Empirical Study: Failure of Glass-to-Metal Seals During Shock Loading

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ABSTRACT

The goal of this thesis was to determine the empirical failure mechanisms and sequence of cartridge actuated devices (CADs) experiencing failure of the glass-to-metal (G/M) seal. Impact loading was conducted with a drop weight machine at room temperature and 300°F, and then empirically analyzed with high speed video. Resulting peak overload force, shear stress, and impulse were all calculated. The room temperature samples were found to absorb twice the impulse upon failure as the elevated temperature G/M seals. Closed-form and three-dimensional finite element analysis was used to determine the stress state and deformation upon loading. Furthermore, high speed data was collected for shock load detonation events to document the failure sequence of a G/M seal under such loading. The shock overload event was found to last 0.82 µsec and propel an electrical feed-through-pin at a terminal velocity of 955 m/s. The core of a multiple pin G/M seal design was found to experience large accumulations of principal stress and deformation during pressure loading of the interior face. High speed video data discovered the G/M seal failed along the glass-to-pin interface during shock overload failure. Overall, this thesis provided definition of failure sequence and highlighted problematic structural areas, as well as design weaknesses for construction of G/M seals.
ACKNOWLEDGEMENTS

It has been a great privilege to have Dr. Eric Skaar as my thesis adviser and committee chairman. He is truly a pleasure to work for, and I benefitted greatly from his expertise, support, and patience. Dr. Skaar provided the overall guidance throughout the past few years, to help this dream become a reality, through his confidence, motivation, and support. We have truly shared some fond moments in philosophical debate over the nature of the universe. I am deeply indebted to Glen Stichling of CAD Inc. for the coordination of their laboratory facilities and for his excellent guidance, particularly during the final stages of this work. His rigorous approach to problem solving is demanding but enlightening. Thanks to Paul Delgrego of Del Imaging Systems for his expertise, help, and suggestions achieving the high speed photography.

On the personal side, my deepest and warmest thanks go to my parents David and Peggy Horton for their unfailing support, encouragement, and love. Additionally, my fiancée Kristen Wallis, more than she can realize, she has taught me much about life and made life worth living. It is her support that made the final stages of this work bearable. To her I dedicate this thesis. The friendship that Charles Hudson and I have developed over the past few years is proof that misery loves company. I hope that I can someday assist him as much as he has helped me. And thanks to my dear friends Tony Martin and Gary Street, who are a constant source of inspiration. Their unending energy, faith, and belief in the future are contagious. Finally, thank you to Daniel Williams for always encouraging me to have the faith in myself to take risks and strive for the best. And most importantly, I thank the Lord for establishing the principles upon which I strive to live my life.
# CONTENTS

