLGG155 static recoil deflections at 63MJ projectile energy

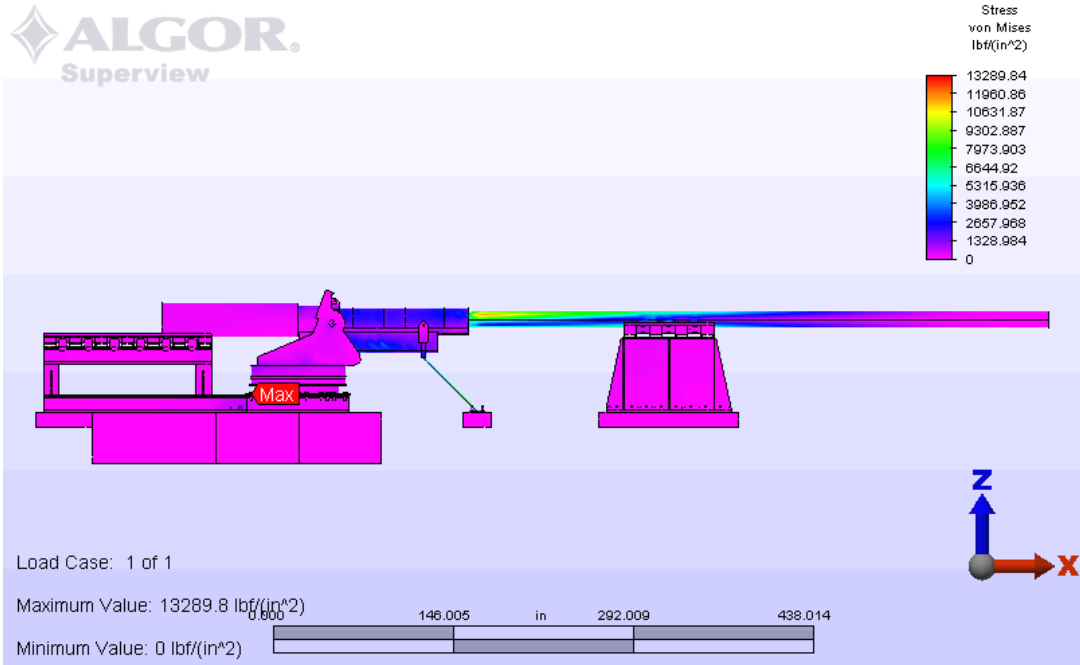


Figure 33 CLGG155 static recoil von Mises stresses at 63MJ projectile energy

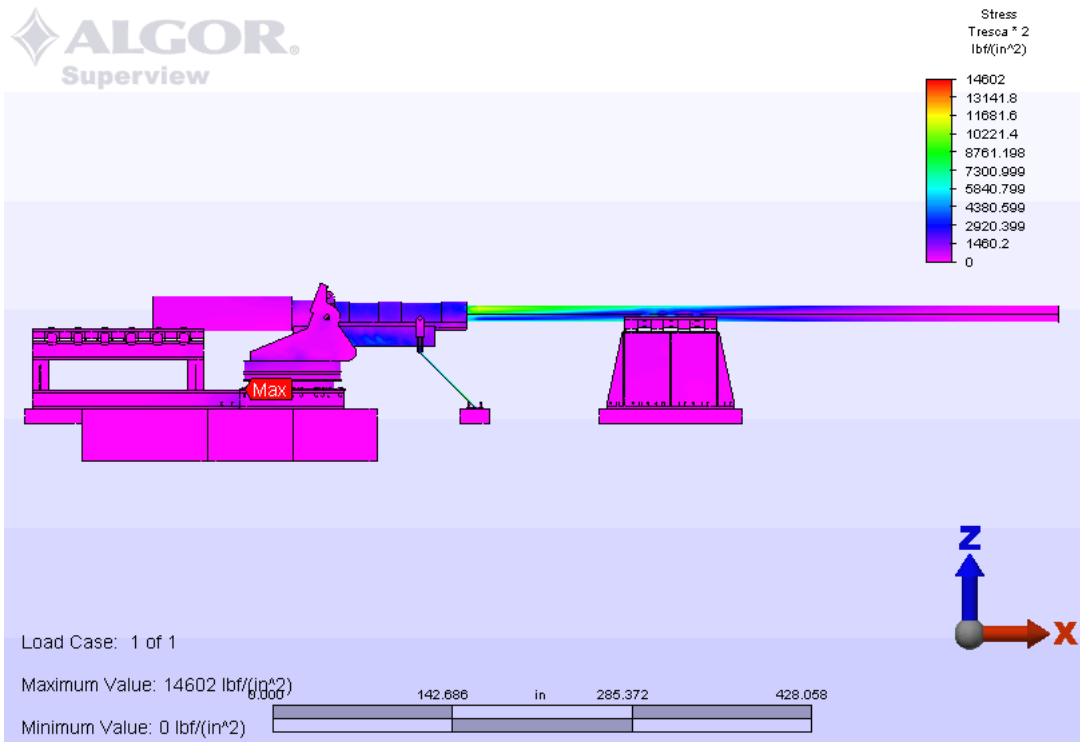


Figure 34 CLGG155 63MJ static recoil Tresca (twice shear) stresses

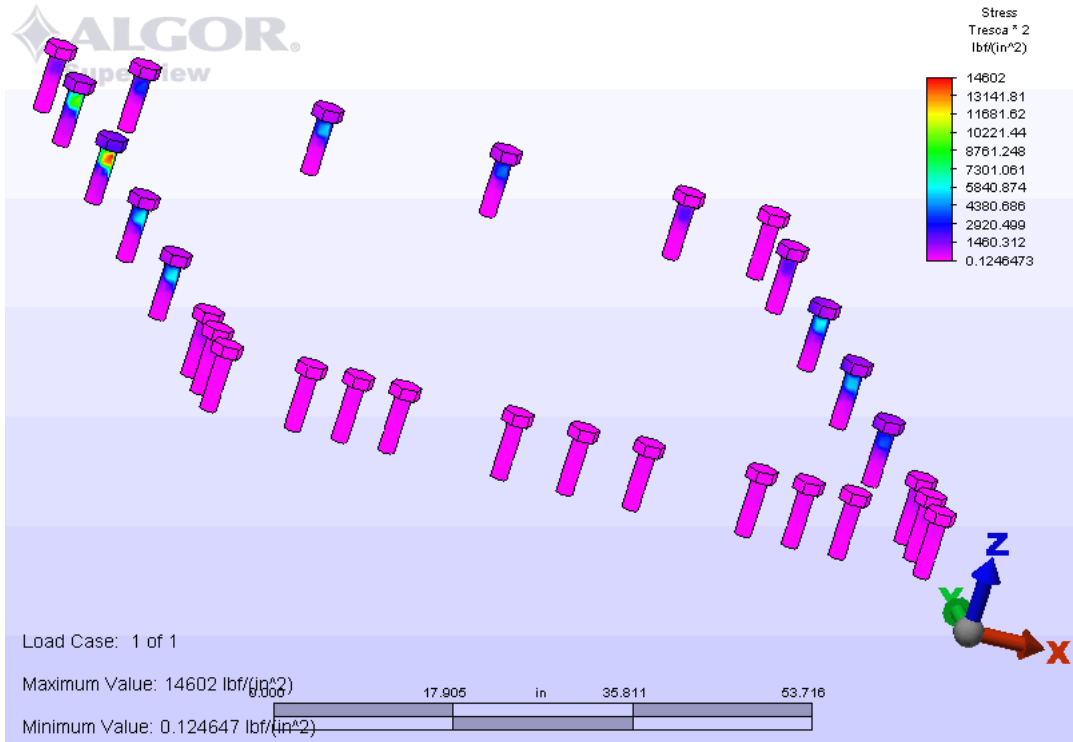


Figure 35 Static recoil 4340 mounting bolt Tresca – 3.2 factor of safety (fs) 1000 shot HCF

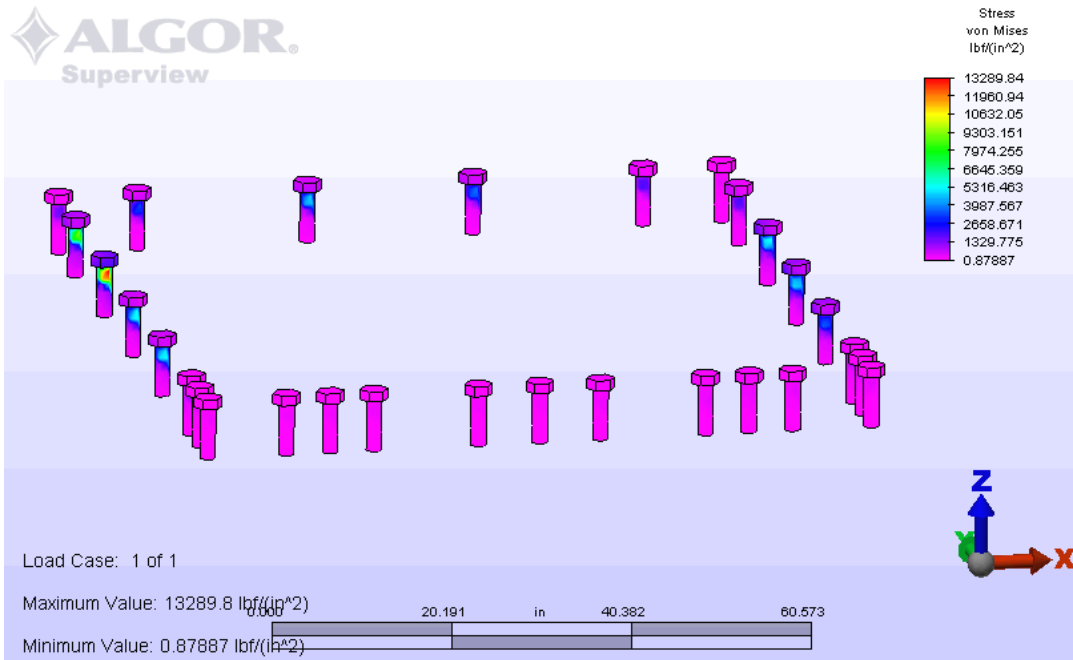


Figure 36 Static 63MJ recoil 4340 mounting bolt von Mises – 3.5 fs 1000 shot HCF

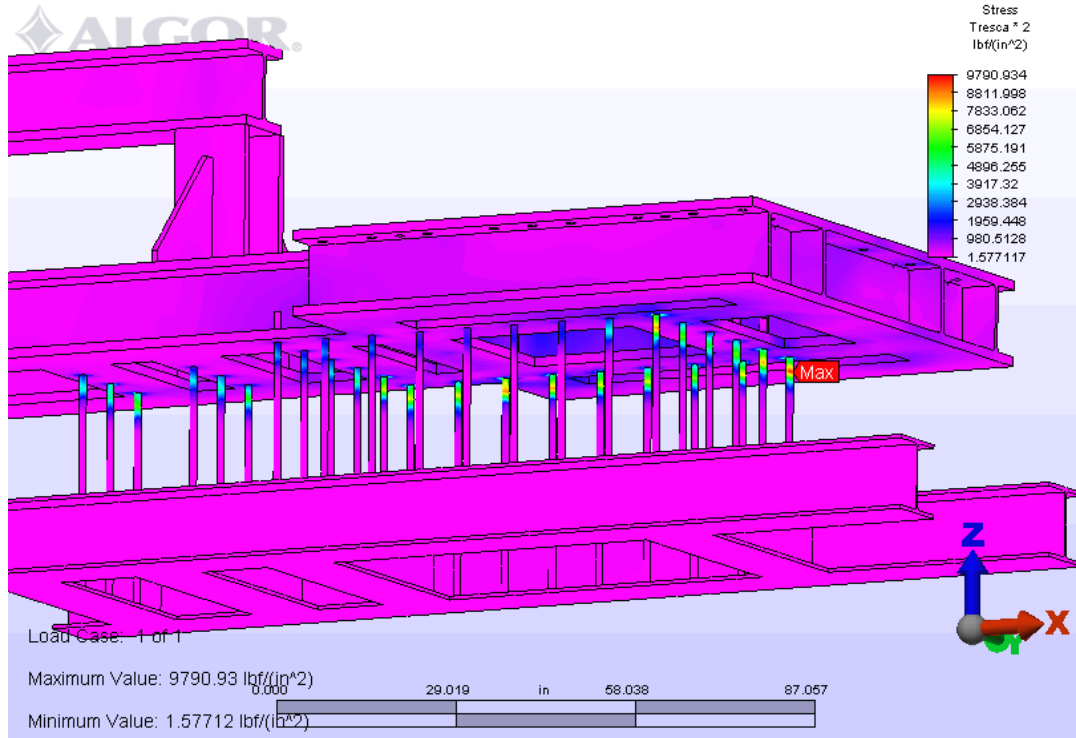


Figure 37 Static 63MJ recoil A490 mounting stud Tresca stresses – 4.0 fs HCF

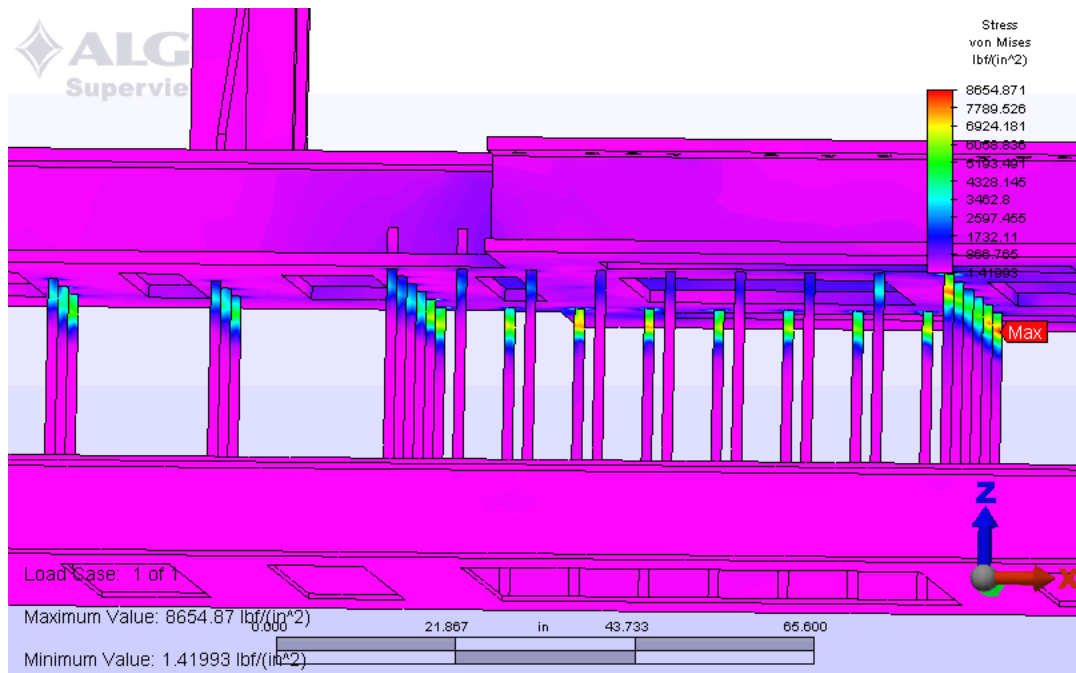


Figure 38 Static 63MJ recoil A490 mounting stud von Mises stresses – 4.6 fs HCF

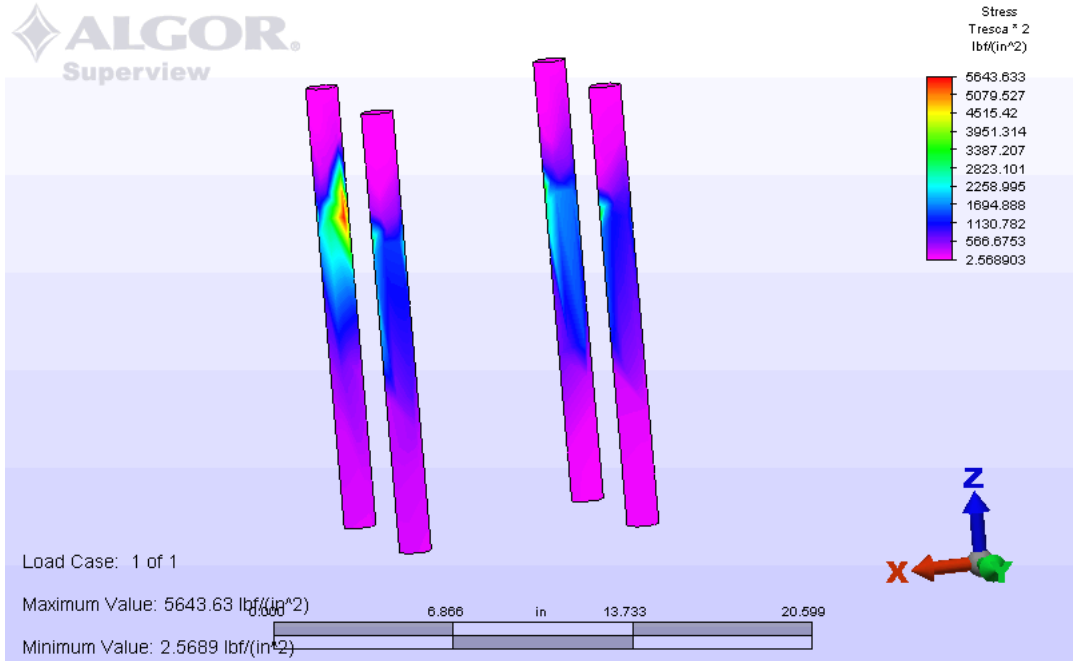


Figure 39 Static 63MJ recoil sleigh beam 4340 tie-down stud Tresca – 8.4 fs 1000 shot HCF

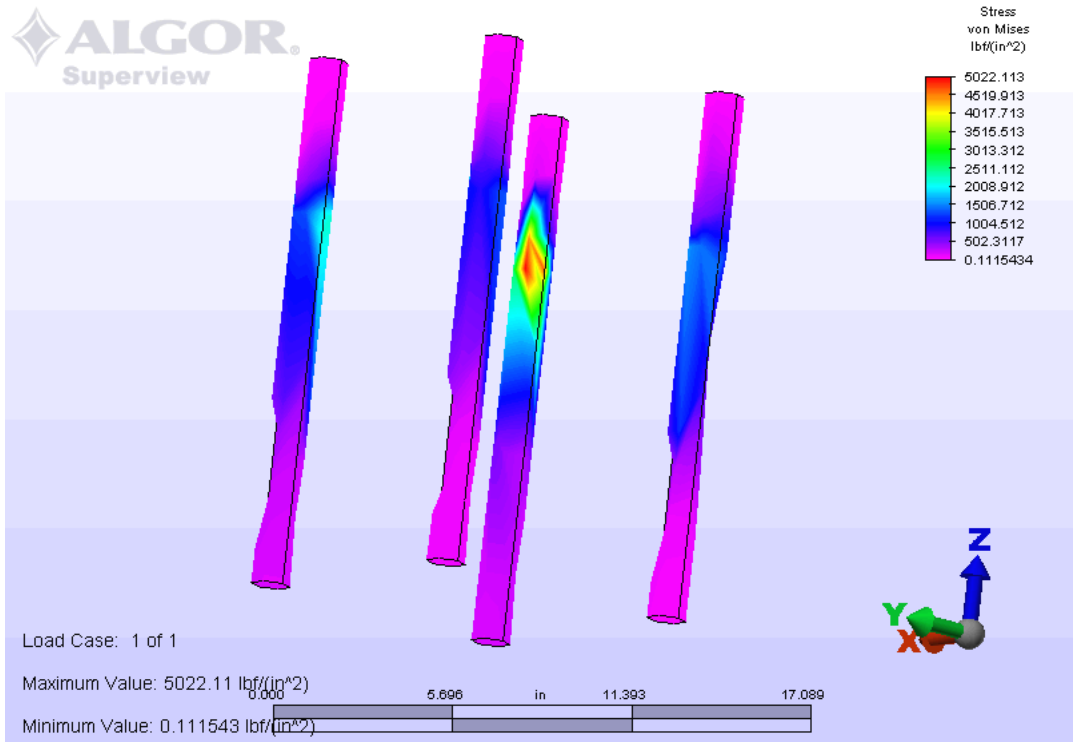


Figure 40 Static 63MJ recoil beam 4340 tie-down stud von Mises – 9.5 fs 1000 shot HCF

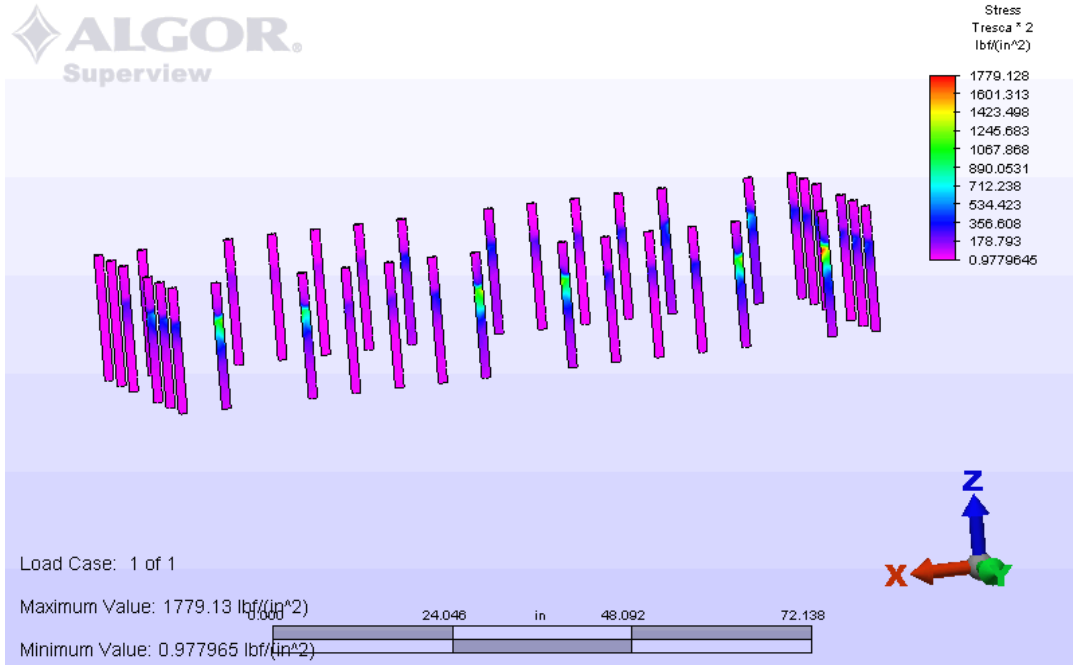


Figure 41 CLGG155 63MJ static recoil barrel support 4340 stud Tresca stresses

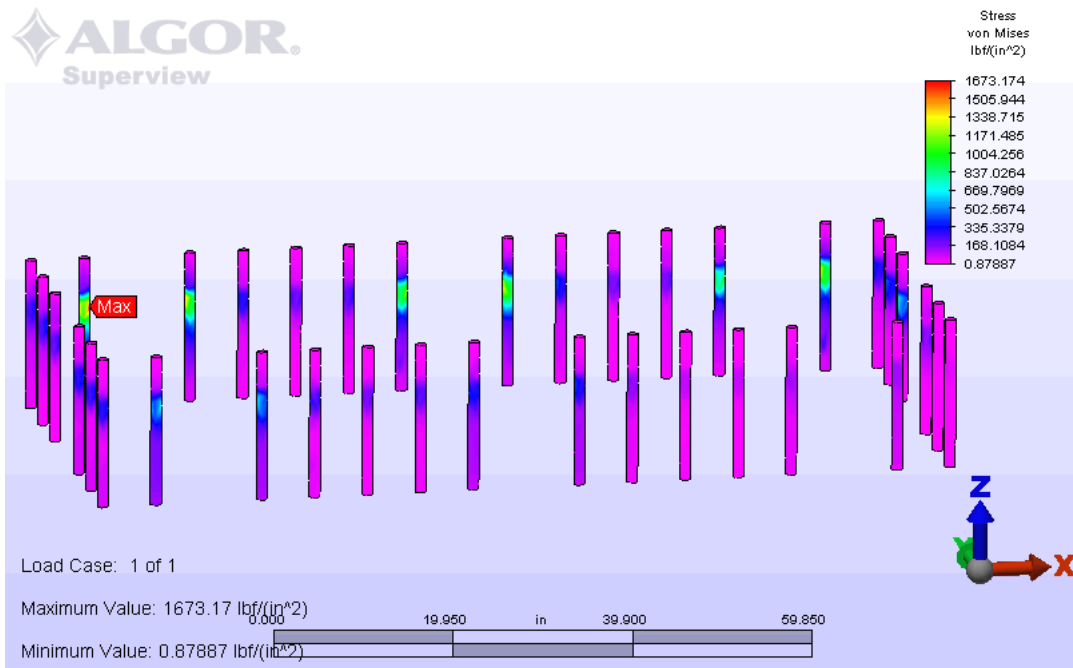


Figure 42 CLGG155 63MJ static recoil barrel support 4340 stud von Mises stresses

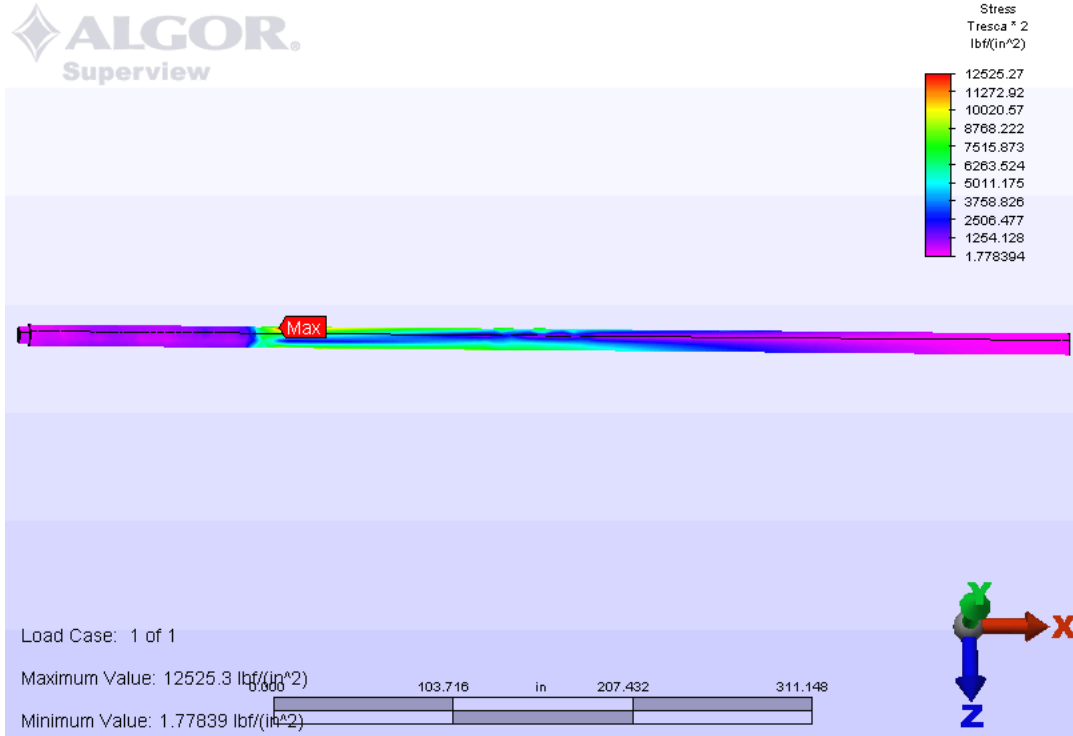


Figure 43 Static 63MJ recoil barrel von Mises stresses – 3.8 fs 1000 shot HCF

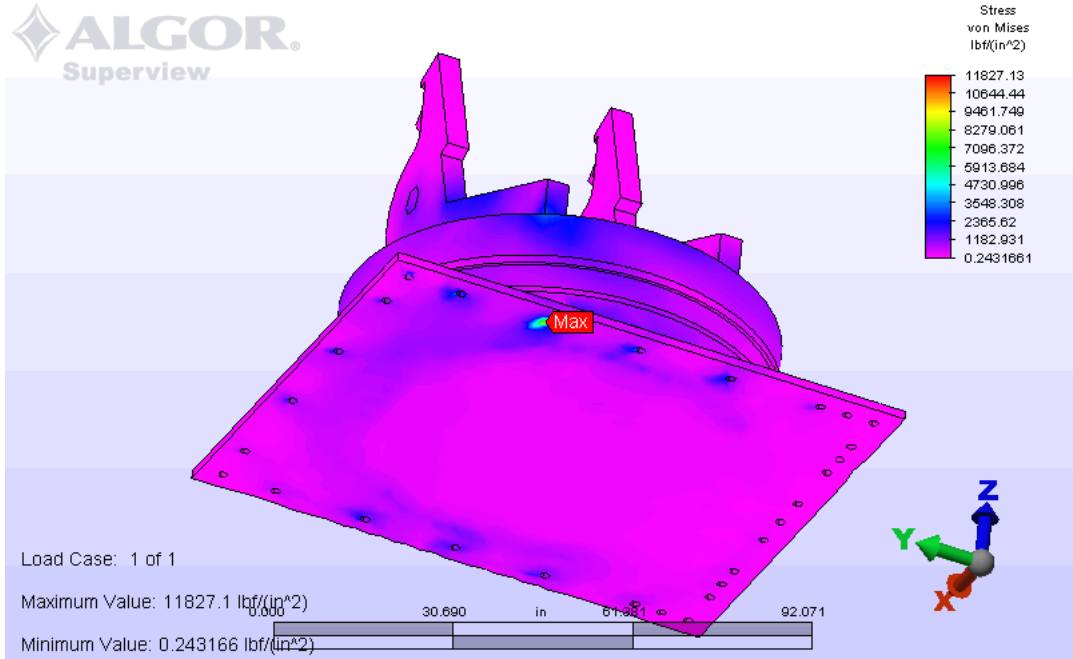


Figure 44 Static 63MJ recoil preexisting mount von Mises stresses



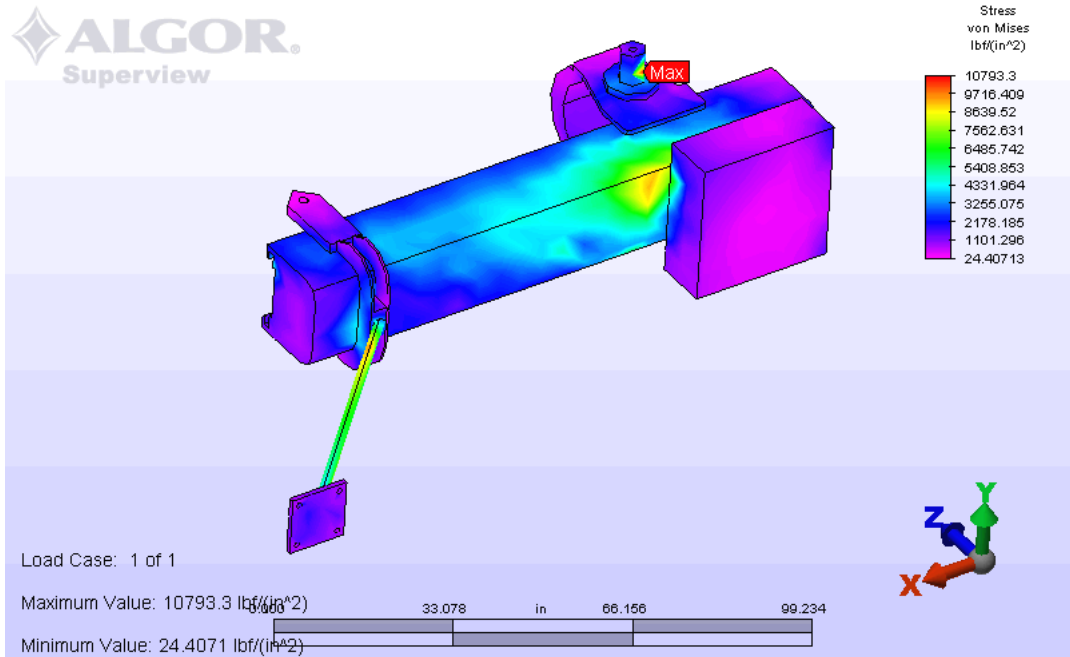


Figure 45 Static 63MJ recoil preexisting sleigh beam-tie down von Mises stresses

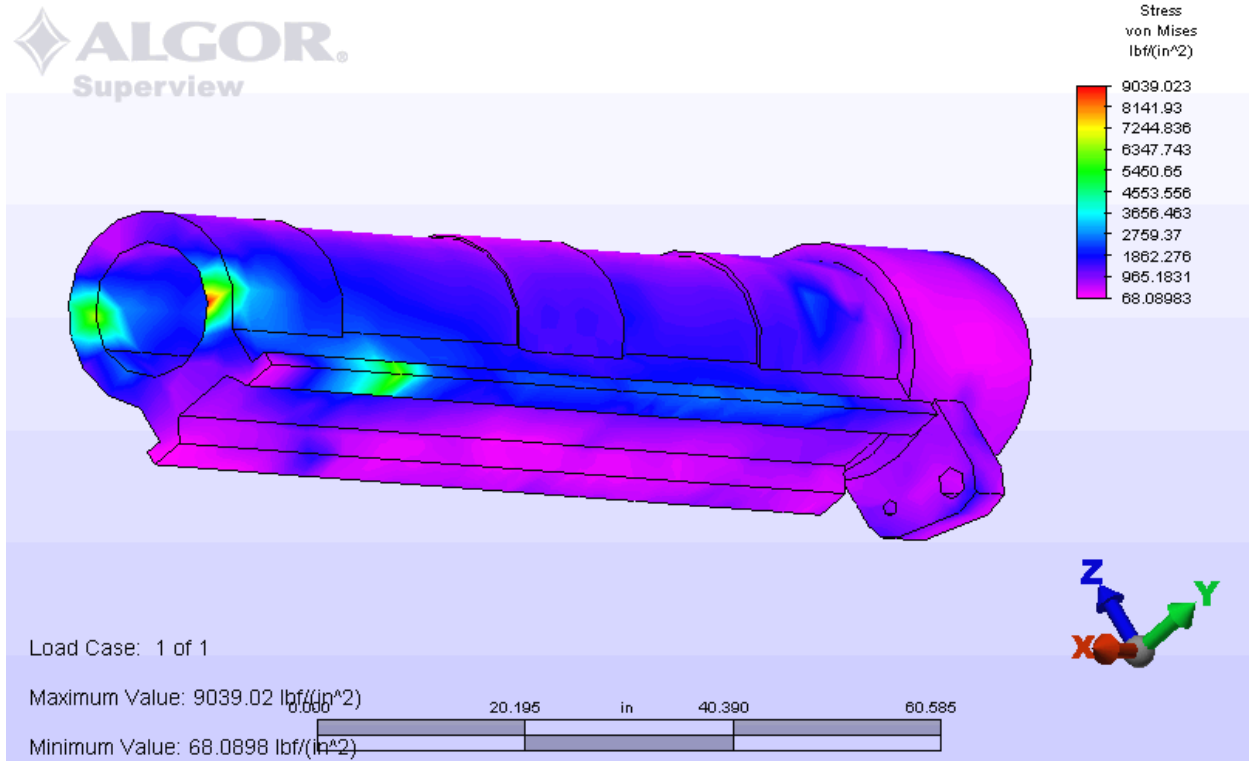


Figure 46 Static 63MJ recoil preexisting sleigh von Mises stresses

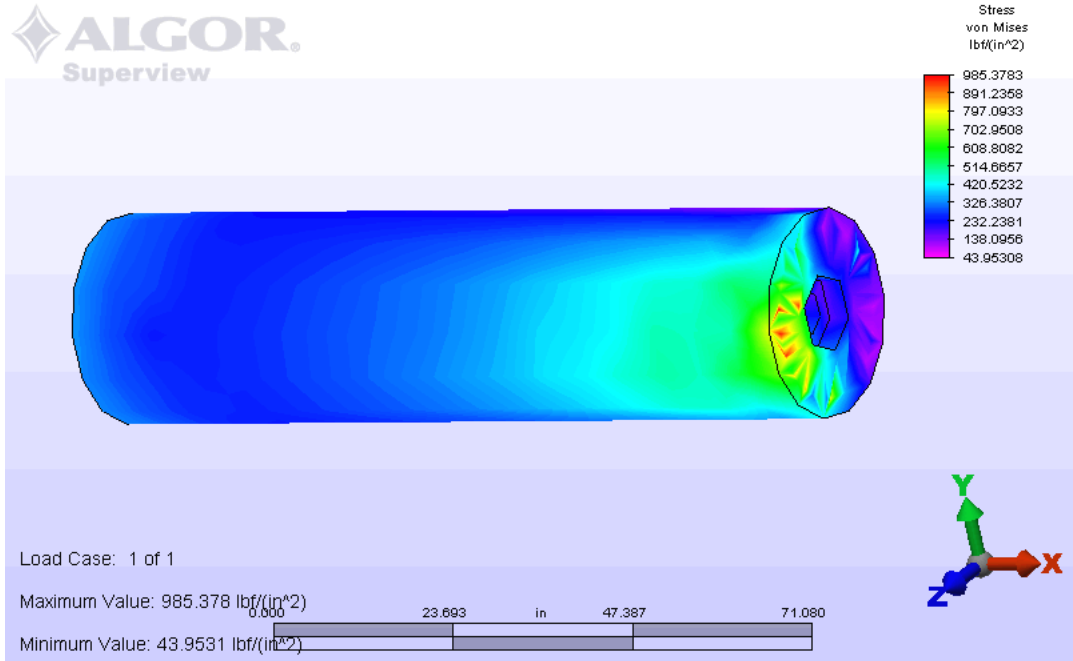


Figure 47 Static 63MJ recoil 4340 chamber von Mises stresses

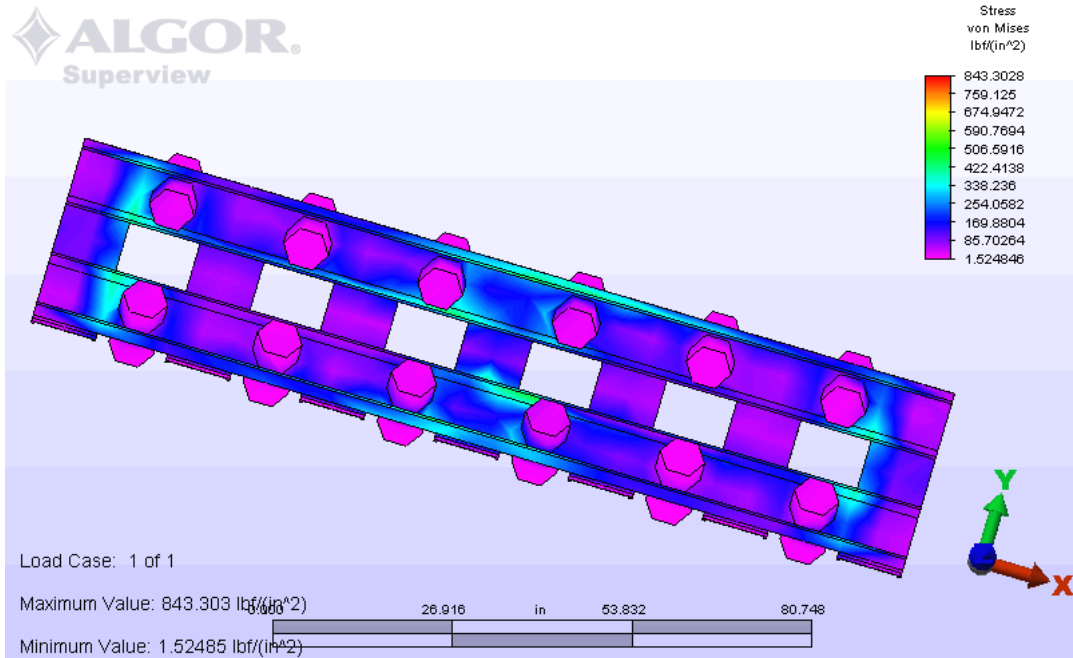


Figure 48 Static 63MJ recoil chamber support von Mises stresses

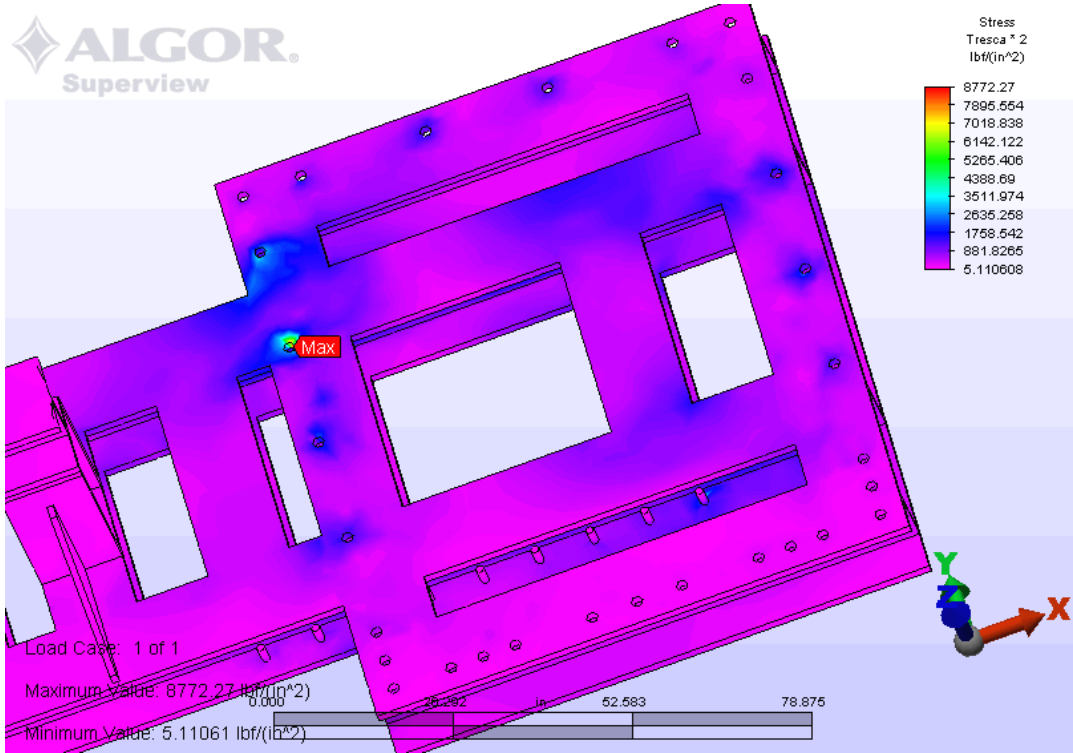


Figure 49 Static 63MJ recoil A36 transition beams Tresca – 2.4 fs 1000 shot HCF

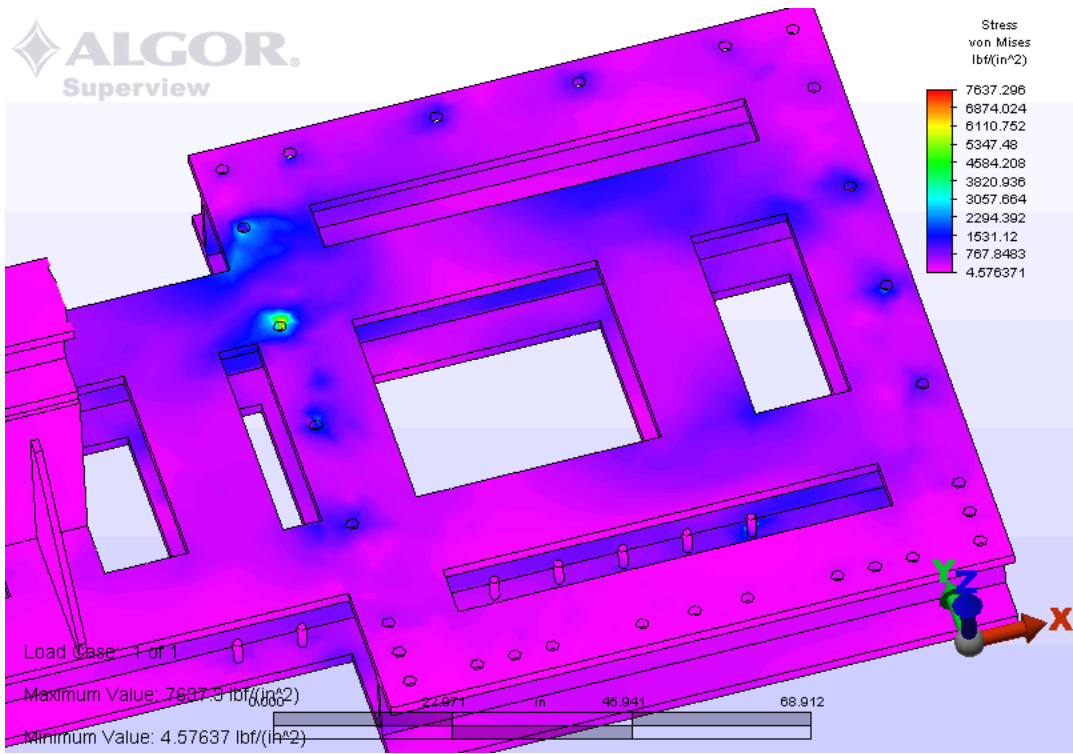


Figure 50 Static 63MJ recoil A36 transition beams von Mises – 2.8 fs 1000 shot HCF