Title Page ............................................................................................................................... i
Abstract .................................................................................................................................. ii
Acknowledgements ............................................................................................................... iii
Contents .................................................................................................................................... iv
List of Figures ....................................................................................................................... v
List of Tables ........................................................................................................................ vi
Nomenclature ...................................................................................................................... vii
Executive Summary .............................................................................................................. 1
  Section 1.1 Introduction ...................................................................................................... 1
  Section 1.2 Overall Project Goal and Objectives ................................................................. 3
  Section 1.3 Methods ........................................................................................................... 4
  Section 1.4 Embodiment of Design ................................................................................... 5
  Section 1.5 Results ............................................................................................................ 8
  Section 1.6 Structure of This Thesis .................................................................................. 8
Literature Survey .................................................................................................................. 10
  Section 2.1 Overview/Organization .................................................................................. 10
  Section 2.2 Mechanical Structure of G/M Seals ................................................................. 11
  Section 2.3 Modeling Deformation of Interfaces ............................................................... 13
  Section 2.4 Interface Diffusion ......................................................................................... 17
  Section 2.5 Shock Deformation ....................................................................................... 18
  Section 2.6 Concluding Thoughts .................................................................................... 21
Mechanical Impact Loading ................................................................................................. 22
  Section 3.1 Introduction ................................................................................................... 22
  Section 3.2 G/M Seal Design ........................................................................................... 22
  Section 3.3 Identification of Test Method ......................................................................... 26
  Section 3.4 Findings ......................................................................................................... 31
  Section 3.5 Concluding Thoughts .................................................................................... 35
Finite Element Analysis ....................................................................................................... 36
  Section 4.1 Introduction ................................................................................................... 36
  Section 4.2 Closed form Solutions .................................................................................... 36
  Section 4.3 Computational Solutions .............................................................................. 40
  Section 4.4 Concluding Thoughts .................................................................................... 46
Shock Loading ....................................................................................................................... 47
  Section 5.1 Introduction ................................................................................................... 47
  Section 5.2 Nonlinear Shock Wave ................................................................................... 48
  Section 5.3 Identification of Test Method ......................................................................... 49
  Section 5.4 Findings ......................................................................................................... 56
  Section 5.5 Concluding Thoughts .................................................................................... 60
Conclusions ............................................................................................................................ 62
Bibliography .......................................................................................................................... 65
Appendix A. Impact Test Machine Drawings ...................................................................... 68
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Dimensions and Materials of G/M Seal Initiator</td>
<td>5</td>
</tr>
<tr>
<td>Figure 2</td>
<td>CAD Assembly and Sequence of Failure</td>
<td>7</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Mechanical Analogy of An Interface</td>
<td>14</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Stress States in G/M Seals</td>
<td>23</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Example Tensile Stresses in G/M Seal</td>
<td>24</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Meniscus Wetting Conditions</td>
<td>25</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Loading of G/M Seal for Push-Out Test</td>
<td>26</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Load Curve for Impact at RT and 300°F</td>
<td>28</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Impact High Speed Photo-Time Stamp 0.392194 s</td>
<td>29</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Impact High Speed Photo-Time Stamp 0.396051 s</td>
<td>30</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Impact High Speed Photo-Time Stamp 0.398622 s</td>
<td>30</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Impact High Speed Photo-Time Stamp 0.428480 s</td>
<td>31</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Glass Geometry Ratio</td>
<td>38</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Maximum Residual Principal Stress</td>
<td>39</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Multiple Pins in Single Glass Bead Design</td>
<td>40</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Axisymmetric Mesh of G/M Seal Used for FEA</td>
<td>41</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Von-Mises Deformation-Interior Face</td>
<td>42</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Von-Mises Deformation-Axial Face</td>
<td>43</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Maximum Principal Stress-Exterior Face</td>
<td>44</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Maximum Principal Stress-Interior Face and Axial Face</td>
<td>45</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Maximum Principal Stress-Interior Face</td>
<td>45</td>
</tr>
<tr>
<td>Figure 22</td>
<td>Typical CAD Assembly</td>
<td>49</td>
</tr>
<tr>
<td>Figure 23</td>
<td>CAD and Isolation Cap</td>
<td>50</td>
</tr>
<tr>
<td>Figure 24</td>
<td>Detonation Test Chamber</td>
<td>51</td>
</tr>
<tr>
<td>Figure 25</td>
<td>Shock Load High Speed Photo-Time Stamp 0.000162 s</td>
<td>52</td>
</tr>
<tr>
<td>Figure 26</td>
<td>Shock Load High Speed Photo-Time Stamp 0.000187 s</td>
<td>52</td>
</tr>
<tr>
<td>Figure 27</td>
<td>Shock Load High Speed Photo-Time Stamp 0.000212 s</td>
<td>52</td>
</tr>
<tr>
<td>Figure 28</td>
<td>Shock Load High Speed Photo-Time Stamp 0.000237 s</td>
<td>53</td>
</tr>
<tr>
<td>Figure 29</td>
<td>Shock Load High Speed Photo-Time Pin Failure</td>
<td>53</td>
</tr>
<tr>
<td>Figure 30</td>
<td>Close Bomb Test Configuration</td>
<td>54</td>
</tr>
<tr>
<td>Figure 31</td>
<td>Typical Pressure Trace of CAD Detonation</td>
<td>55</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1. Thermal and Mechanical Properties ................................................................. 4
Table 2. Load and Stress for Impact Test ........................................................................ 27
Table 3. Pin Displacement, Velocity, and Acceleration ................................................. 53
Table 4. Closed-Bomb Pressure Data .......................................................................... 55
Table 5. Average CAD Closed-Bomb Data .................................................................. 56
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Effective coefficient of expansion (20°C to 445°C)</td>
</tr>
<tr>
<td>K</td>
<td>Thermal Conductivity</td>
</tr>
<tr>
<td>Cρ</td>
<td>Heat Capacity</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
</tr>
<tr>
<td>E</td>
<td>Modulus of Elasticity</td>
</tr>
<tr>
<td>ET/E</td>
<td>Ratio of Plastic Modulus to Elastic Modulus</td>
</tr>
<tr>
<td>ν</td>
<td>Poisson’s Ratio</td>
</tr>
<tr>
<td>σy</td>
<td>Yield Strength of Ductile Metal</td>
</tr>
<tr>
<td>στ</td>
<td>Uniaxial Tensile Stress Limit</td>
</tr>
<tr>
<td>σc</td>
<td>Uniaxial Compressive Stress Limit</td>
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Explanation</th>
</tr>
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<tbody>
<tr>
<td>G/M</td>
<td>Glass-to-Metal</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>CAD</td>
<td>Cartridge Actuated Device</td>
</tr>
<tr>
<td>CMZ</td>
<td>Cohesive Zone Model</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>RT</td>
<td>Room Temperature</td>
</tr>
<tr>
<td>GGR</td>
<td>Glass Geometry Ratio</td>
</tr>
<tr>
<td>psi</td>
<td>pounds per square inch</td>
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SECTION 1.1 INTRODUCTION