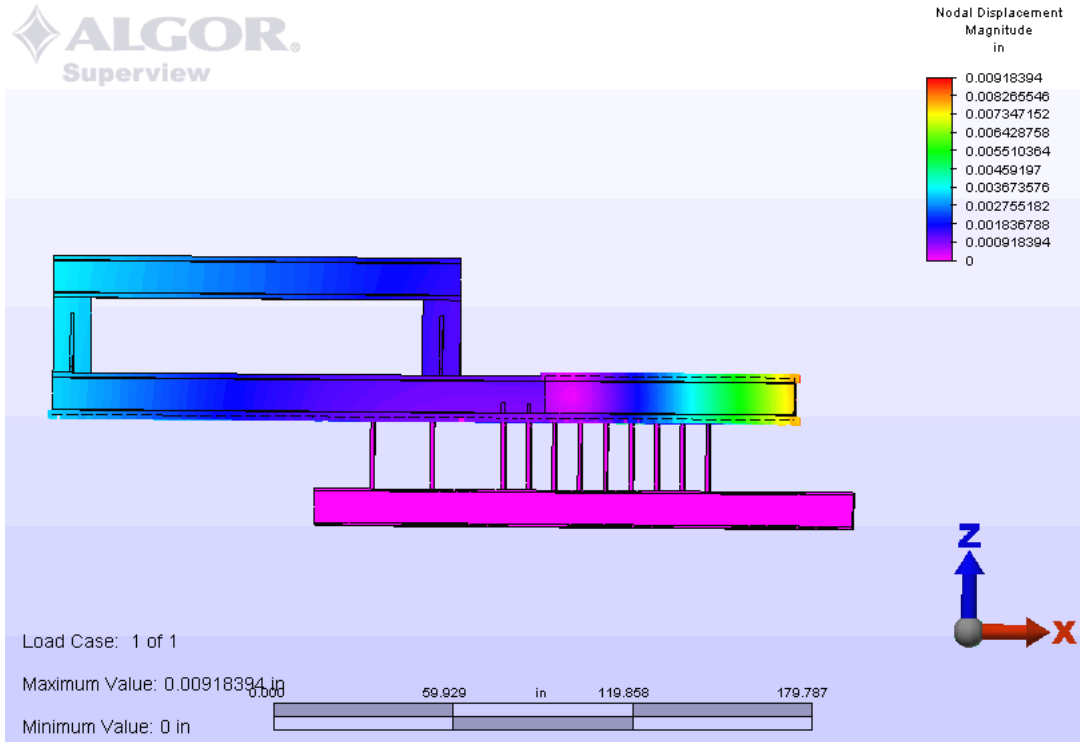


Figure 51 Static 63MJ recoil A36 transition beam deflections

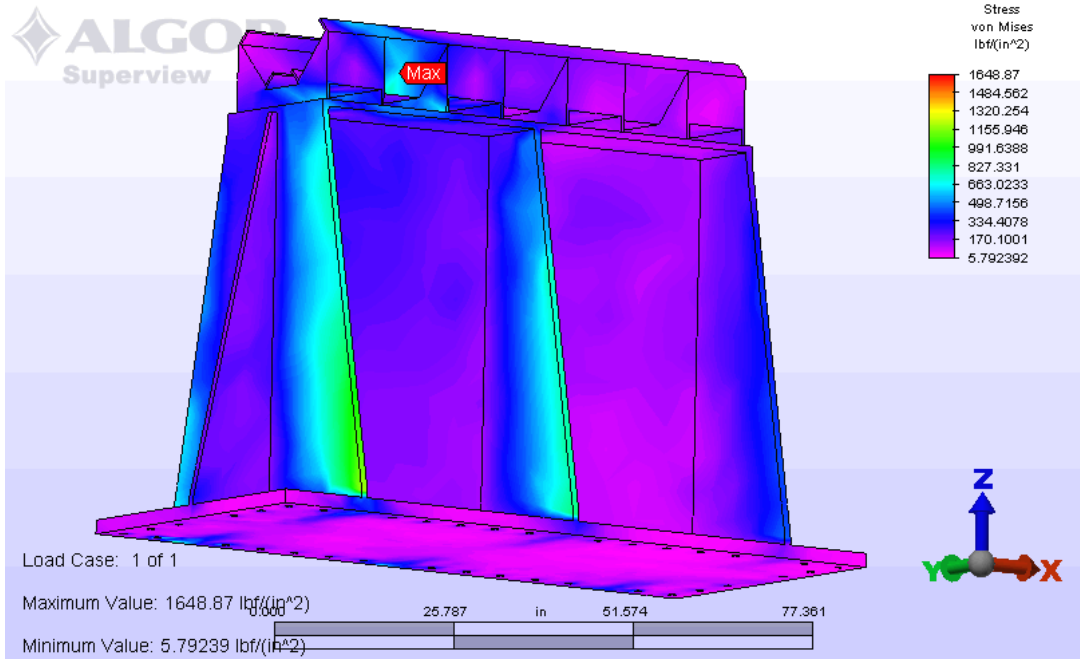


Figure 52 Static 63MJ recoil A36 barrel support von Mises stresses

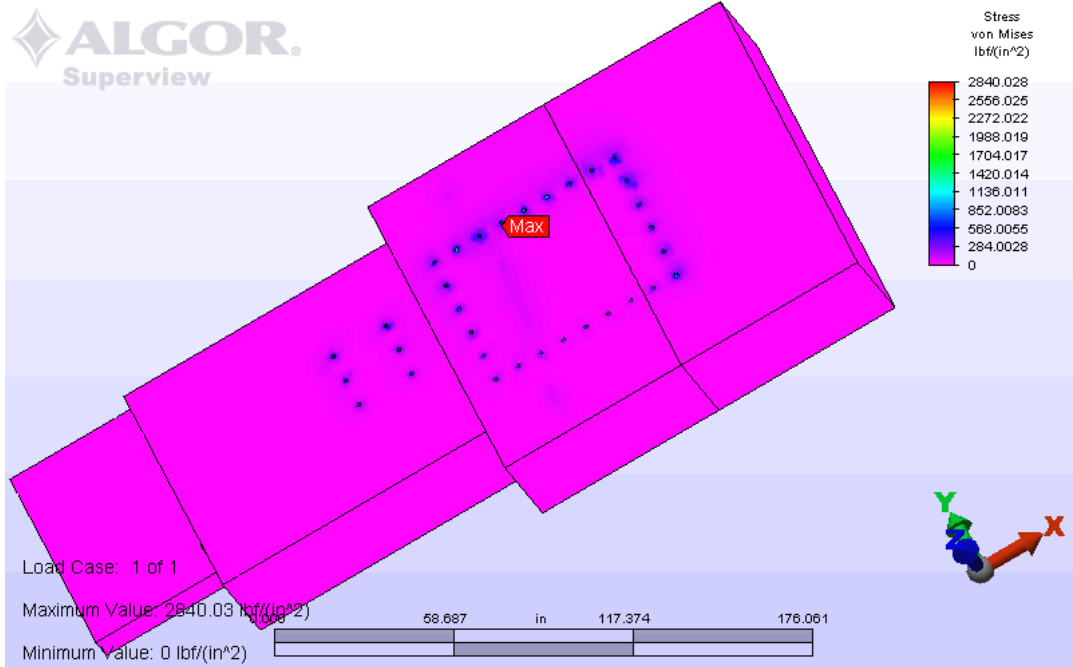


Figure 53 Static 63MJ recoil concrete foundation von Mises stresses

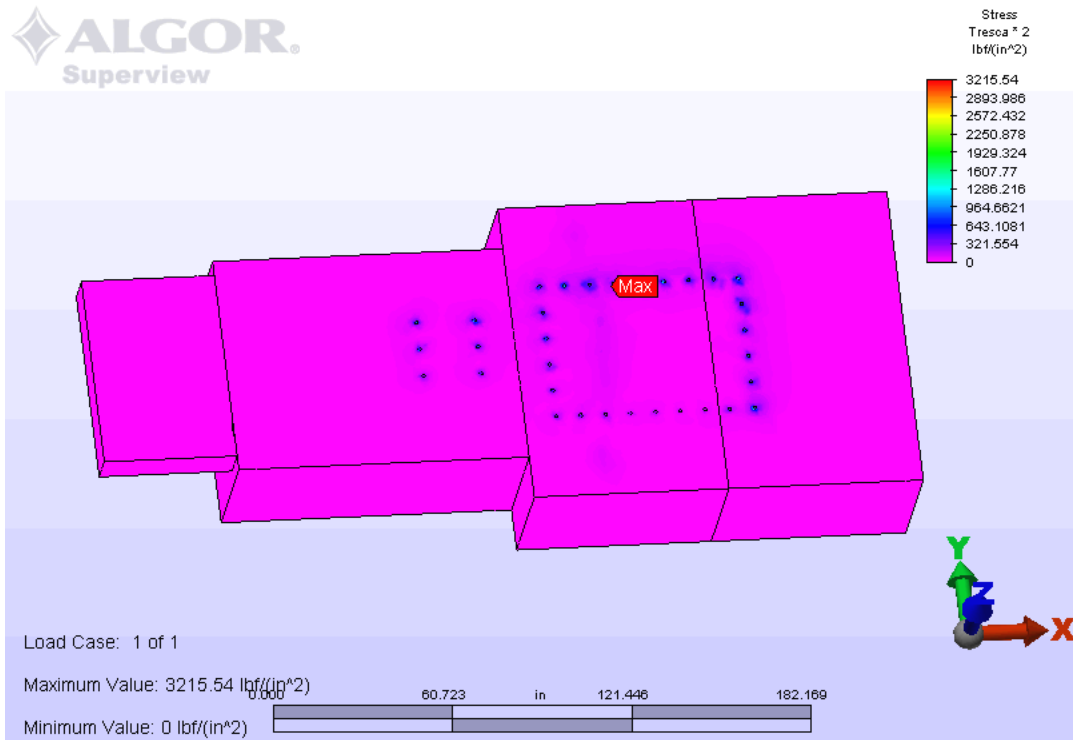


Figure 54 Static 63MJ recoil concrete foundation Tresca stresses

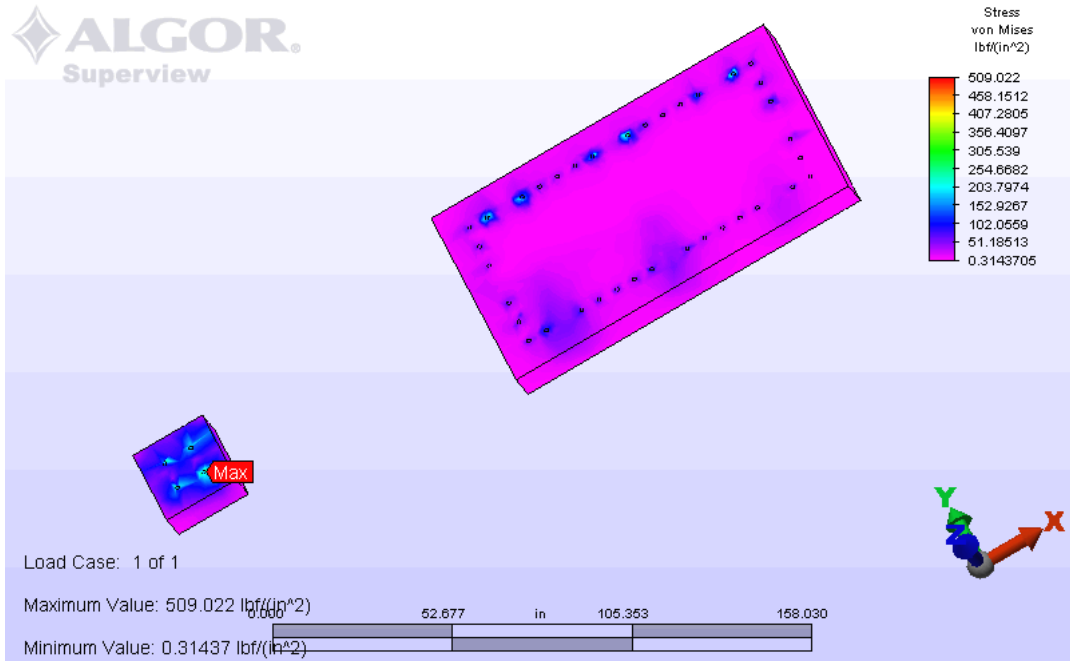


Figure 55 Static 63MJ recoil sleigh tie down & barrel support concrete von Mises

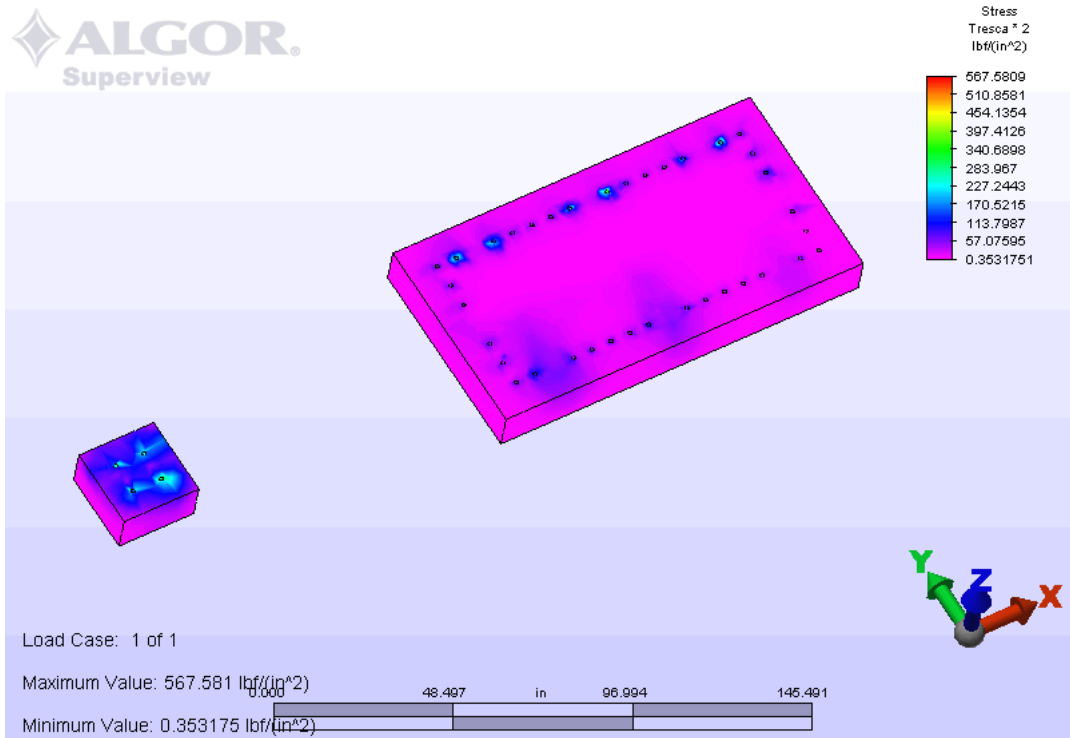


Figure 56 Static 63MJ recoil sleigh tie down & barrel support concrete Tresca stresses

Minimum Machined ASTM490 Bolt High Cycle Fatigue Strength

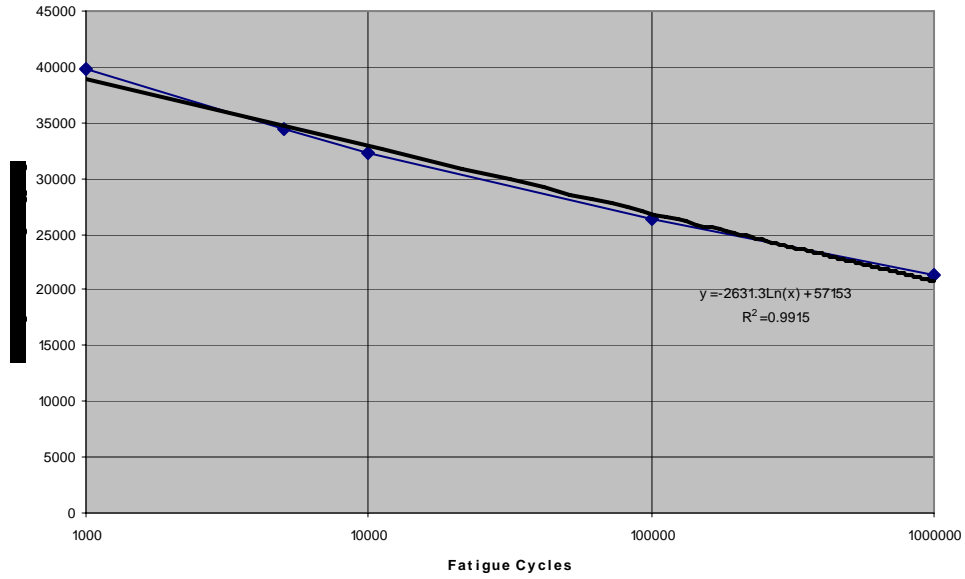


Figure 57 Foundation bolt high cycle fatigue (HCF) life

Minimum Machined 4340 RC40 High Cycle Fatigue Strength

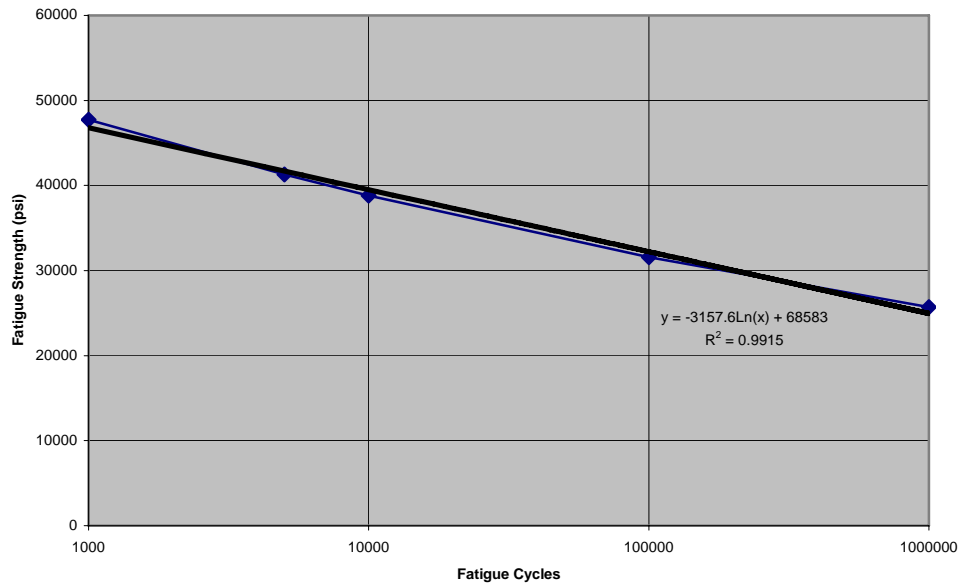


Figure 58 Mount bolt, chamber and barrel HCF life

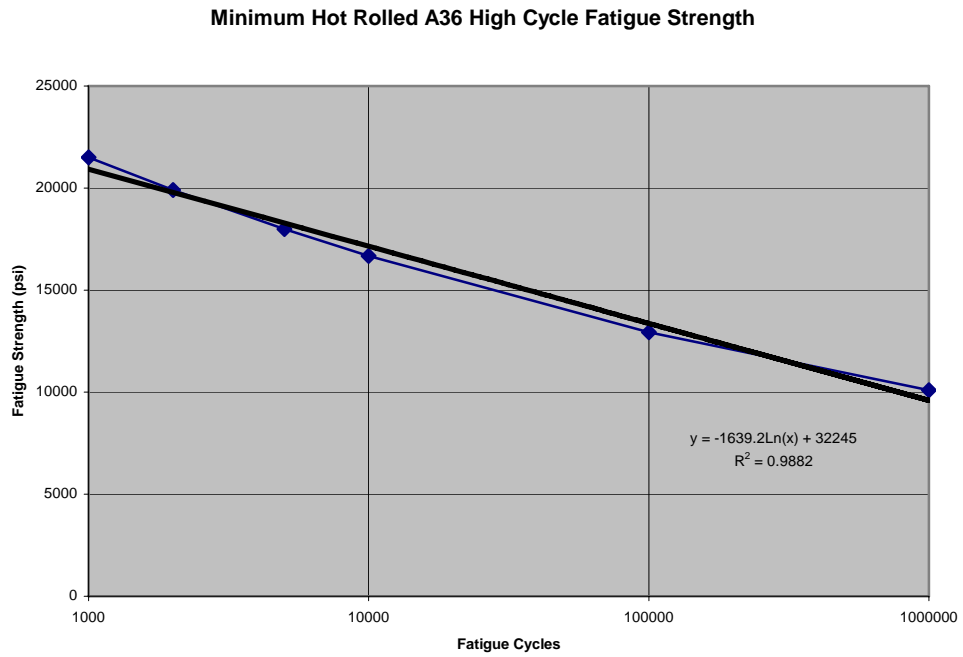


Figure 59 HCF life for transition beams, chamber support and barrel support.

### CLGG155 Natural Frequencies

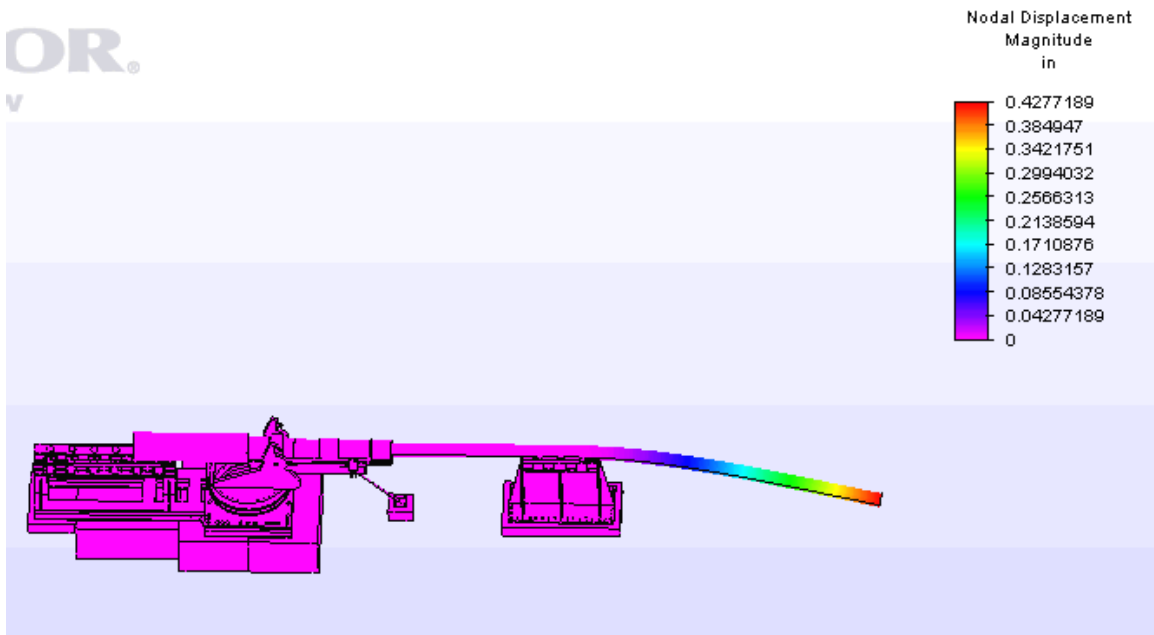


Figure 60 Mode 1 – 4.4 Hz barrel bending mode shape



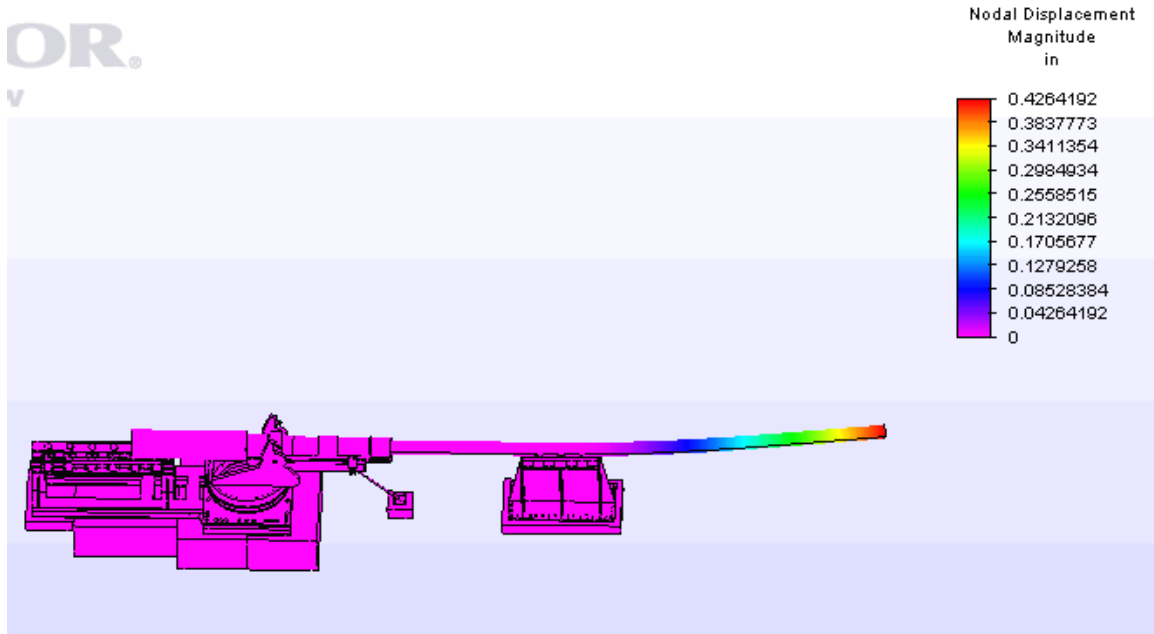


Figure 61 Mode 2 – 4.5 Hz barrel bending mode shape

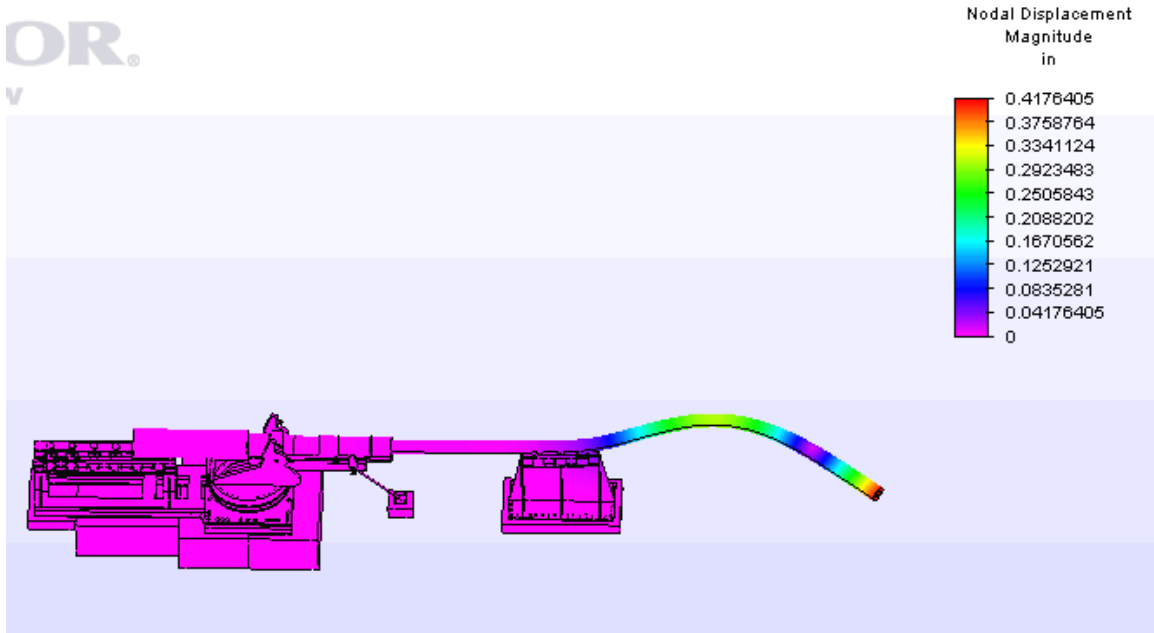


Figure 62 Mode 3 – 26.8 Hz barrel bending mode shape

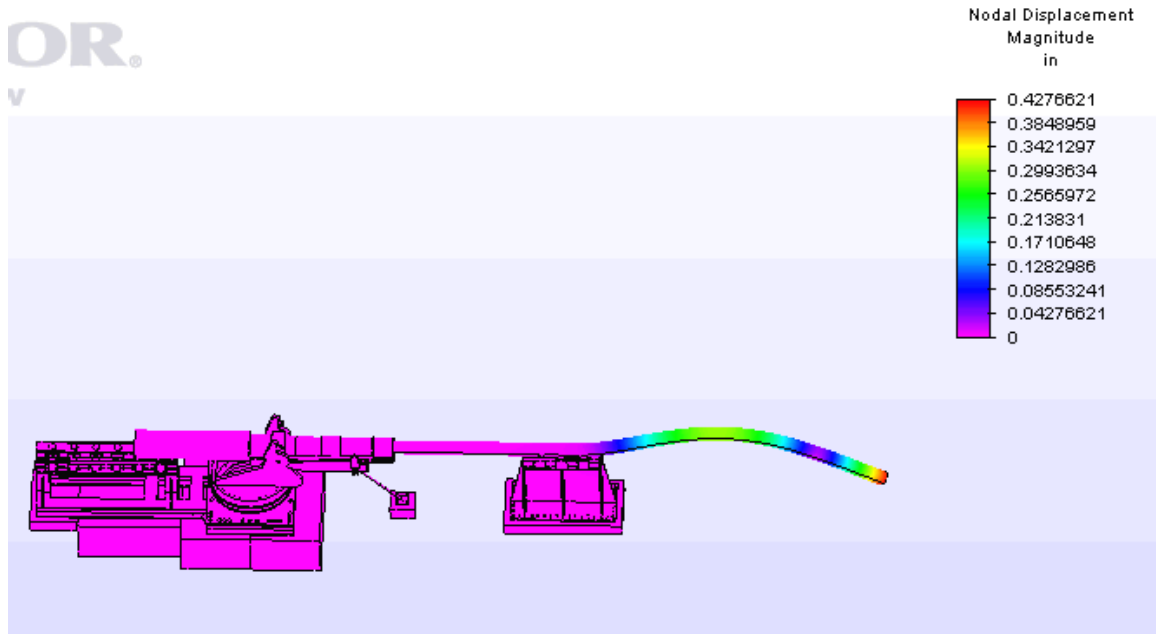


Figure 63 Mode 4 – 27.3 Hz barrel bending mode shape

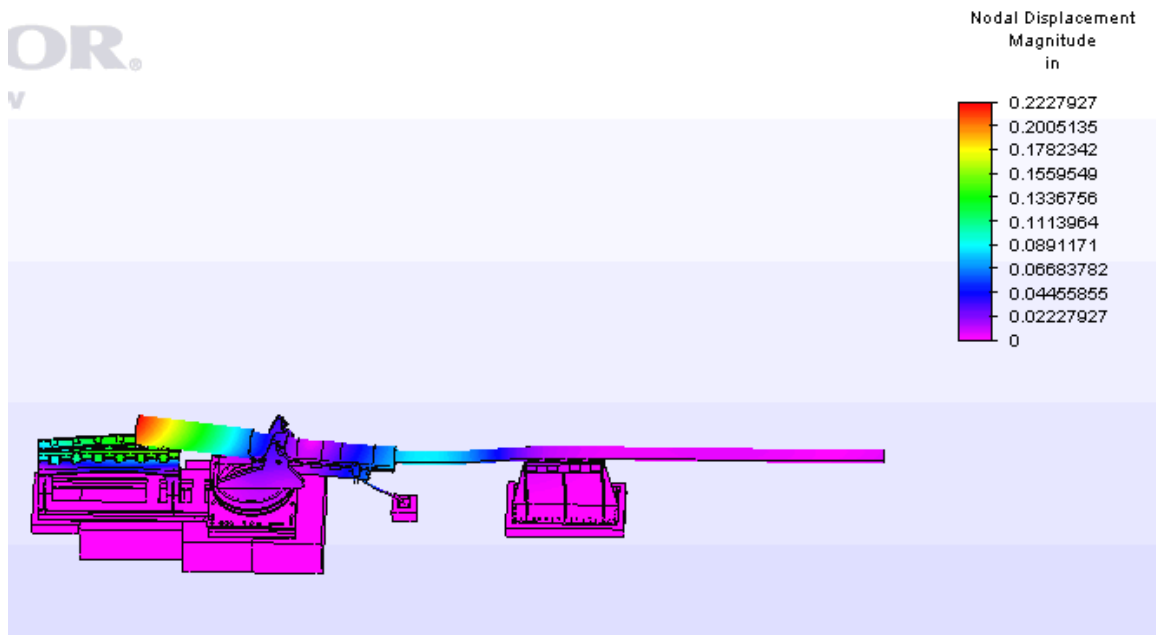


Figure 64 Mode 5 – 31.6 Hz chamber bending mode shape

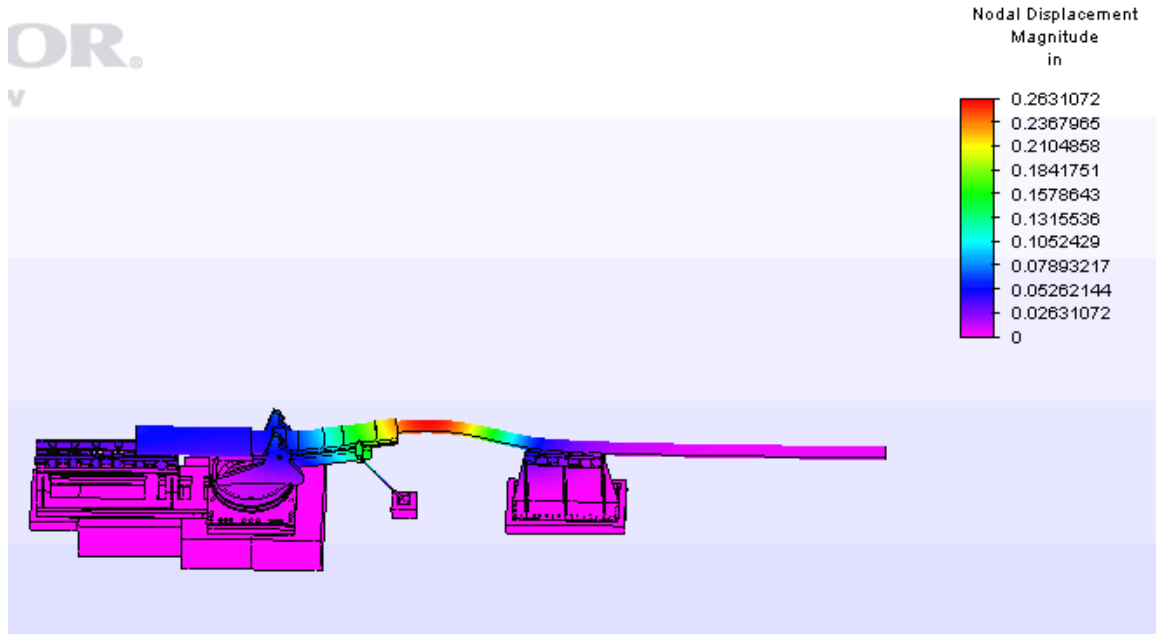


Figure 65 Mode 6 – 38.3 Hz midsection bending mode shape

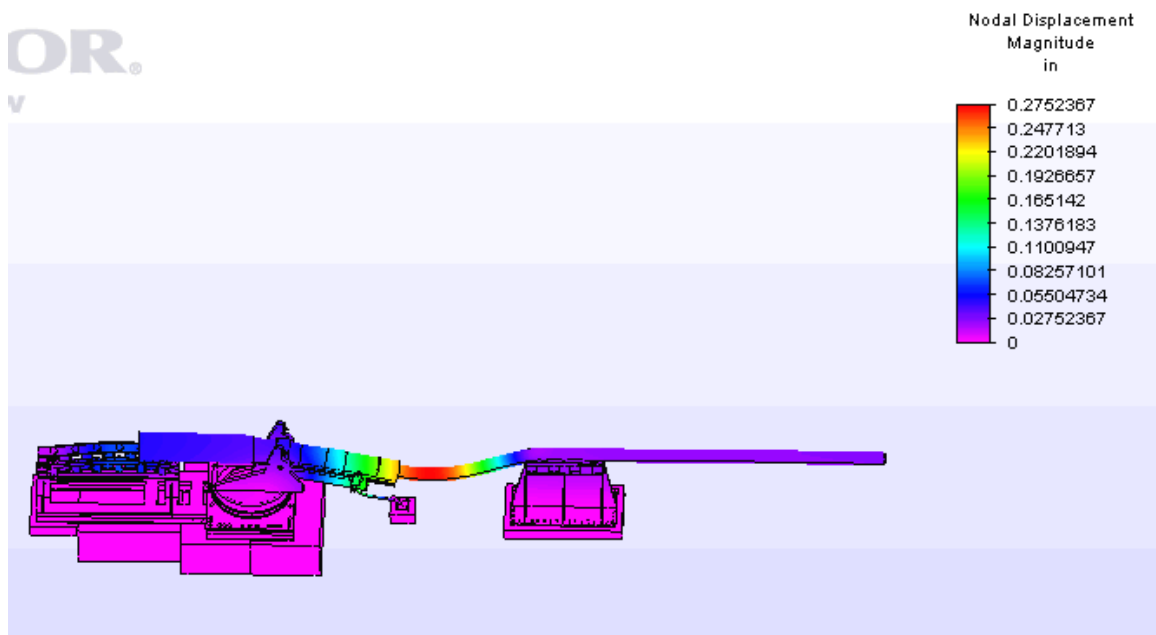


Figure 66 Mode 7 – 48.8 Hz midsection bending mode shape

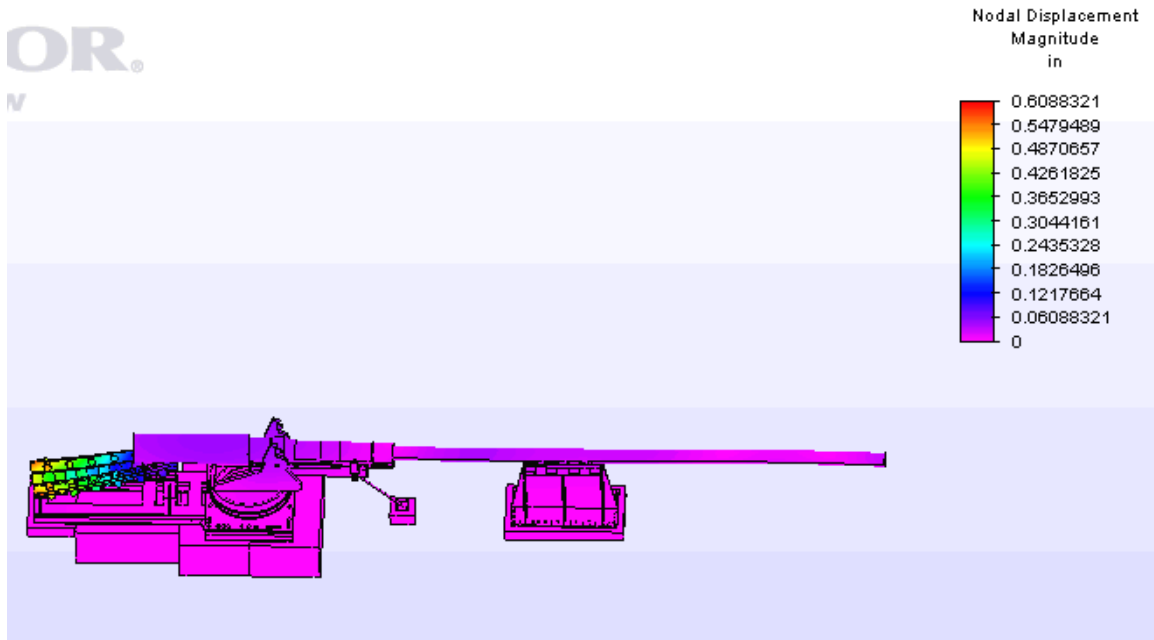


Figure 67 Mode 8 – 62.1 Hz horizontal chamber support bending mode shape

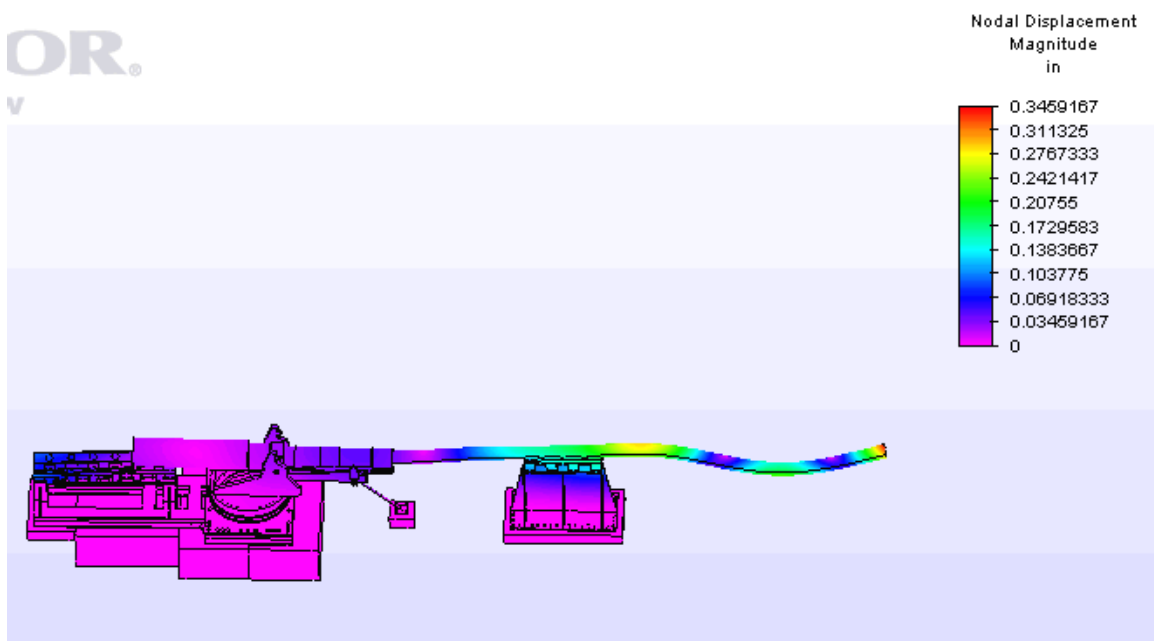


Figure 68 Mode 9 – 65.4 Hz barrel bending mode shape

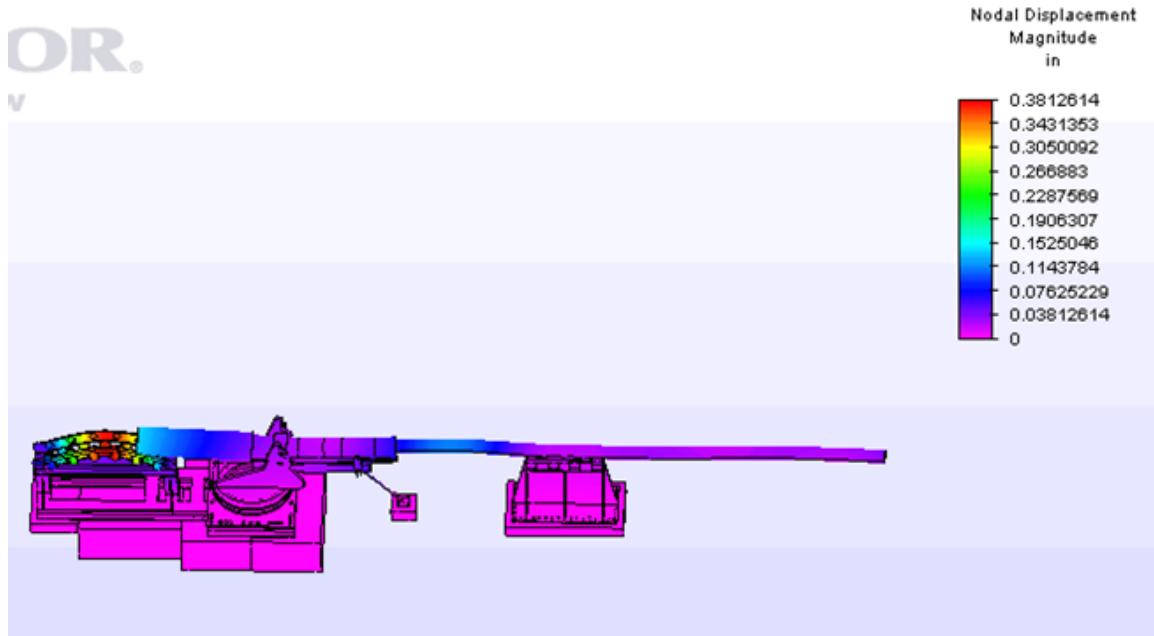


Figure 69 Mode 10 – 66.7 Hz vertical chamber support bending mode shape

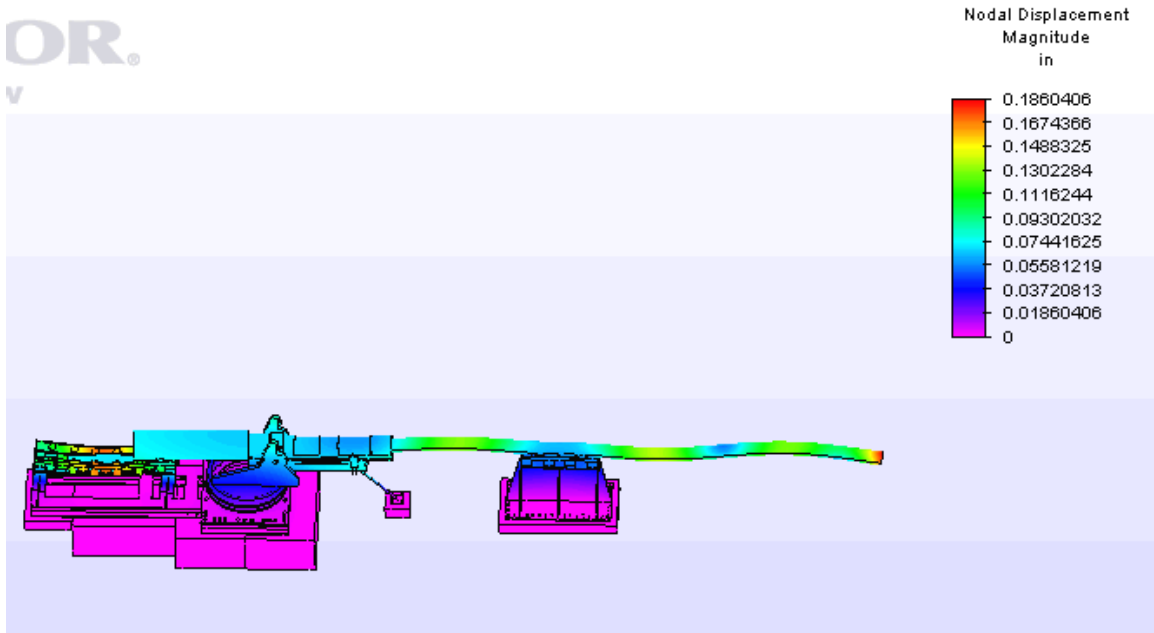


Figure 70 Mode 11 – 72.1 Hz recoil unit bending mode shape

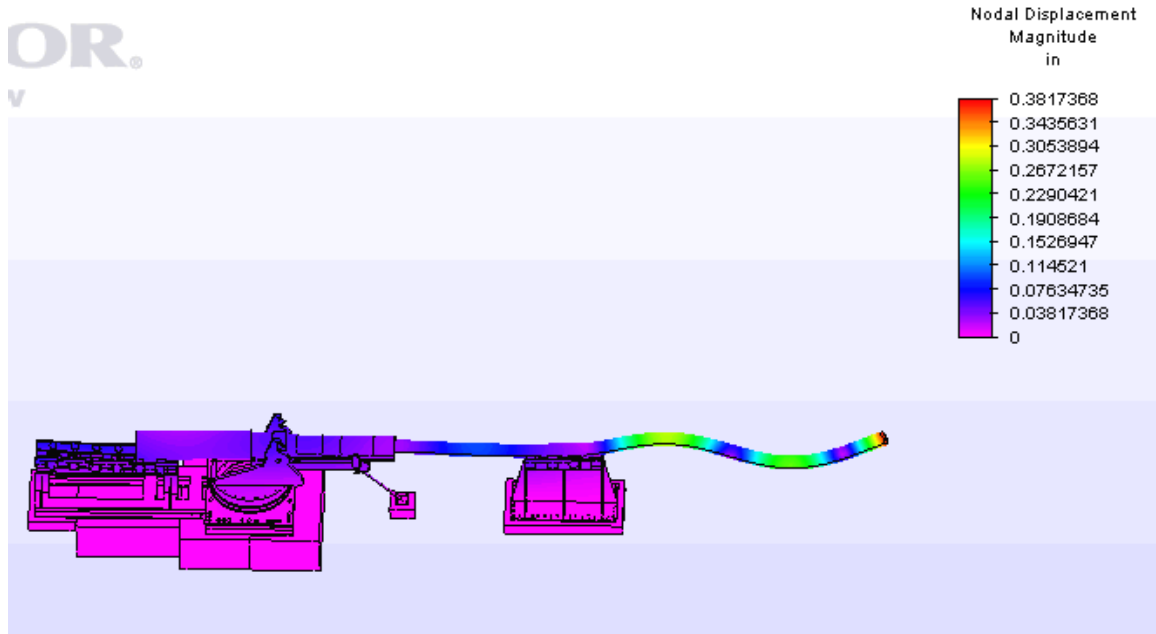


Figure 71 Mode 12 – 75.8 Hz barrel bending mode shape

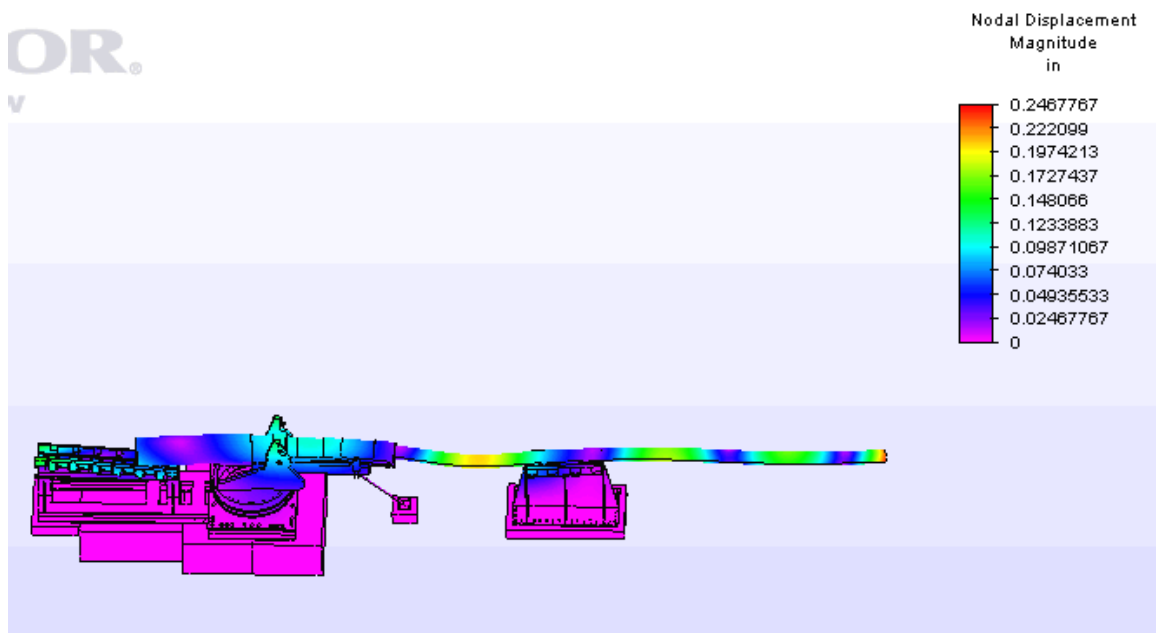


Figure 72 Mode 13 – 76.1 Hz recoil unit bending mode shape

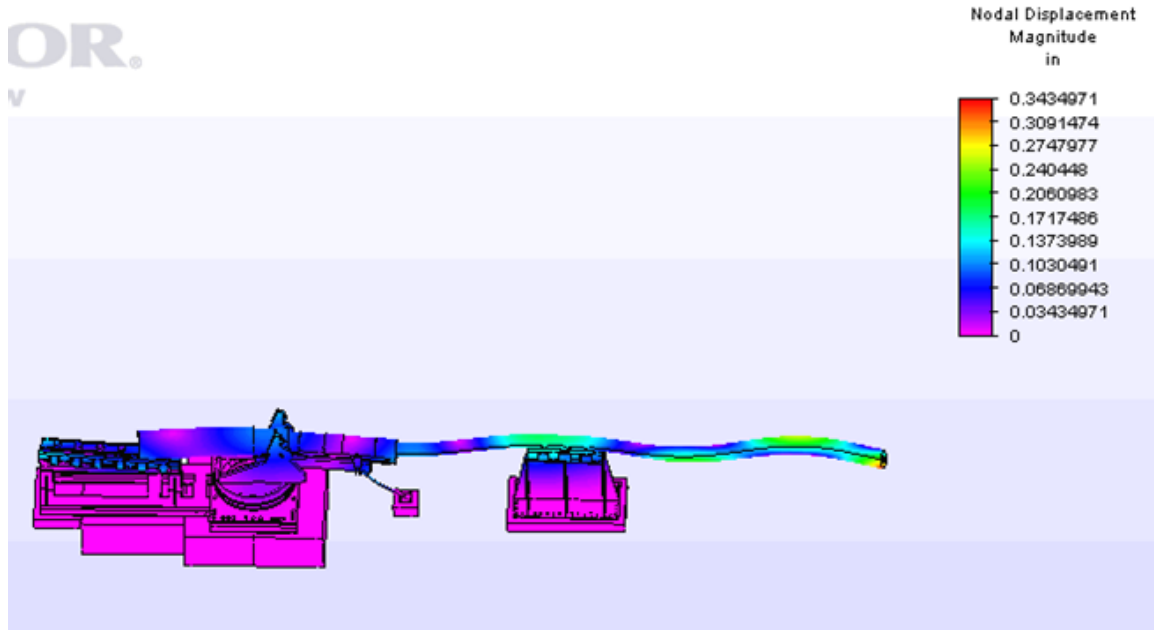


Figure 73 Mode 14 – 89.5 Hz recoil unit bending mode shape

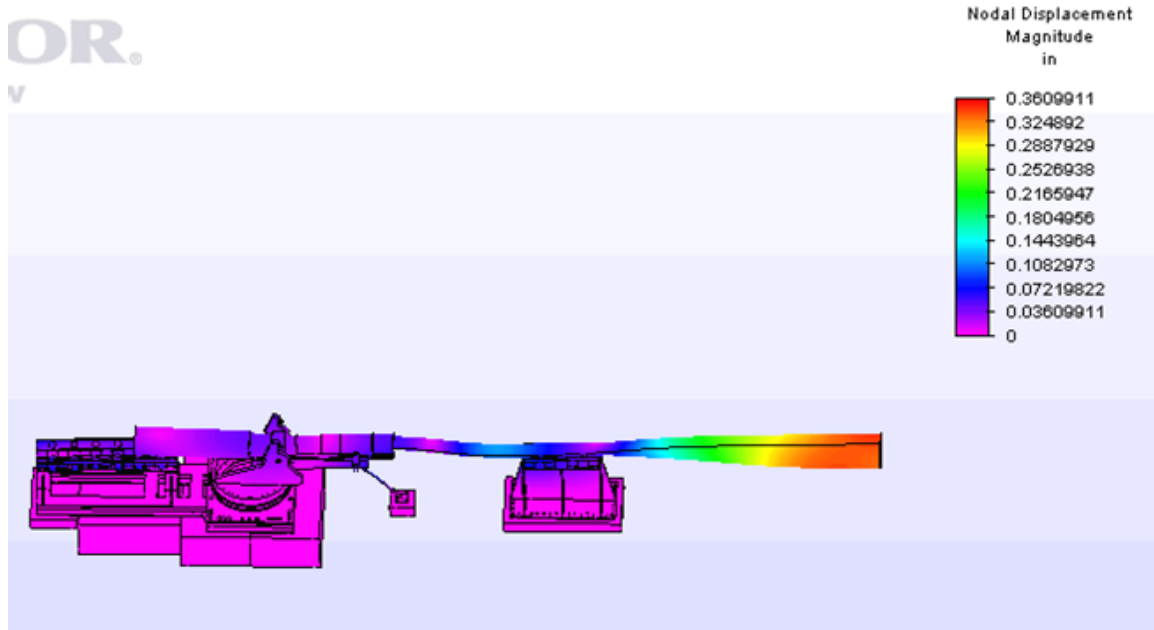


Figure 74 Mode 15 – 98.8 Hz barrel radial mode shape

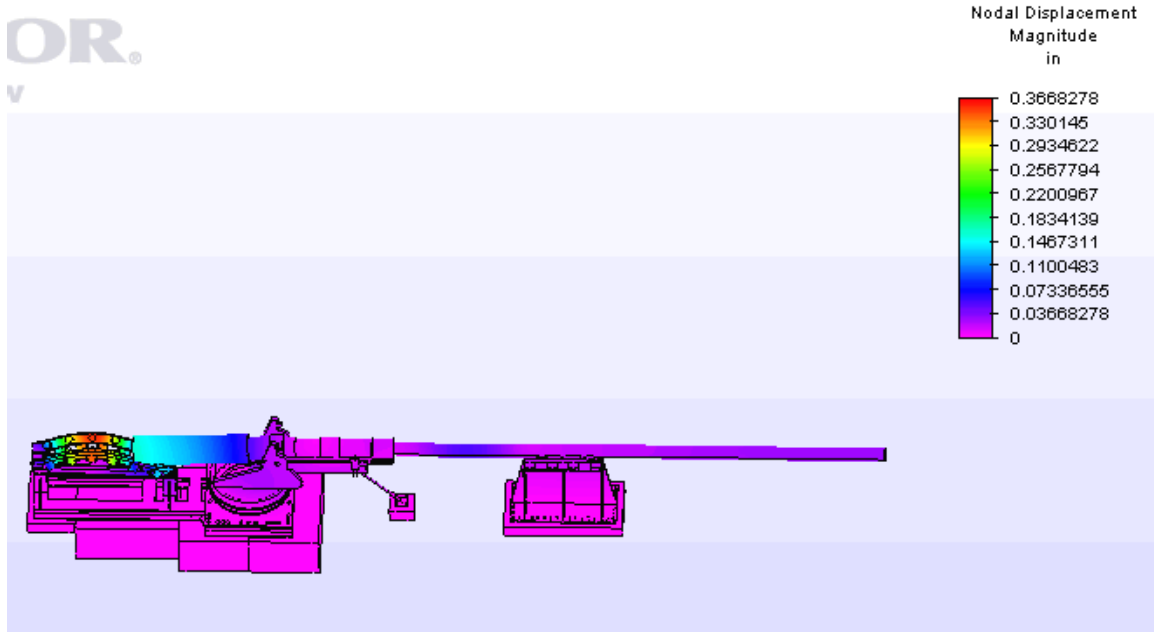


Figure 75 Mode 16 – 104.7 Hz vertical chamber support bending mode shape

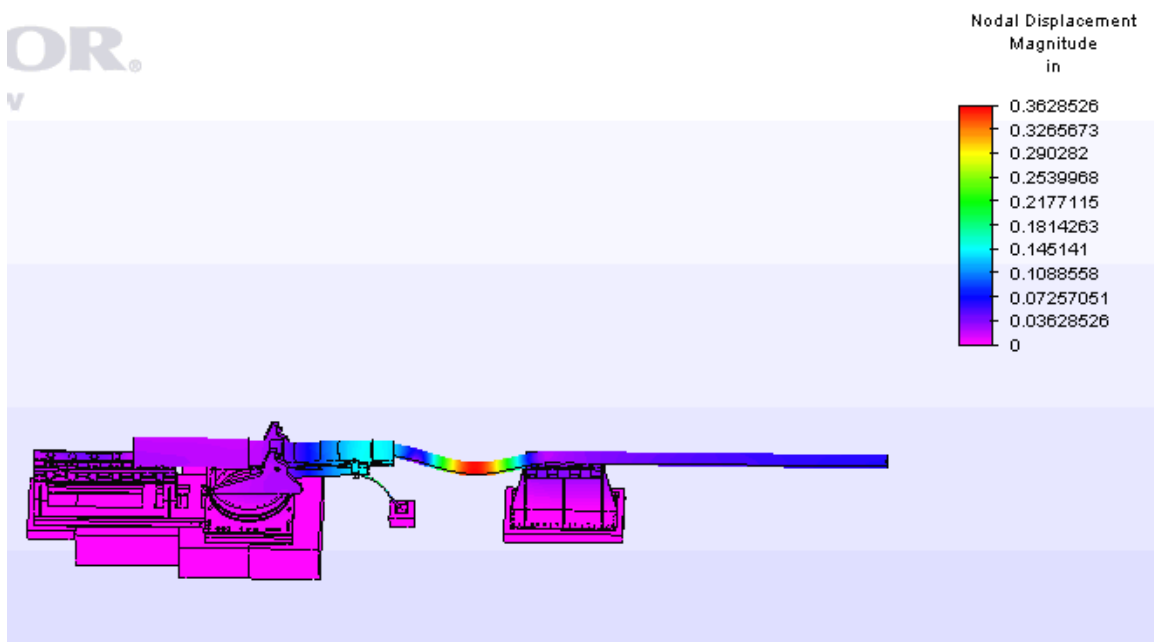


Figure 76 Mode 17 – 113.8 Hz barrel bending mode shape



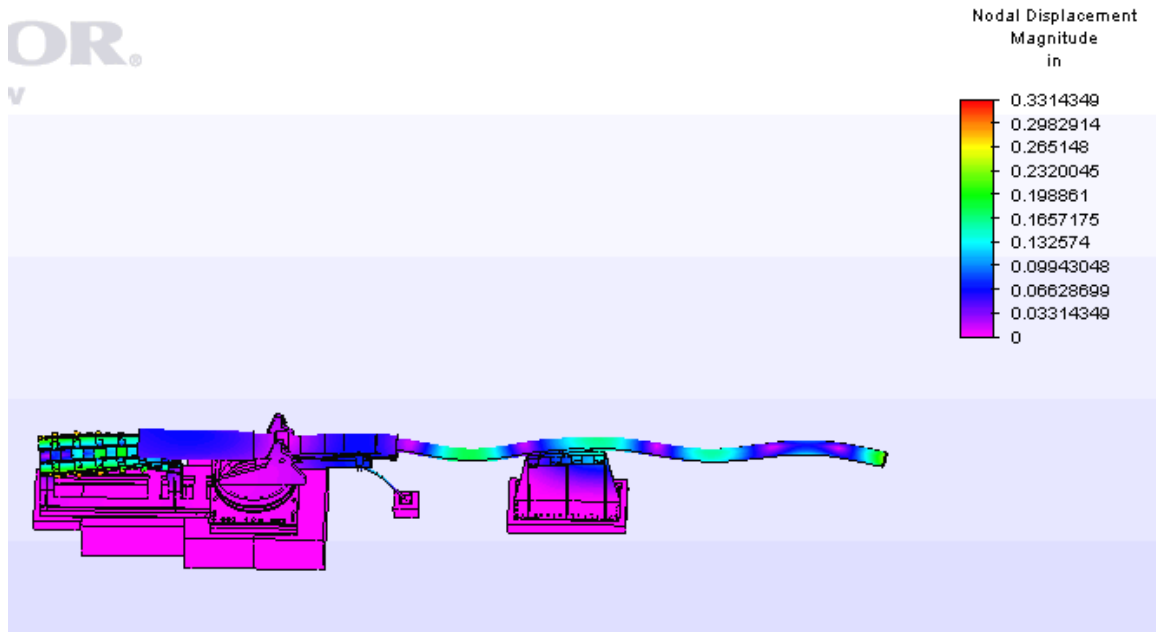


Figure 77 Mode 18 – 114.6 Hz recoil unit bending mode shape

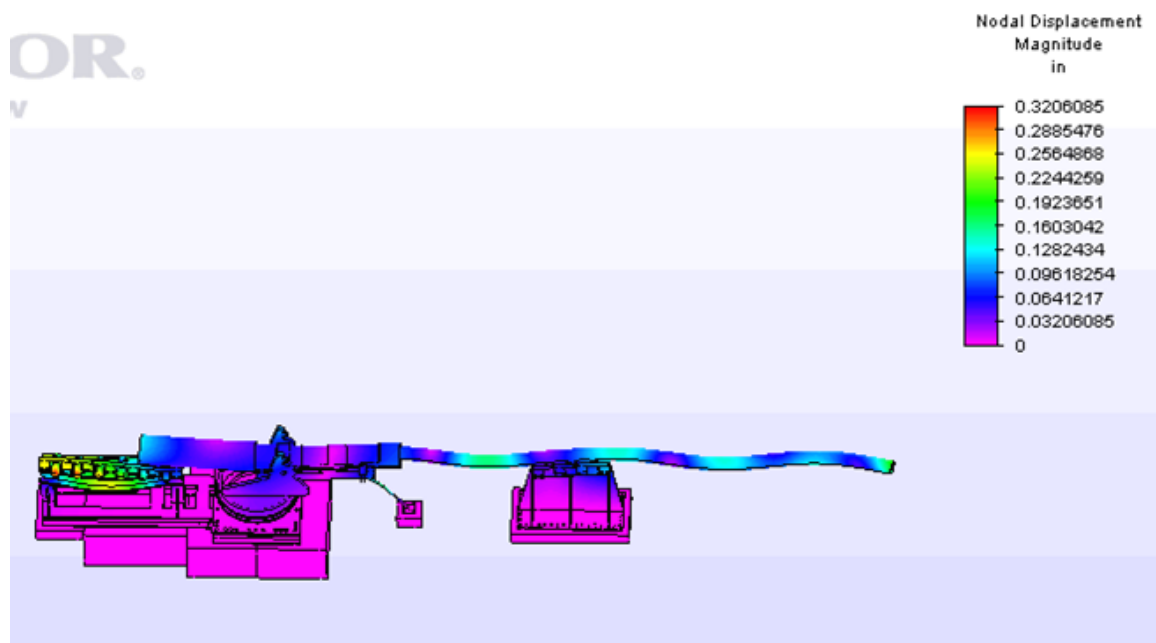


Figure 78 Mode 19 – 122.8 Hz recoil unit bending mode shape

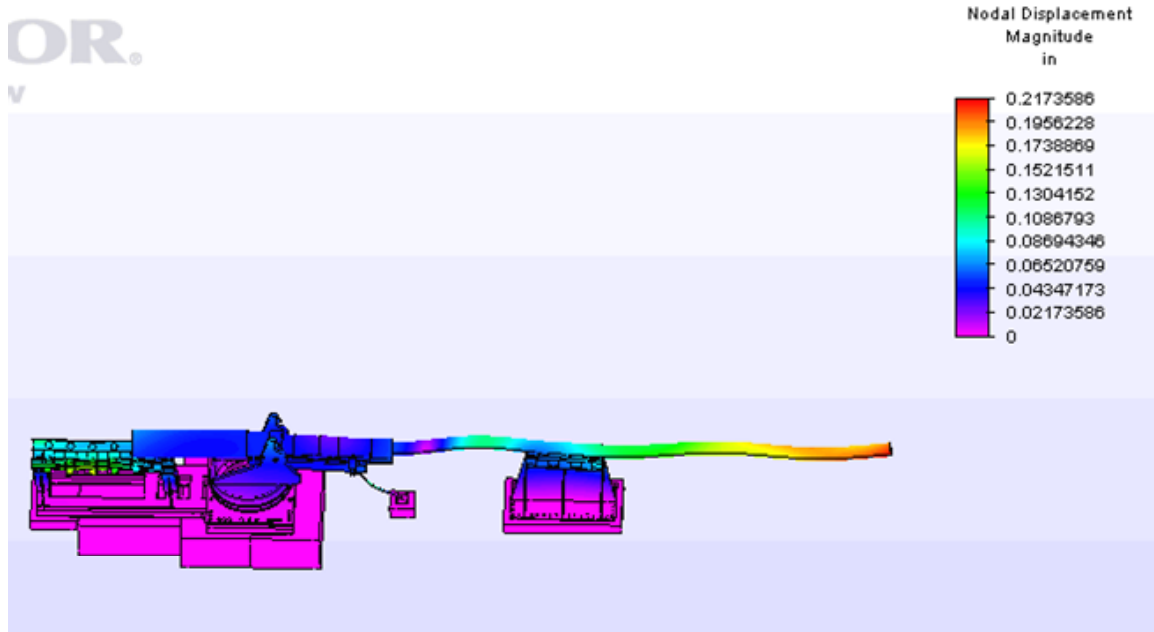


Figure 79 Mode 20 – 123.2 Hz barrel bending mode shape

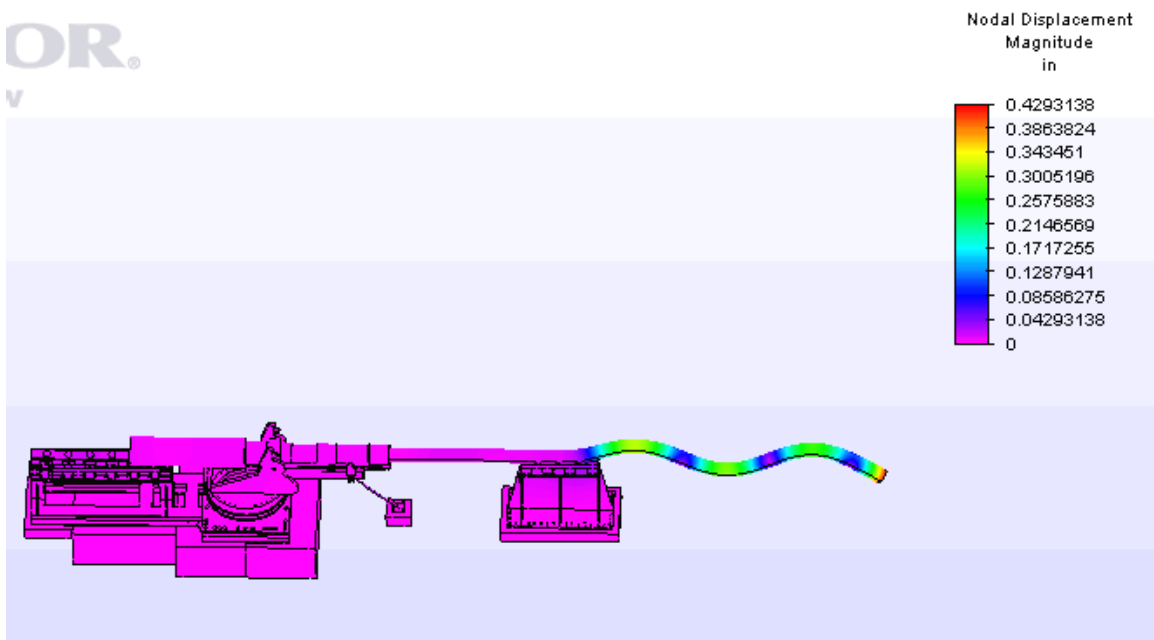


Figure 80 Mode 21 – 144.7 Hz barrel bending mode shape

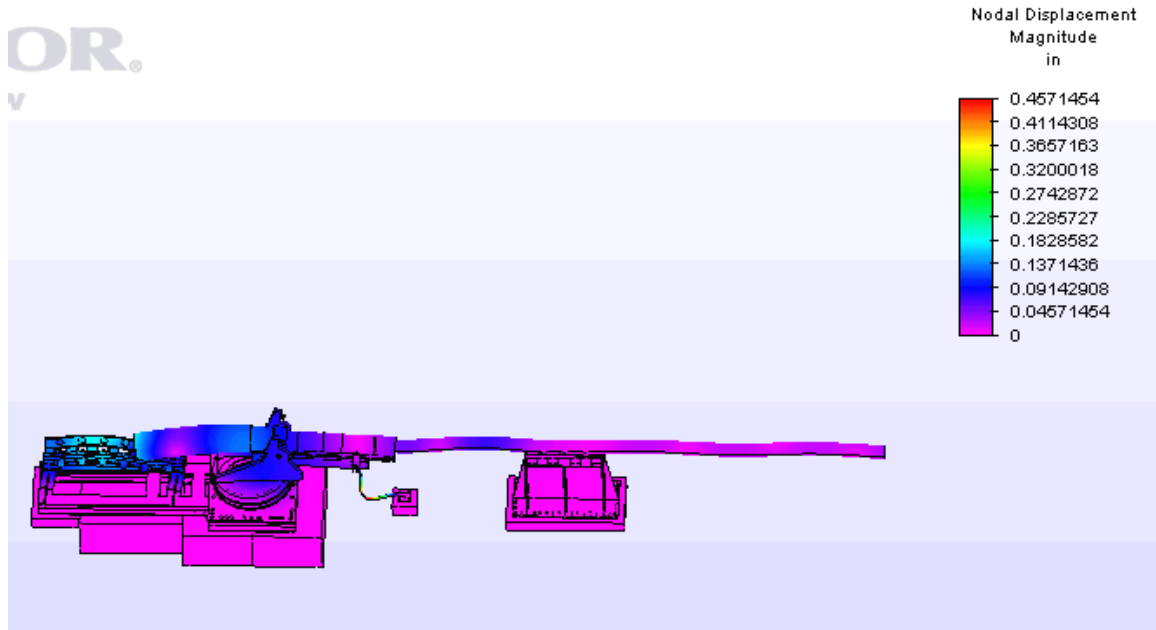


Figure 81 Mode 22 – 150.2 Hz recoil unit bending mode shape

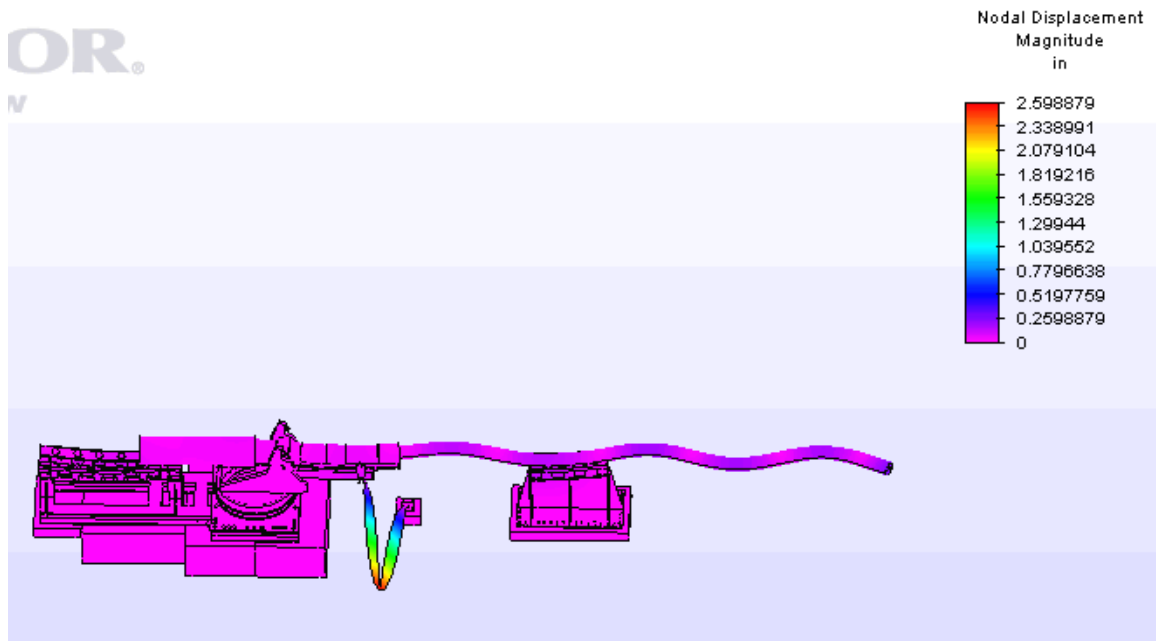


Figure 82 Mode 23 – 151.6 Hz vertical tie rod buckling mode shape

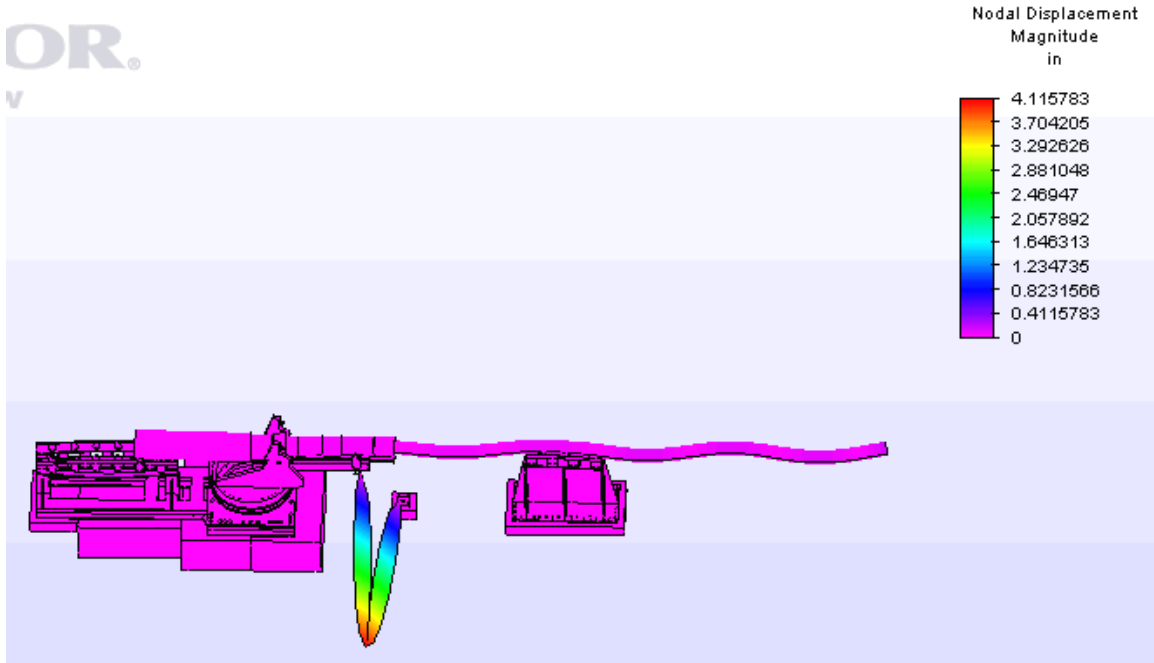


Figure 83 Mode 24 – 153.6 Hz horizontal tie rod buckling mode shape

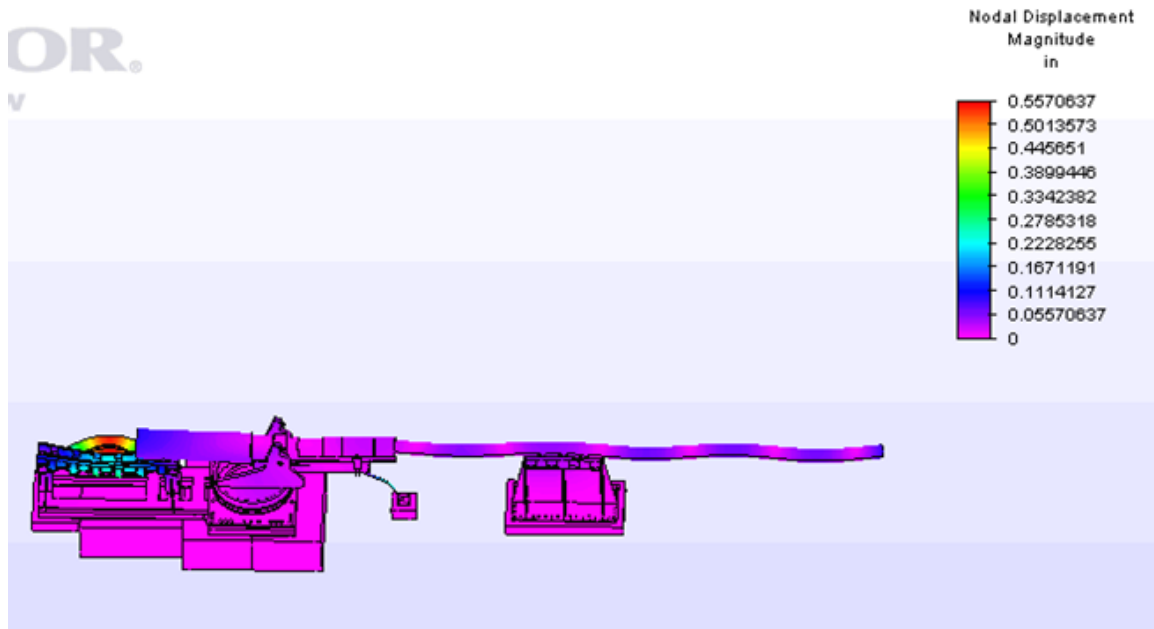


Figure 84 Mode 25 – 156.7 Hz chamber support beam bending mode shape

**Appendix D – Shipboard Integration Studies**

## **SHIPBOARD INTEGRATION STUDIES:**

During the 2005 Calendar Year (CY) Utron's Ship Integration team investigated a wide variety of shipboard alternatives to determine the feasibility of putting the Combustion Light Gas Gun (CLGG) System onboard a future Navy Land Attack Combatant Ship. The US Navy's next generation Destroyer DD(X) was used as a baseline for the CLGG shipboard studies. DD(X) will be a multi-mission surface combatant tailored for land attack and maritime dominance, providing forward presence and deterrence while operating as an integral part of joint and combined expeditionary forces. The DD(X) is a 14,000 ton ship fitted with a new developmental gun system called the Advanced Gun System (AGS). This gun is projected to be capable of firing a Long-Range Land Attack Projectile (LRLAP) up to 83 nm. The AGS qualification testing is scheduled for 2009-2010 timeframe. Full-rate production is expected to begin in 2011. We chose to compare a CLGG System against the AGS because the CLGG could provide a future upgrade for the DD(X) with enhanced capabilities and improved performance.



The CLGG with a potential range of 200nm will result in a significant positive impact on future DD(X) concept of operations. Each DD(X) will have the equivalent of about 1/2 an artillery battalion's firepower.

Data from the US Navy and public sources was used to estimate requirements and ship system configurations from which to make comparisons. Active participation involving experts in Naval Architecture, Navy weapons systems and warfighters from US Navy Commands and private contractors helped us obtain or develop the data used in these analyses.

This section will address the potential for installation of a notional CLGG gun system onboard a future Navy combatant ship. The assessments will include space/weight reservation on the ship, combat capabilities, impact of changes to doctrine,

and overall feasibility of integrating the weapon system into a future Land Attack Destroyer e.g. DD(X). Shipboard integration issues will be discussed.

### **Study Assumptions:**

Assumptions were made based upon best estimates from data available from various Navy, commercial, industry and public information sources. These assumptions include:

- DD(X) with the AGS will be used as a baseline ship for comparison purposes
- Two 155mm guns will be located forward of the deckhouse as on DD(X)
  - FWD Gun is located between frames 15-21
  - AFT Gun is located between frames 27-33
- The CLGG system on a DD(X) will produce its own propellant (i.e. liquid hydrogen, LH<sub>2</sub>, and liquid oxygen, LOX) and will store enough propellant to fire all 750 stored rounds.
- An automated magazine and gun mount system is required
  - Minimum manpower and maintenance are a priority
- Concept of Operations (CONOPS) for fire support was based upon an assumed scenario after discussions with Navy personnel. Better information should be available from the US Navy/Marine Corps after the Initial Capabilities Document (ICD) is formally signed (target date is February 2006). Our assumed fire support scenario for this study was:
  - Fire 100 rounds followed by down time of six (6) hours; continue this rate of fire support until all rounds are exhausted at which time the ship goes off line for 24 hours to replenish projectiles and return. Total mission time on station of 36 hours plus replenishment time of 24 hours for a total of 60 hours.
- Propellant Production scenarios include firing at various ranges:
  - Mission I assumes firing all 750 rounds to the maximum range of 200nm. This provides maximum capability which can be supported by the gun however also requires the most space for shipboard equipment.
  - Mission II assumes firing ¼ of the rounds to 200nm, 150nm, 100nm and 70nm each. This was deemed to be a more realistic scenario however still quite demanding on support equipment.
- DD(X) hull data was obtained from Northrop Grumman Ship Systems (NGSS) from which an estimate of space arrangements was made for each gun (see ref EE, DD(X) Hull 34A Deck & Bulkhead drawings dated July 2004). General arrangements which would show space compartments and boundaries were not provided by NGSS.

(Note: it was learned in December 2005 that the DD(X) current design stores 300 projectiles per magazine for a total of 600 rounds. Some of the rounds will be the Long Range Land Attack Projectiles (LRLAP) and some may be Autonomous Naval Support Round (ANSR))

### **Propellant Production**

The CLGG system has the potential to provide significant improvement in Naval Surface Fire Support (NSFS) by offering the ship the capability to produce its own propellant. A system to produce and store LH2 and LOX on board a Navy ship is not available commercially and would have to be developed. Various commercial vendors involved in hydrogen and oxygen production and liquefaction were contacted and were able to provide limited information for our use. All cryogenic equipment that was identified is being used for industrial purposes and significantly larger than will be required onboard a combatant ship. Our study estimated equipment size and weight based upon data from current systems.

The total ship impact of a propellant production system (size, weight, energy, and cost) will have a big effect on the DD(X). The extent will depend upon the requirements imposed upon the system. The rate of propellant production determines the size of the equipment which then drives the area and volume required onboard the ship. The production plant we designed was sized to replenish all the liquid propellant over a relatively short period of time to meet the assumed scenario. We also designed the ship to store a full load of LH2 and LOX to fire all 750 rounds.

Production of propellant is possible from several different methods. After investigating these methods the following were determined to be the most viable for application to a ship.

### **Hydrogen Generation Systems:**

#### **Electrolysis:**

Supplying electrical energy to water can separate into its component elemental parts: hydrogen and oxygen. Electrolysis has the advantage of producing a relatively clean hydrogen stream in comparison to reforming processes, but has the disadvantage of requiring a high input of electrical power to perform the hydrogen and oxygen separation. The overall heat to hydrogen efficiency for existing electrolysis systems range from 20 to 25 percent. Additional research and development is ongoing for high temperature electrolysis systems which have efficiencies in the range of 30 to 35 percent. A schematic of an electrolysis system is in figure 1.

Electrolysis hydrogen generators for naval service have been previously developed and placed in service. The systems used for CLGG system shipboard feasibility/layout purposes are medium pressure proton exchange membrane electrolyzers utilizing a solid electrolyte with capability of delivering hydrogen at 1100 pounds per square inch (psi) and manufactured by Treadwell Corporation. The capability to deliver medium pressure hydrogen directly from the hydrogen generation device eliminates the need for a transfer compressor from hydrogen generation equipment to the hydrogen liquefaction process cold box. The electrolyzers require deionized water for cooling as well as a feedstock. Ocean water would be the preferred medium to furnish the required cooling for the electrolyzers and appears possible using the operating temperature



parameters of the electrolyzers and an indirect heat exchanger. It has been assumed that the DDX has systems capable of producing the required amount of deionized water. The electrolyzers can be manufactured to operate on either alternating current (AC) or direct current (DC) power. The highest hydrogen output capability per equipment unit volume is achieved when DC power is furnished as the input.

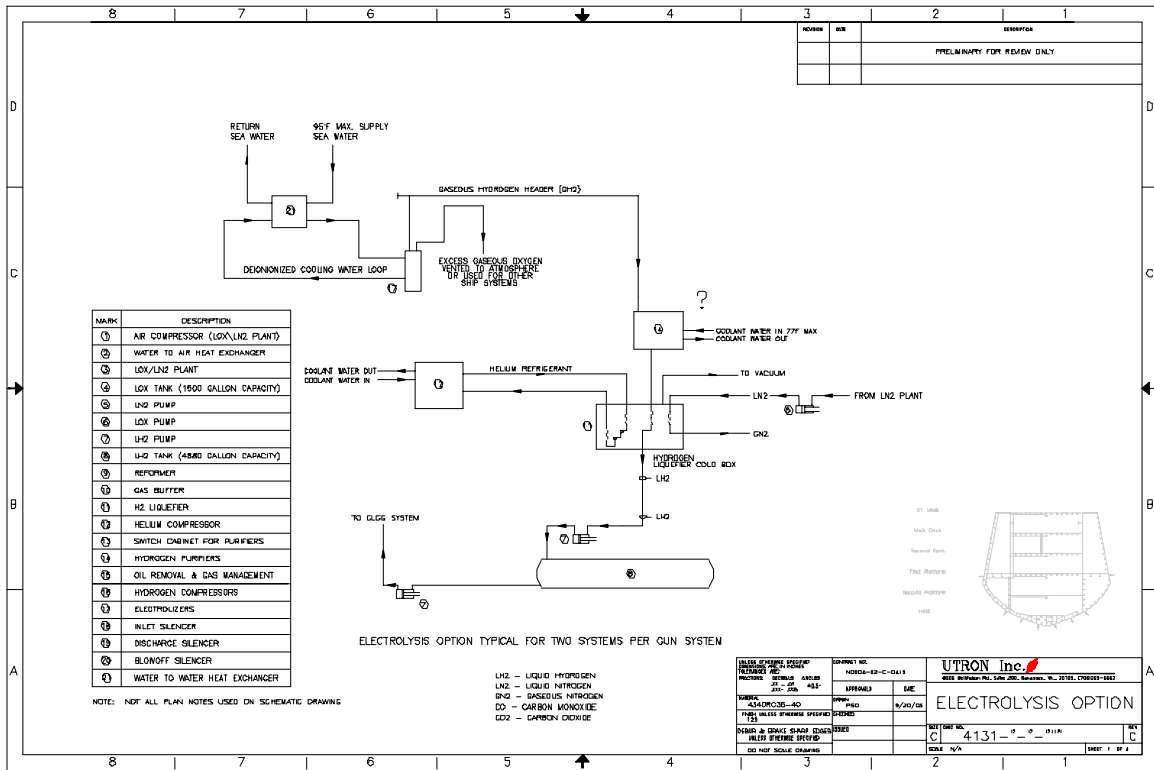


Figure 1 Electrolysis Option

Hydrocarbon Reforming:

Hydrocarbon reforming involves one of several possible processes (i.e. partial-oxidation, autothermal, plasma, etc) and a hydrocarbon feedstock (natural gas, gasoline, diesel, etc.). Reforming is a chemical process which breaks the hydrogen to carbon electron bonds of the hydrocarbon feedstock and thus produces free hydrogen. The specific process and equipment used for CLGG system shipboard feasibility/layout purposes is an autothermal fuel processor developed by the Idaho National Laboratory under Navy funding. The fuel processor was developed to supply hydrogen from NATO F-76 diesel fuel for a ship service fuel cell. The fuel processor was developed utilizing mature industrial reforming techniques. More advanced reforming fuel processors are currently under development under Navy funding, but detailed specifications are currently not available. Additional cleanup of the hydrogen stream is required to make a

product suitable for hydrogen liquefaction. This is a disadvantage of reforming diesel fuel. However, reforming diesel fuel onboard the ship has two major advantages. First of all diesel fuel is readily available in the shipboard environment, and secondly the autothermal diesel reformer has a thermal efficiency of approximately thirty-six percent; ten percent higher than the electrolysis system. A schematic of the hydrogen reformer system is shown in figure 2.

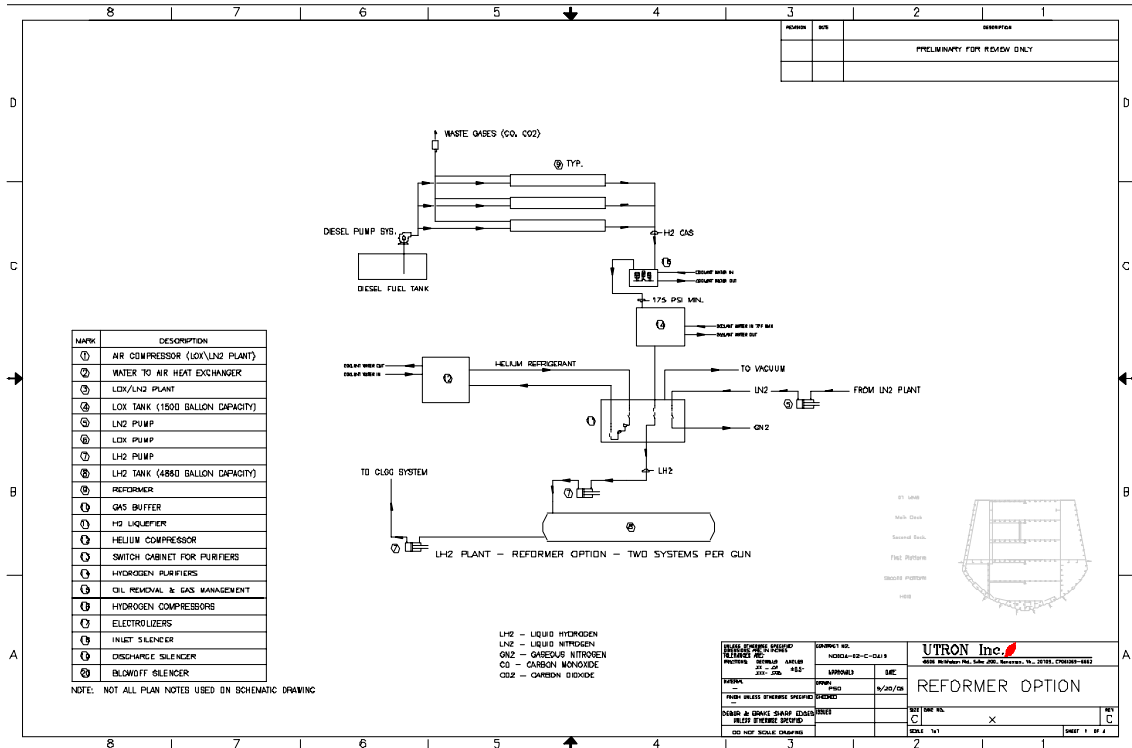


Figure 2 Reformer Option

Oxygen Production Systems:

The oxygen content of the earth’s lower atmosphere is 23.2 percent by weight. Several industrial processes have been developed to separate oxygen from air. These processes are cryogenic distillation, oxygen generators utilizing pressure swing absorbers (PSA), and ceramic membrane oxygen generators. PSA and ceramic membrane oxygen generators both produce oxygen in gaseous form. The CLGG for rapid fire is proposed to use liquid oxygen (LOX). As a result, the cryogenic distillation of oxygen systems was the main focus. Cryogenic distillation plants also have an added benefit in that they can also produce liquid nitrogen. Liquid nitrogen is required for pipe precooling as well as supplemental refrigeration for the main hydrogen liquefaction system currently under

review. A cursory comparison between equivalent PSA and cryogenic distillation (LOX/LN2 plant) was performed. Both the systems require air compressors and are nearly the same footprint. Also the separation portions of the plants are also very comparable in size with the PSA tanks requiring more height. Another advantage of the LOX plants is that they have been installed and operated successfully on naval ships in the past. A limited amount of vendor data was obtained from manufacturers for a 2.2 ton per day as well as a 5 ton per day LOX/LN2 plant. Data was obtained from Gas Equipment Company and Cosmodyne. This information was used in the CLGG system shipboard feasibility/layout scenarios. A schematic for the LOX/LN2 plant is shown in figure 3.

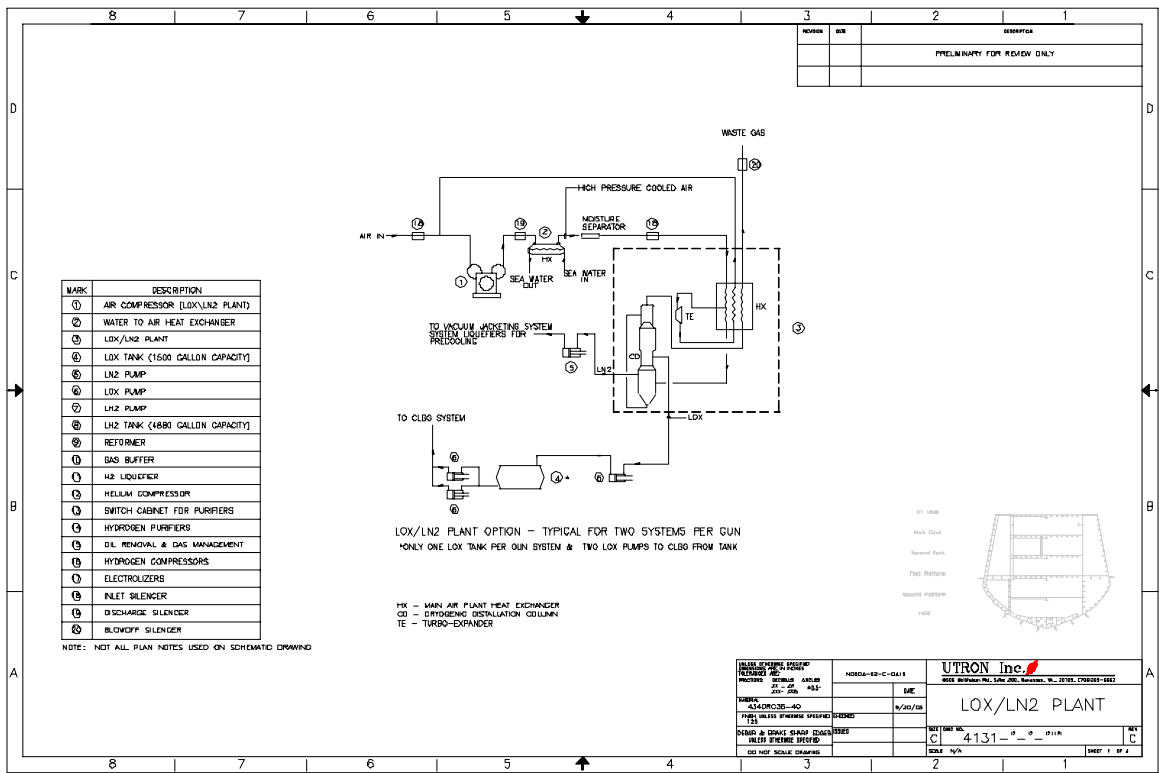


Figure 3 LOX/LN2 Plant

**Hydrogen Liquefaction Systems:**

Two different hydrogen liquefaction systems were utilized in equipment layouts. The two systems were a liquefier employing the Stirling refrigeration cycle manufactured by Stirling Cryogenics and Refrigeration and the second using Helium-refrigerated reverse Brayton cycle manufactured by Linde. Neither system was designed specifically for naval applications. The coolers manufactured by Stirling occupied more floor space for a given output of liquefied hydrogen product when compared to the Linde system.

Since floor space is of a premium, the helium refrigerated reverse Brayton cycle is the system of primary current interest. The reverse Brayton cycle liquefaction equipment from Linde requires liquid nitrogen as a hydrogen feed precoolant to operate the liquefaction system at rated capacity. A cascade type system using multiple refrigerants is a potential system but would likely require a fully custom design and no engineering layout information has been found to use in equipment layouts. Magnetic refrigeration technologies are also under review since there is ongoing research in this field. A hydrogen liquefaction system description which we used to help us design our systems was developed by Linde and is described in Reference A.

**Propellant Storage - Liquid Oxygen, Nitrogen, and Hydrogen Storage Dewars (Tanks)**

Liquid oxygen and nitrogen tanks have been manufactured for and used in the shipboard environment. Liquid hydrogen tanks have been used in the aerospace industry for over forty years. These applications in general utilize an inner tank, a vacuum space, a multilayer insulation system, and an external tank. The vacuum space prevents heat transfer into the cryogen by conduction and the multilayer insulation system minimizes radiant heat transfer from ambient to cryogen. Approximate tank dimensions have been estimated using general guidelines used by tank manufacturers. These dimensions were used in equipment layouts for the CLGG.

The above propellant production methods were used to size the various equipment alternatives which were investigated in CY2005.

**Shot Requirements:**

The amount of propellant required per shot depends upon the projectile size and range required. Our initial calculations were for Mission I with all shots fired at maximum range i.e. 200nm. Since it requires approximately twice the propellant to fire a projectile 200nm than 100nm there is a significant impact on the size of the machinery plant and resulting ship impact.

The propellant mass and volume required to shoot 750 projectiles at various ranges is given in the table 1 below:

Table 1 Propellant Required vs. Range

Range (nm)	Hydrogen (LH2)		Oxygen (LOX)	
	mass (lbs)	Vol (gal)	mass (lbs)	Vol (gal)
200	4,317	7310	8,565	900
150	3,267	5,532	6,482	681
100	2,286	3,871	4,534	477
70	1,658	2,807	3,289	346
<b>Mix Totals</b>	<b>11,528</b>	<b>19,520</b>	<b>22,870</b>	<b>2,404</b>
	<b>6,614</b>	<b>11,199</b>	<b>13,122</b>	<b>1,378</b>

<b>All @ 70</b>				
<b>All @ 100</b>	<b>9,121</b>	<b>15,445</b>	<b>18,091</b>	<b>1,901</b>
<b>All @ 200</b>				
<b>Baseline</b>	<b>17,220</b>	<b>29,162</b>	<b>34,167</b>	<b>3,590</b>

**Propellant Required Comparison for various assumed missions:**

All 750 shots at 200nm (Mission I) = Baseline

Mixture of shots (Mission II) = -33%

All shots at 100nm = -47%

All shots at 70nm = -62%

A system capable of generating enough LH2 and LOX to replenish the entire ship load of 750 projectiles over a 60 hour period at 200nm, Mission I, resulted in the most capable system meeting or exceeding all current and projected NSFS requirements. This system however would also have the greatest ship impact and would require additional volume over the AGS system, based on the current DD(X) Hull Design.

To design a system to fit into the assumed space, based on the hull drawings we had available, we reduced the shot requirements to Mission II. This lowered the propellant production by 33% and provided some space reduction.

**Description of Alternatives::**

The shipboard studies which were investigated in CY2005 looked at several alternative systems. These concept level designs that were done determined the relative size and arrangement of CLGG systems and support equipment. There was some commonality between the systems yet each alternative has its distinct characteristics also. Each of the system alternatives is composed of the following subsystems:

1. 155mm Gun and mount
2. Autoloader and projectile feed system
3. Propellant Storage Tanks and feed system
4. Hydrogen and Oxygen generation equipment
5. Hydrogen and Oxygen liquefaction equipment

Storage of CLGG projectiles was assumed to be on the main deck in spaces outside AGS spaces (approximately 900 sq. ft.). LH2 Storage tanks for 750 rounds are on the Hold level outside AGS spaces. Sizing for most LH2 and LOX production equipment was based upon vendor input for current commercial off-the-shelf (COTS) technology. The hydrogen reformer size was estimated based upon data from the Navy fuel cell development program prototype. This prototype is still relatively large for shipboard applications and the US Navy currently has a research and development program to reduce that size. We are following that R&D very closely and will leverage off any improvements to the reformer design.

The arrangement of equipment within the assumed available spaces was done based upon the following criteria:

- Both Forward and Aft Guns would each have 375 projectiles, an autoloader, and a complete propellant production system with redundancy for improved reliability.
- LH2 tanks (2) are located low in the ship (hold) and sized for 375 shots per gun.
- Reformers & LOX equipment is on the 2nd platform.
- H2 purifiers and compressors are on the 1st platform.
- Autoloader system plus projectile storage is on main deck and 2<sup>nd</sup> deck
- For the Forward Gun System space is needed on the main deck for helium and air compressors.
- Each alternative was designed for unmanned system operation.

Alternative System Configurations:

The initial studies developed system data on the alternate configurations given below in Table 2 :

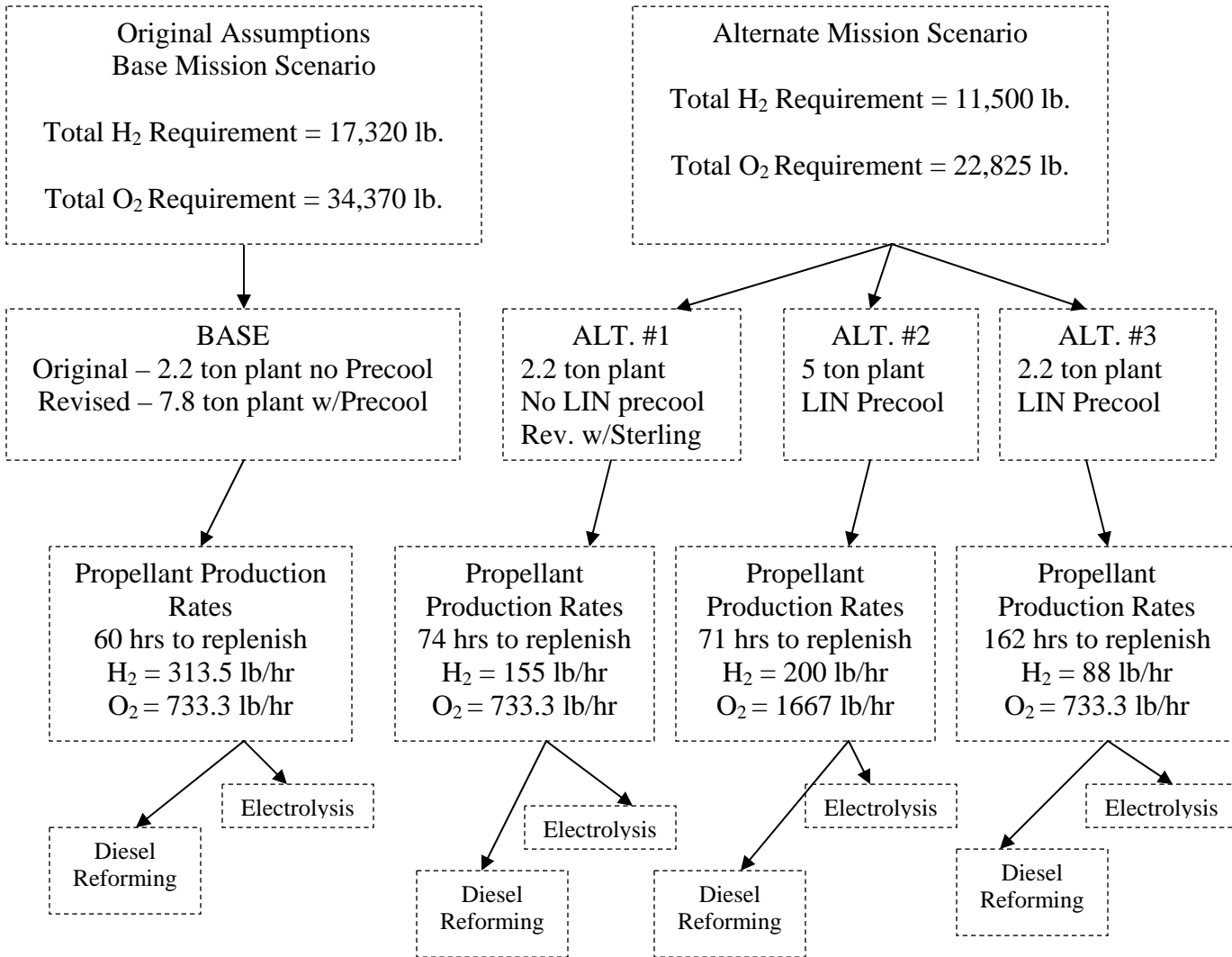


TABLE 2 Propellant Production Alternatives

## Baseline:

The baseline system incorporated our original assumptions of firing all rounds to the maximum range of 200nm and complete replenishment of propellant within our assumed mission time of 60 hours. This system results in a high end system that would exceed the capabilities of the AGS on DD(X). Because of the large volume/space required to fit this baseline system on our notional DD(X) we decided to investigate alternate systems with less capability and smaller size. The original baseline system had a 2.2 ton liquefaction plant with no LN2 precool. After revised by a separate consultant (Cryogenic Technical Services CTS) it was determined that this plant would not operate without precool therefore a larger 7.8 ton plant with precool was designed and the result was a much larger system. The baseline plant was the only plant which could meet our original production rate and replenish propellant in the 60 hour time profile.

A machinery list for the Baseline is given in Appendix B-1. Arrangement drawings for the Baseline plant are listed in Appendix A-1 (reformer) and A-2 (electrolysis).

## Alternate #1

This system was a variation of the baseline system but for a lower production rate required for the alternate Mission II. Mission II required approximately 33% less propellant than the baseline. Since this system used no LN2 precool it too was eliminated from our studies. Arrangement drawings for Alternate #1 machinery are listed in Appendix A-3 and A-4.

## Alternate #2

This alternate incorporates a larger liquefaction plant (5.0 tons) with LN2 precool. It was able to produce liquid propellant reasonably close to our original profile (72 hours vs. 60 hours needed) under Mission II. This system fit into the ship spaces which we estimated from initial DD(X) information obtained from Northrop Grumman. This system met most of our requirements and appeared to be a good fit for our CLGG support system. Later revised space information from MPR determined that the AGS system uses less area/volume than the CLGG (see Reference B, MPR Inc Design & Evaluation Report 1-2006 ).

The Forward Gun and Aft Gun machinery arrangements for the Alternate #2 reformer and electrolysis options are given in Appendix A-5 and listed in A-6.

## Alternate #3

This concept is similar to alternate #2 however has a smaller production plant (2.2 tons) and requires a much longer time to replenish the storage tanks (162 hrs vs. 71 hrs). Arrangement drawings for Alternate #3 are listed in Appendix A-7 and A-8.



## Comparison of CLGG Alternative Systems:

Our initial baseline was designed to meet all the original assumed requirements, i.e. firing 750 shots at maximum range over a 60 hour period with complete onboard propellant replenishment. While this was a noble goal it was determined from the study that too much space would be required from the DD(X) space thought to be available. The machinery volume estimated to be available was obtained from hull drawings made available by Northrop Grumman Ship Systems (NGSS), (Ref. D, DD(X) Hull 34A Deck & Bulkhead drawings dated July 2004). The space indicated that there might be as much as 3,300 sq. ft. available however without general arrangement drawings the available space was only an estimate. Our assumed space included deck areas under the DD(X) gun mount locations between frames 15-21 for the forward gun and between frames 27-33 for the aft gun (see ref xxx drawings). Our assumption was that space was available on the second platform and first platform for propellant production and in the ship hold for hydrogen storage. The autoloader was located on the main deck and the gun mount on the 01 level as on DD(X).

Maximum redundancy for gun support equipment was assumed in order to provide a highly reliable system. Redundant LOX/Ln2 plants for each gun were included in the designs along with six (6) diesel reformers per gun. The LOX tank and equipment was kept separate from hydrogen and petroleum products as a safety issue. Reformers & LOX equipment are located on 2nd platform while H2 purifiers and compressors are on 1st platform. Bulkheads were used to separate hydrogen and oxygen equipment when necessary for safety reasons. The autoloader and projectiles were assumed to be closer to gun system on the main deck under the turret. LH2 tanks (2) were located below decks in the ship Hold. For the forward gun system which is located in spaces with less beam, need the main deck for helium and air compressors. Figure 1 below is a notional ship arrangement of a reformer system.

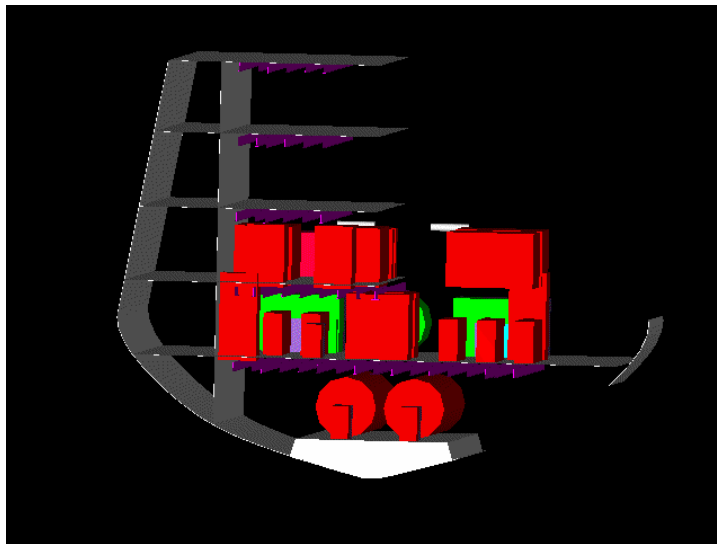


Figure 1

Conceptual machinery arrangements are available in CAD format and are listed in the Reference A.

A general comparison of a reformer option versus an electrolysis option is given below;

#### Reformer System advantages

- Significantly less energy
  - fuel consumption (50% fewer gallons diesel)
  - kW (70-80% less power)
- Significantly less weight (-140 LT equipment)
- Slightly less deck space

#### Electrolysis System advantages

- More mature technology
- More arrangeable volume

#### Diesel Reforming (H<sub>2</sub>) plus Cryogenic Distillation (O<sub>2</sub>) (for Alternate #2, Mission II)

- System Electric Load = 2,431 kW
- Total Load = 158,724 kWh
- GTG Fuel Consumption = 9,895 gallons
- Reformer Diesel Fuel Cons. = 13,098 gal.
- Total Diesel Fuel per 750 rounds = 22,993 gallons (75 LT)

#### Electrolysis (for Alternate #2, Mission II)

- System Electric Load = 11,751 kW
- Total Load = 695,556kWh
- GTG Fuel Consumption = 43,361gallons
- Total Diesel Fuel per 750 rounds = 43,361 gallons ( 141.5 LT)

A Relative Rating Matrix was developed which further compared the various reformer and electrolysis option characteristics such as weight, volume, power, etc.. This matrix, which will be further refined in CY 2006, is given in Appendix D.

#### **Comparison of CLGG to a notional AGS System on DD(X):**

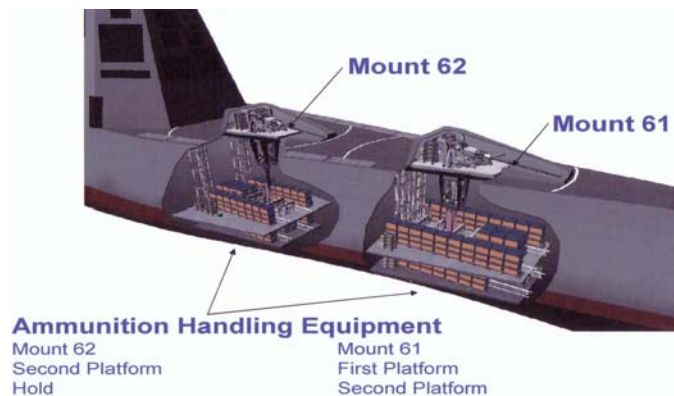
Since we were unable to obtain access to the US Navy's DD(X) ship general arrangements this year, we contracted with MPR Associates to evaluate our design work and make a general comparison with the DD(X) AGS System. By doing a general comparison, MPR was able to give us an indication of where we needed to make changes or improvements in our system designs without releasing data under their security agreement with the Navy.

In November MPR Associates reviewed the Utron system design alternative #2 to the AGS system. The objective was to make a first order assessment of the ability of the CLGG design to fit into the DD(X). An independent technical review of the CLGG systems was conducted by MPR engineers. within the framework of installing these systems aboard ship. The evaluation of the CLGG System will continue into CY 2006

and will include the size, weight, footprint, system arrangement, operability, manning, safety, reliability and maintainability. Preliminary results presented in December 2005 indicate that a maximum capability CLGG system with full redundancy, full production capability and storage will not fit into the current AGS spaces.

The two DD(X) AGS gun systems use approximately 2,560 ft<sup>2</sup> per gun and are located on the 1<sup>st</sup> and 2<sup>nd</sup> platforms. Each AGS gun includes approximately 300 rounds of munitions. The CLGG Alternate #2 design uses the Hold, 2<sup>nd</sup> Platform, 1<sup>st</sup> Platform and Main Deck and takes up significantly more space (approximately 3,300 ft<sup>2</sup>). The CLGG however includes the capability to fire over 200nm, produce propellant, has separate and redundant systems, and can carry 375 projectiles per gun.

A concept drawing of the AGS on DD(X) is given below:



Because of the great difference in ship space requirements it was decided, after review of the concepts with MPR, that Utron would look at alternatives to reduce the equipment size to be closer to the current AGS space and capabilities. Preliminary results indicate that a reduced capability system can be designed to fit into the AGS spaces. Work on this and other alternate designs will continue in CY2006.

An MPR summary report of the initial comparison between the CLGG and AGS is given in Reference B. A final comparison report will be available in February 2006.

### **Areas for Investigation on Continuing Shipboard Studies – CY2006 Work**

During calendar year 2006 design iterations will be investigated for CLGG configurations which fit into the current AGS space volume and identify the resultant system capabilities and shortfalls. Ways to reduce the plant size will include the following ideas:

- The minimum CLGG Navy contract requirements will be revisited with a goal of fitting a reasonable plant into the current DD(X) spaces which still meet minimum requirements. Equipment design with fewer but larger components will be investigated as well as eliminating redundant equipment where possible.

- Commercial vendor design efforts may be necessary to obtain better data on a reduced size system for the Navy. Visit(s) to commercial manufacturers to look at equipment and get feedback on ways to reduce size may also improve design alternatives.
- Replenish propellant at a much lower production rate. Current design replenishes and stores 750 shots of LH2/LOX in 72 hours. Our assumed Volume of Fire (# rounds fired over time) is an estimate based upon discussions with ONR and may not be realistic compared to historical gun fire data or to AGS requirements
- Store some of LH2 within a PVLS compartment(s) in modular cryogenic tanks.
- Alternatives will be investigated with various projectile ranges, firing rates, projectile weights and propellant replenishment times to determine effect on the size of plant. We will work with Navy and MC personnel to define more realistic scenarios based upon historical information and current CONOPS.
- Equipment/systems which are modularized may help us to quickly identify a range of plant configurations and capabilities as requirements are better defined.
- A design option which has no shipboard production only storage may not be a very attractive but is feasible. Many worldwide facilities have or could have the capability to produce LH2 and store in cryogenic tanks. This alternative will have the least ship impact on the DD(X).

Beyond the ship impact studies there are areas of interest which were not addressed in detail in CY2005 but need to be addressed further in CY2006-7 (not in priority order):

- Fire suppression systems for CLGG machinery spaces
- Hydrogen leak detection systems and leak handling procedures
- Identify compartment ventilation systems design requirements
- Design method to jettison hydrogen and/or oxygen in an emergency situation
- Extend the investigation of an electrolysis system
- Investigate advanced hydrogen storage systems
- Continue to design and refine ship board safety, fire fighting and operational requirements based on newly developed operational data. Subcontractors will be engaged to assist in the design of safety system.
- Design a CLGG 155mm auto loader to fit in the AGS space
- Determine procedure for removing a loaded round after an abort
- Design & Build Prototype H2/O2 Production & Storage System
- Design, test and operate a sub-scale reformer using diesel as the feed stock to extract hydrogen and use it to fuel the 155mm Subcontractors, National and DoD laboratories will be engaged to design and develop reformer.
- Conduct a design analysis on the gun muzzle blast overpressure on surrounding ship structures
- Conduct an analysis on gun shock spectra on ship structure
- Conduct a study comparing the CLGG system to an EM Gun System. The EM gun has an estimated range comparable to the CLGG however has a significant problem with energy storage and rail cooling. The size of an

EM gun system should be comparable to the CLGG baseline and Alt #2 systems.

- Investigate the possibility of gaseous injection of oxygen (cold gas) in order to help alleviate some of the problems associated with LOX.
- LH2 has technical and safety concerns but probably engineering solutions
- LOX storage has safety concerns which could present significant problems in a confined shipboard environment
  - All options must be addressed and a risk reduction program identified

### **General Conclusions from the CY 2005 CLGG Shipboard Studies**

It is feasible to install the CLGG System onboard a US Navy Combatant ship similar to the DD(X) and either meet or exceed the current requirements for long range guns. The impact of generating CLGG propellant on board a ship is significant both from an engineering design and safety standpoint. Based upon Utron's initial feasibility studies and discussions with various Navy, commercial and industry consultants we feel that with proper design development and testing a CLGG shipboard system can be developed to meet all Navy requirements.

The CLGG has the capability of firing a wide range projectile sizes and ranges. The production system for producing propellant also ranges in size as the CLGG capabilities increase. Our initial studies determined that to fire all shots at a maximum range of 200nm would result in a plant much larger than the current AGS system. While this might be a possible alternative for a different ship, it is not realistic on the DD(X). Even firing shots at a mix of ranges from 200 to 70 nm would result in a large system if our operational requirements are

The specific CLGG operational performance requirements need to be optimized in order to take advantage of the gun's unique capabilities yet not produce a severe impact on the size and cost of the ship. The CLGG requirements will parallel the Navy/Marine Corp Naval Surface Fire Support requirements which are still under development. As these requirements become available during FY06 we will adjust the CLGG system to meet them.

References:

- A. Linde Report 27.04.05.JJC “Hydrogen liquefaction System – Purification and Liquefaction equipment for a 300l/h plant”.
- B. MPR Associates report Design Evaluation of the Combustion light Gas Gun, January 2006.
- C. Northrop Grumman, DD(X) Hull 34A Deck & Bulkhead drawings dated July 2004 (CAD files).

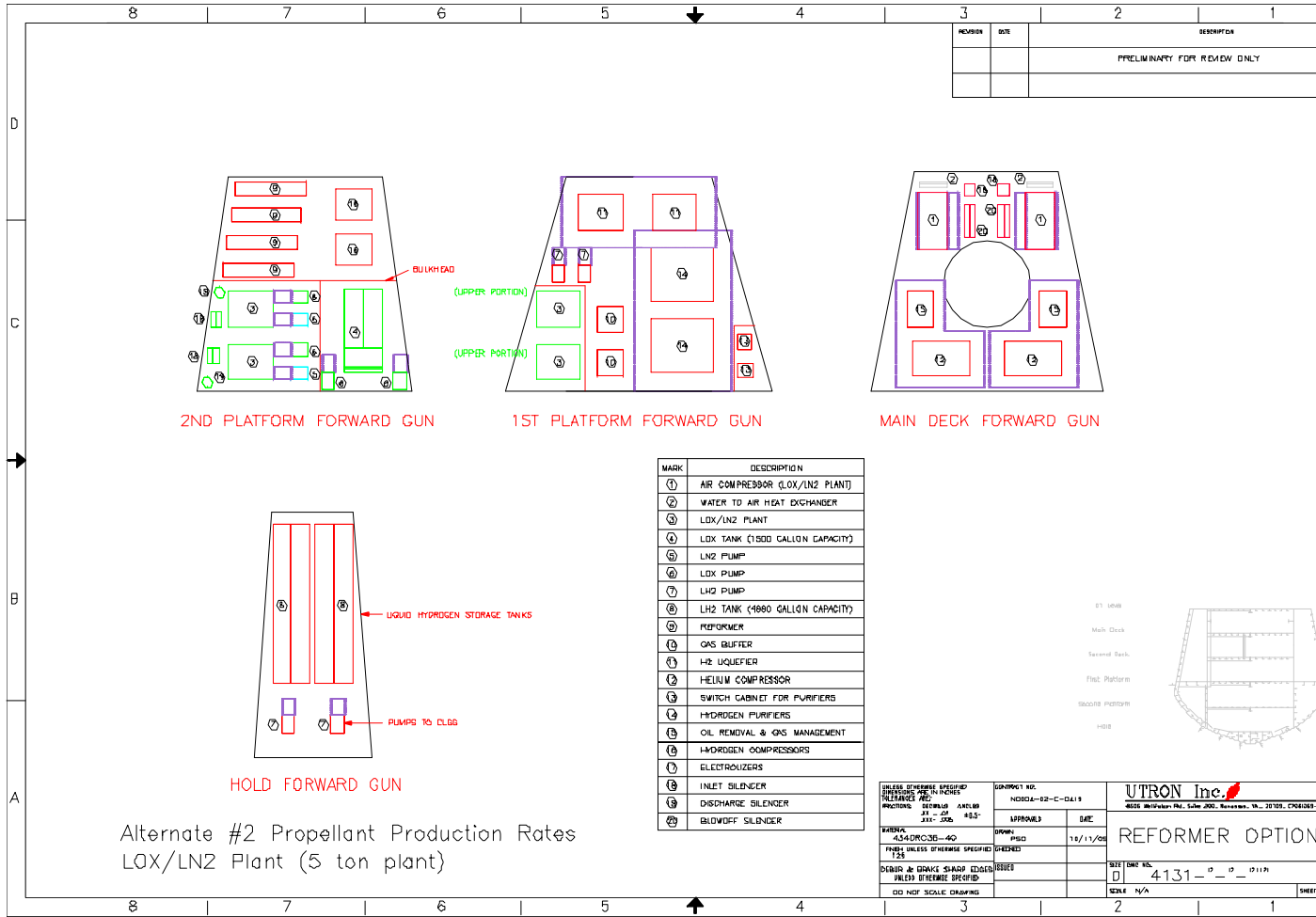
List of Appendices:

Appendix A Machinery Arrangement Drawings

(Note: only Alternate #2 Systems are shown below however CAD drawings are available at Utron, Inc for all system arrangements listed)

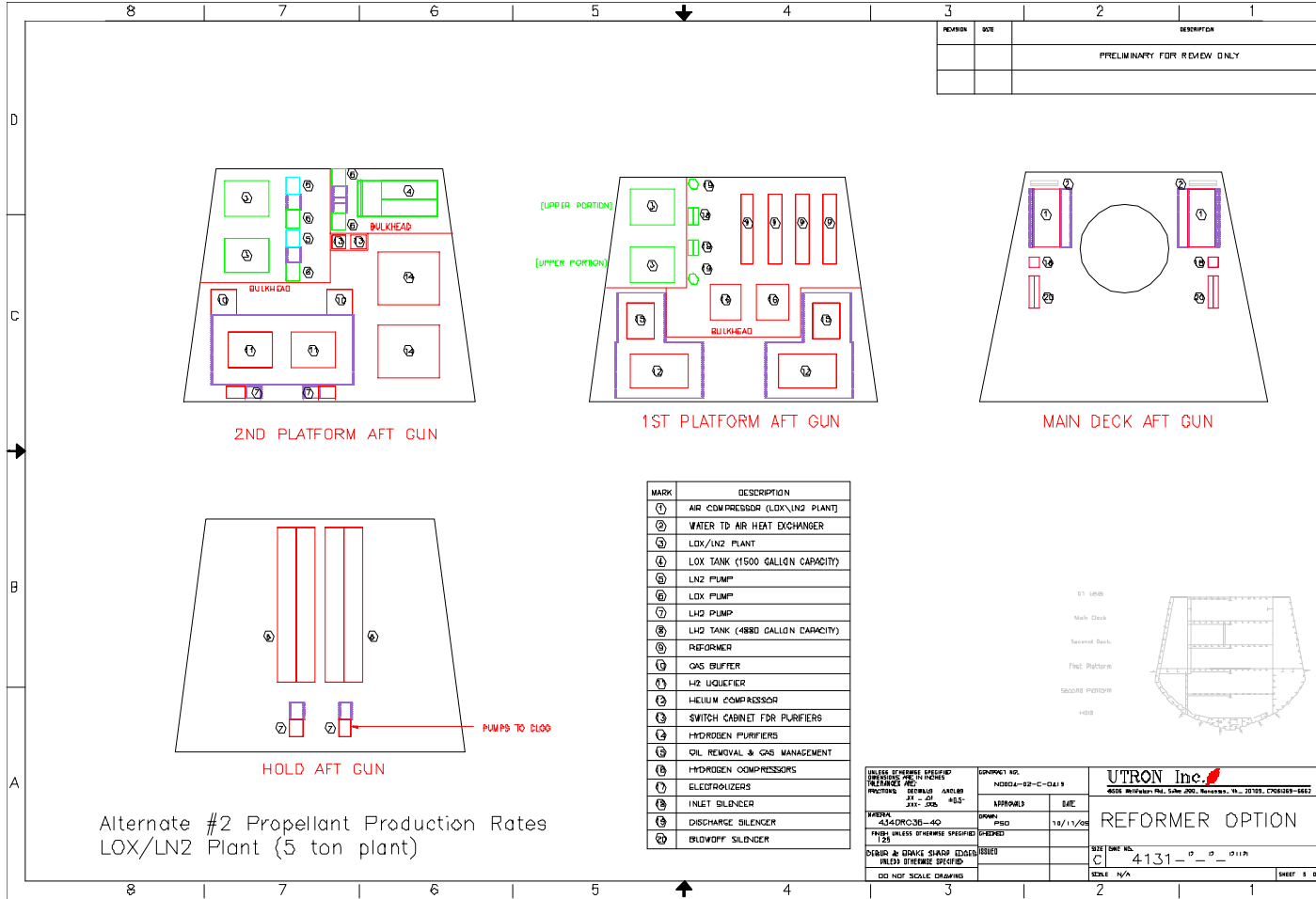
- A-1 Machinery Arrangement – Baseline System Reformer Option (on file)
- A-2 Machinery Arrangement – Baseline System Electrolysis Option (on file)
- A-3 Machinery Arrangement – Alternate #1 Reformer Option (on file)
- A-4 Machinery Arrangement – Alternate #1 Electrolysis Option (on file)
- A-5a & b shown below
- A-6a & b shown below
- A-7 Machinery Arrangement – Alternate #3 Reformer Option (on file)
- A-8 Machinery Arrangement – Alternate #3 Electrolysis Option (on file)

# A-5a Machinery Arrangement – Alternate #2 Reformer Option Forward Gun

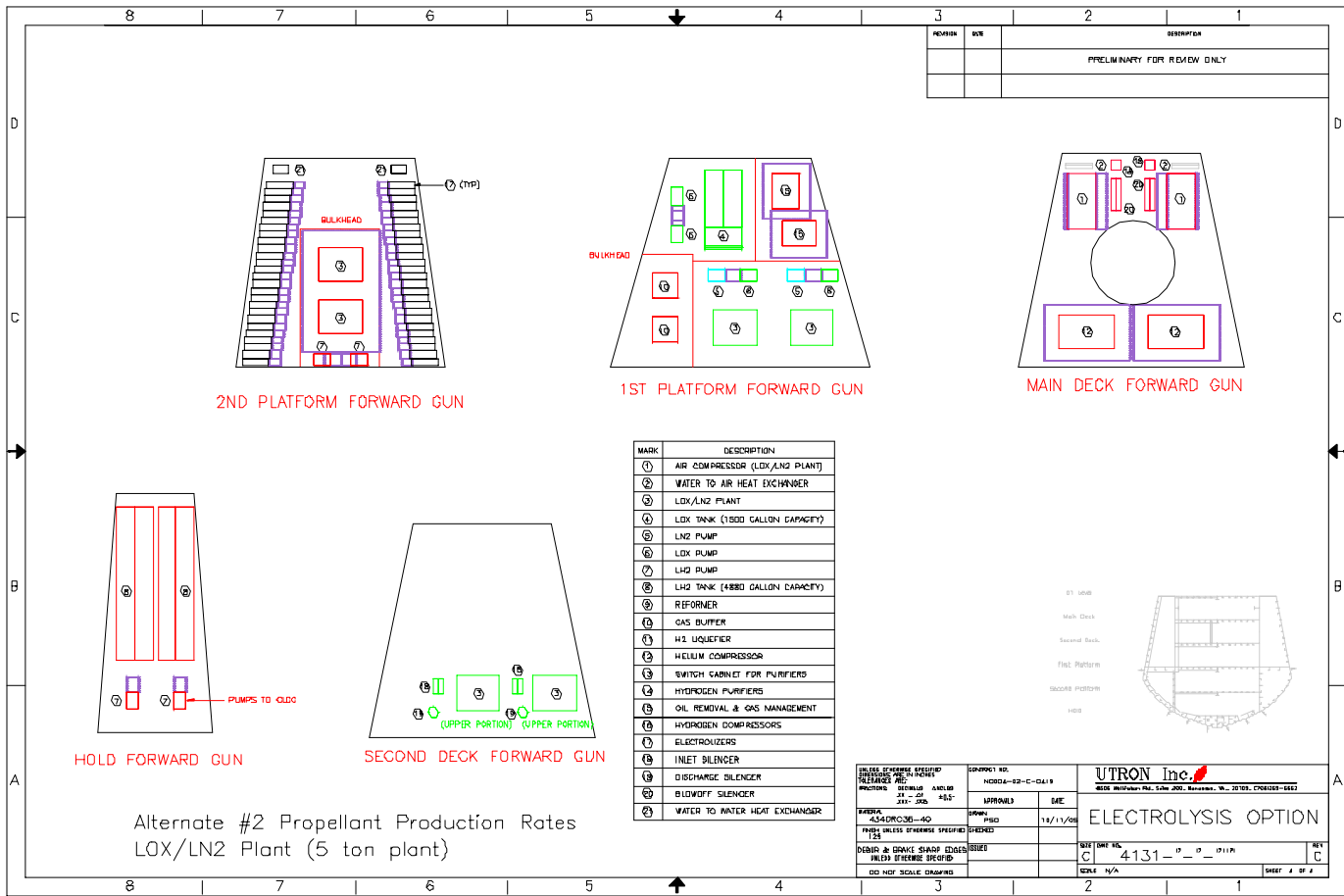




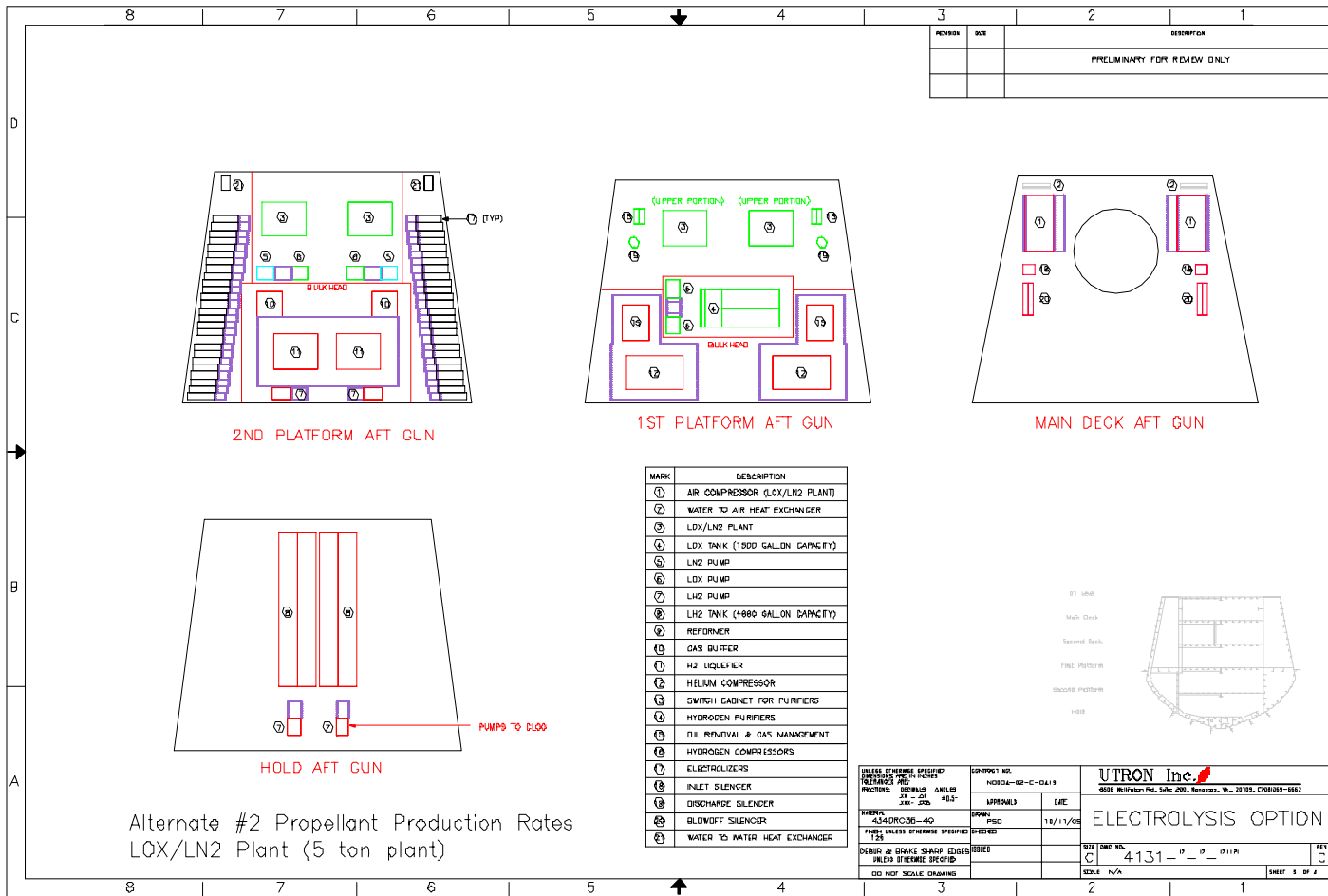
# A-5b Machinery Arrangement Alternate #2 Reformer Option Aft Gun



# Appendix A-6a Machinery Arrangement Alternate #2 Electrolysis Option Forward Gun



# Appendix A-6b Machinery Arrangement Alternate #2 Electrolysis Option Aft Gun



Appendix B – Machinery Equipment List for Baseline & Alternatives

No.	Equip. Description	Baseline	Baseline	Alternate	Alternate	Alternate	Alternate	Alternate	Alternate
		with Reformer per Gun	with Electrolysis per Gun	#1 Reformer per Gun	#1 Electrolysis per Gun	#2 Reformer per Gun	#2 Electrolysis per Gun	#3 Reformer per Gun	#3 Electrolysis per Gun
		Quantity	Quantity	Quantity	Quantity	Quantity	Quantity	Quantity	Quantity
1	Air Compressor	2	2	2	2	2	2	2	2
2	Heat Exchanger	2	2	2	2	2	2	2	2
3	LN2/LOX Plant	2	2	2	2	2	2	2	2
4	LOX Tank	1	1	1	1	1	1	1	1
5	LN2 Pumps	2	2	2	2	2	2	2	2
6	LOX Pumps	4	4	4	4	4	4	4	4
7	LH2 Pumps	4	4	4	4	4	4	4	4
8	LH2 Tank	2	2	2	2	2	2	2	2
9	Reformer	6	0	3	0	4	0	2	0
10	Gas Buffer	2	2	0	0	2	2	2	2
11	H2 Liquefier Cold Box	2	2	0	0	2	2	2	2
12	Helium Compressor Switch Cabinet for Purifier	2	2	0	0	2	2	2	2
13	Hydrogen Purifiers	2	2	2	2	2	2	2	2
14	Oil Removal & Gas Mgt.	2	2	2	2	2	2	2	2
15	Hydrogen Compressors	2		2		2		2	
16	Electrolyzes	0	72	0	36	0	52	0	22
17	Sea Water Heat Exchanger						2		

Notes:

1. Hydrogen system liquefier KWs for reduced hydrogen production scenarios based on a linear KW per hydrogen KG based on LH2 production capabilities of system and 0.73 liters of liquid nitrogen per liter of H2.

Appendix C System Relative Rating Matrices for Design Alternatives

Appendix C-1 Rating Matrix for Reformer Options

**Systems Rating Matrix**

Category	Reformer							
	Base*		Alternate 1		Alternate 2		Alternate 3	
	Category	Rating	Category	Rating	Category	Rating	Category	Rating
Area (Sq. Ft.)	3,459	15	3,310	33	3,341	29	3,323	32
Volume (cu. Ft.)	24,011	23	23,087	37	24,267	18	20,961	71
Weight (lb.)	613,142	83	565,142	96	549,142	100	549,142	100
Power (kW)	2,906	92	2,906	92	2,431	95	1,758	100
Fuel Consumption (Gallons)	34,615	68	23,098	100	22,993	100	29,839	81
Hydrogen Production Mass Flow (lb/hr)	313.5	100	155.3	30	200.2	50	88	0
Replenishment Time (hours)	60	100	74.4	86	72	88	161	0
Cost Operation Maintenance Technology Readiness Level Safety								
Composite System Rating		40		39		40		32
Overall Rank		2		3		1		4

Appendix C-2 Rating Matrix for Electrolysis Options

**Systems Rating Matrix**

Category	Electrolysis							
	Base*		Alternate 1		Alternate 2		Alternate 3	
	Category	Rating	Category	Rating	Category	Rating	Category	Rating
Area (Sq. Ft.)	3,577	0	3,143	54	3,323	32	2,776	100
Volume (cu. Ft.)	25,426	0	22,213	51	24,530	14	19,137	100
Weight (lb.)	929,782	0	713,782	57	777,782	40	629,782	79
Power (kW)	15,826	0	9,346	46	11,751	29	5,678	72
Fuel Consumption (Gallons)	59,195	0	39,686	54	43,361	44	48,694	29
Hydrogen Production Mass Flow (lb/hr)	313.5	100	155.3	30	200.2	50	88	0
Replenishment Time (hours)	60	100	74.4	86	72	88	161	0
Cost Operation Maintenance Technology Readiness Level Safety								
Composite System Rating		17		31		25		32
Overall Rank		8		6		7		5



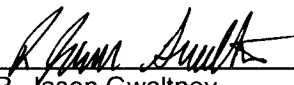
Appendix E – Executive Summary of Independent Ship Integration,  
Comparison and Safety Analysis



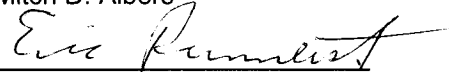
# ***Design Evaluation of the Combustion Light Gas Gun***

MPR-2921  
Revision 0

April 12, 2006

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Reviewed by:   
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*Prepared for*

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# Executive Summary

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## Background

The Combustion Light Gas Gun (CLGG) is an impulse-propulsion gun firing a 155 mm guided projectile. The projectile is powered by liquid hydrogen and liquid oxygen that is injected into the gun chamber and combusted. Utron, Inc. has been responsible for the design and development of the CLGG. This gun has been under development since 1996 and a 45 mm prototype has experimentally demonstrated muzzle velocities greater than 4 km/sec (13,120 ft/sec).

## System Description

The CLGG System includes all of the support equipment necessary to operate the Combustion Light Gas Gun, including:

- Liquid Hydrogen and Oxygen Production Plants
- Liquid Hydrogen and Oxygen Storage Tanks
- Projectile Stowage

Additionally, this equipment has been designed such that it will fit into a typical gun magazine-type space on a Navy destroyer. Currently the CLGG System design has two options for hydrogen production: electrolyzers and diesel reformers. Electrolyzers are the more mature technology; the model being used in this design is also installed on Navy submarines. Diesel reformers are more energy efficient and will consume less diesel fuel than the electrolyzers. This report considers both options.

## Capabilities

The CLGG System compares favorably to other proposed gun systems with respect to system size, weight, firing rate and operability. The CLGG however, has several distinct advantages over other gun systems, such as:

- Variable range up to 200 nautical miles
- Insensitive, guided projectiles (safer storage and supports more rounds per ship)
- Lower operating costs, including projectile cost
- Easily scalable to support longer sustained rates of firing (i.e. larger H<sub>2</sub> storage tanks allow more rounds to be fired at a given firing rate)
- Single H<sub>2</sub>/O<sub>2</sub> production system can support multiple guns of different sizes

# 4 Conclusions and Recommendations

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## 4.1 CONCLUSIONS

The Combustion Light Gas Gun (CLGG) System compares well to other proposed gun systems with respect to system size, weight, firing rate and operability. Overall, the CLGG has substantial potential as a next-generation gun system. Several distinct advantages over other gun systems include:

- Variable range up to 200 nautical miles which greatly exceeds other guns systems with ranges of 80 nautical miles
- Insensitive, guided projectiles (safer storage and supports more rounds per ship)
- Lower operating costs, including projectile cost
- Easily scalable to support longer sustained rates of firing (i.e. larger H<sub>2</sub> storage tanks allow more rounds to be fired at a given firing rate)

## 4.2 RECOMMENDATIONS

The design of the CLGG is still evolving and there are areas of the system that need additional refinement. In particular, the CLGG has the following limitations:

- Limited impact energy (limited to kinetic energy of projectile)
- Health and fire risks associated with onboard H<sub>2</sub> and O<sub>2</sub> storage
- Risk of spilled H<sub>2</sub> and O<sub>2</sub> embrittling/weakening ship structure

These limitations can be overcome through modifications to the existing design. The following recommendations have been developed to resolve or mitigate the current limitations of the system:

- Determine if kinetic energy projectiles are sufficiently lethal to satisfy Naval Gun Fire Support (NGFS) CONOPS
- Determine if existing munitions technology will enable launching of projectiles containing high explosives (HE) at the high muzzle velocities used by the CLGG
- Research the best industry practices for storage and handling of cryogenic materials
- Design a fire detection and suppression system and develop a damage control and recoverability approach

- Compare the safety risks of a traditional gun system to the CLGG taking into consideration the proposed fire detection and suppression system

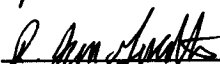
# **Combustion Light Gas Gun, Safety Analysis Report**


MPR-2958  
Revision 0

July 2006

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Reviewed by:   
Jason Gwaltney

Approved by:   
Eric Runnerstrom

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## *Prepared for*

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# Executive Summary

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The Combustion Light Gas Gun (CLGG) is an impulse-propulsion gun that combusts a pure hydrogen and oxygen mixture in the breech to propel the projectile. The gun is intended for installation on a naval surface combatant. This report evaluates safety considerations associated with this installation and provides a review of generation, handling, and storage of gaseous and liquid hydrogen, oxygen and nitrogen. The purpose of this report is to identify specific areas for more detailed development and design to enable a safe, effective installation of the CLGG aboard ship.

Reviews of NASA and industry experience with the production, storage and use of liquid and gaseous hydrogen and oxygen were undertaken to identify risks and mitigating actions associated with these materials in a shipboard environment. Design considerations and operating actions were identified to prevent cryogenic burns to personnel and to limit the risks for fires and explosions. Firefighting techniques for fires involving hydrogen and oxygen were also reviewed and are described in this report.

Liquid hydrogen is a cryogenic liquid that poses a burn risk if it contacts the skin. Gaseous hydrogen is an asphyxiant. These risks can be mitigated through appropriate insulation of piping and tanks and by appropriate ventilation of ship spaces. Hydrogen is also a fire/explosion hazard. Hydrogen fire risks can be mitigated by appropriate ventilation, effective leak detection and, for fire suppression, water spray deluge systems.

Liquid oxygen and nitrogen (which is used in the system) are also cryogenic and can cause burns on contact with skin. Nitrogen gas is also an asphyxiant. Risks can be mitigated through appropriate insulation and ventilation. Oxygen leaks can lead to high oxygen environments that increase the risk of fire. These risks can be mitigated through leak detection, space ventilation and an installed water deluge system.

Based on the review of risks associated with the generation and storage of hydrogen and oxygen on a Navy ship, we conclude there is no fundamental reason that these materials cannot be used to support a ship installation of the CLGG. Industry experience indicates that through the implementation of proper system design, formal operating procedures, personnel training and leak detection, the risks associated with storing liquefied hydrogen and oxygen can be brought to within reasonable levels. Additionally, there are features of the CLGG system (with kinetic energy projectiles) that are likely to make it more safe than a traditional munitions system:

- Off-shore handling hazards associated with munitions handling are eliminated,
- Eliminates need to transport explosive materials from the shore to ships,

- Allows the ship to jettison its hazardous payload in a safe and environmentally friendly manner (if CLGG equipment is operational, the payload of oxygen and hydrogen can be replenished after the hazardous situation has been resolved), and
- Ship can go into a system lay-up mode without offloading munitions.

# ***Fire Risk Analysis for a Combustion Light Gas Gun***

Prepared for

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Manassas, VA 20109

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# 2

## Summary of Results and Conclusions

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### 2.1 SUMMARY OF RISKS

The following six fire scenarios are considered in this Fire Risk Analysis, and are discussed in Section 5:

- Weapons hit
- Severe fire in an adjacent space (such as due to a weapons event)
- Fire involving oxygen leak
- Fire involving hydrogen leak
- Fire involving NATO F-76 diesel fuel (for reformer option)
- Electrical or general combustible fire

For these six scenarios, the risk rankings are summarized in Table 2-1.

**Table 2-1.** Summary of Fire Risk Rankings for CLGG Magazines

Fire Scenario	Consequences	Likelihood	Unmitigated Risk Index <sup>1</sup>	Effectiveness of Mitigating Features	Mitigated Risk Index
Weapons hit	Catastrophic	Remote	2	Low	High
Severe fire in adjacent space	Critical	Remote	3	High	Low
Fire involving oxygen leak	Catastrophic	Remote	2	High	Low
Fire involving hydrogen leak	Catastrophic	Remote	2	High	Low
Fire involving NATO F-76 diesel fuel (for reformer option)	Critical	Remote	3	High	Low
Electrical or general combustible fire	Critical	Occasional	2	High	Low

<sup>1</sup> 1 is most hazardous, 4 is least hazardous

# 6

## Conclusions

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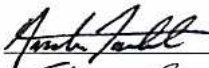
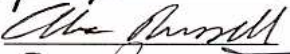
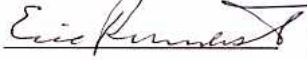
### 6.1 REQUIRED FIRE PROTECTION FEATURES

The following features of the Combustion Light Gas Gun magazine are considered necessary to ensure that a low mitigated fire risk index will be achieved:

- The CLGG magazine will have a dedicated exhaust/ventilation system. This will include shutoff dampers that will only be activated in the event of a fire.
- Exhaust ventilation takes suction low in the space, near deck level, to remove oxygen and reduce the concentration.
- Hydrogen equipment compartments contain high point vents with no overhead dead spaces which could trap the gas.
- Oxygen and hydrogen leak detection systems will alert the crew to a breach in a pressure boundary or the inability of the ventilation system to remove normal levels of leakage from the system.
- The magazine is assumed to have three common fire detection systems: smoke aspiration, optical flame detectors (OFD), and linear heat detectors (LHD).
- The optical flame detectors, linear heat detectors, and any other detection systems are designed and located for optimal detection.
- Electrical equipment is enclosed by cabinets or similar enclosures and these enclosures will be of sufficient structural integrity to contain the energy release from any faults that can occur within the enclosure.
- Electrical/electronic enclosures and cabinets are designed to prevent water spray damage to energized equipment.
- Rapid de-energization of electrical equipment and circuits within the magazine is provided as part of the response to a fire.
- Cabinets are watertight in accordance with MIL-STD-108 (Reference 2).
- A deluge-type water sprinkling system.

January 4, 2007

Mr. Richard Milligan  
Utron Inc.  
8506 Wellington Road Suite 200  
Manassas, VA 20109

Prepared by	
Reviewed by	
Approved by	

Subject: Comparison of CLGG and Modern Gun Magazine Fire Risk Analyses

Dear Mr. Milligan:

MPR has completed evaluations of the fire risk of the Combustion Light Gas Gun (CLGG) magazine and of a representative modern gun magazine. The magazine of the CLGG is significantly different from both traditional and modern gun magazines. The CLGG magazine includes hydrogen (H<sub>2</sub>) production and storage, oxygen (O<sub>2</sub>) production and storage, and inert projectile storage. Modern gun magazines are a departure from traditional magazines in that they include high voltage electronics, machinery associated with fully automated munitions loading, and storage of munitions on composite pallets, in addition to the warhead and propellant materials in the projectiles.

The results of the FRAs show that the Mitigated Risk Assessment (i.e., the risk associated when all mitigation features are considered) for the CLGG magazine and the modern gun magazine is "low" for all plausible fires except Weapons Events. The main factor in driving the overall risk to "low" was the effectiveness of the mitigation features. Typically, Weapons Events are considered over-matching conditions and the results of these FRAs simply confirm this characterization. A weapons event for either design that involves hydrogen detonation, an oxygen fed fire, or munitions detonation, will likely reduce mission capabilities, disable the ship, and result in loss of life.

The CLGG magazine introduces two fuels not found in conventional or modern gun magazines, F-76 diesel and hydrogen, as well as oxygen, which significantly lowers ignition temperatures of combustibles. Accordingly, the CLGG magazine has 3 fire scenarios that do not apply to the modern gun magazine. However, the CLGG magazine will not contain the munitions/propellant

present in modern gun magazines. To mitigate these hazards, the CLGG shipboard installation also must contain:

- Dedicated hydrogen ventilation including shutoff dampers, vents located in the overhead, and a special design to minimize trapped gasses.
- Oxygen ventilation with vents located near the deck.
- Hydrogen and oxygen gas detectors.
- Specialized detectors to “see” an invisible hydrogen flame.

However, the most critical protection feature of the CLGG is proper arrangement of equipment which significantly reduces the chance of a fuel and ignition source combining to ignite a fire:

- Hydrogen production and storage components and oxygen production and storage components are separated by bulkheads.
- Installing H<sub>2</sub> production equipment in hermetic enclosures.
- Minimizing fuels in spaces with heat sources or electrical equipment.

In addition, providing blast panels for spaces containing the H<sub>2</sub> storage tanks (or locating these spaces near the exterior of the ship, if possible) can significantly reduce the consequences of a hydrogen detonation to the ship.

From a fire risk perspective, the CLGG does offer some advantages over the modern gun magazine:

- The CLGG system can be completely inerted by purging the H<sub>2</sub> and O<sub>2</sub> from the system. The H<sub>2</sub> and O<sub>2</sub> can easily be recovered, unlike munitions and equipment after the flooding or sprinkling of a modern gun magazine.
- The supply chain to support the CLGG does not require transport and storage of explosive munitions. This is a significant advantage over a modern gun magazine as many of the difficulties associated with the munitions (e.g., storing, loading, and unloading) are removed.
- The modern gun magazine’s use of high voltage electrical equipment inside the magazine for automatic gun loading is a significant divergence from the Navy’s historical safeguards for magazines. Although the CLGG system has an autoloader, it is not located with the hydrogen or oxygen.

- Flooding of the CLGG magazine will likely result in temporary loss of equipment whereas flooding or sprinkling of a modern gun magazine will likely result in permanent damage of munitions or handling equipment.

Overall however, the CLGG does introduce new fire hazards that are not typical for Navy magazines, specifically the storage and use of hydrogen on board a ship. Although new to Navy applications, hydrogen has been used successfully in industry and its required fire protection features are well understood. Oxygen has been safely produced and stored aboard Navy ships for some time, particularly aircraft carriers.

We conclude that, with good design, the CLGG magazine can present less fire risk to the ship than a modern gun magazine. In particular, the CLGG can be purged of hazardous materials, operations permitting, so that the fire risk is eliminated, and easily restored to operation when needed. In addition, the elimination of explosive ordinance from the supply chain is a significant fire risk reduction for the entire Navy with the CLGG.

Sincerely,



Eric Runnerstrom

Enclosure: Comparison of CLGG and Modern Gun Magazine Fire Risk Analyses

Attachment 1: Fire Risk Analysis for a Combustion Light Gas Gun

Attachment 2: Fire Risk Analysis for a Representative Modern Gun Magazine

cc: D. Massey, D. Kruczynski