Cartridge Actuated Devices (CADs) are commodity items that function as a system component. In operation, they release a precise explosive of propellant energy to perform controlled work. They function in a variety of military system applications, including aircrew escape, fire suppression, and stores/emergency release systems. Even air bag approaches are CAD-driven based on the quick response time and space/weight to force restrictions.

CAD composition consist of pyrotechnic material, electrical bridge wire for ignition, and an insulating feedthrough containment consisting of a Glass-to-Metal Seal. Degradation of the G/M seal can cause the CAD to not be hermetically sealed and malfunction or function improperly. About 3,100 different configurations are now in use by all Military Services. Many of these configurations are man-rated, mission essential, requiring a high degree of reliability.\[1\] They are normally developed as a component of a weapon or life support system. All have a defined shelf/service life and must be replaced

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\[1\] Man Rated: Controls hazards with sufficient certainty to be considered safe for human operations, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations.
periodically. CADs that are needed for safety of flight or ship systems can cause the grounding or dry-docking of the vessel if they are defective or past their defined shelf life.

Glass-to-Metal (G/M) seals are a very important part of the packaging and insulation of electrical and chemical components within the CAD. Specifically, for military applications outside the traditional static design criteria, the G/M seal must provide hermetic containment of very corrosive and reactive materials from surrounding environments. Additionally, they must perform to a very tight specification of electrical insulation properties to ensure detonation. The Navy currently utilizes a comprehensive set of specifications and design criteria for CADs, but fundamental knowledge of the behavior of G/M seals under these conditions is lacking.

Modern knowledge in the field of sealing technology provides ample results for static loading; however, the area of high-strain shock-loading of G/M seals is unstudied and unknown. For example, a prime DoD CAD manufacturer utilizes empirical proof-testing results to certify designs of G/M seals, but has little fundamental knowledge of seal behavior under shock-loading. Currently, this proof-testing is limited to the redundant destruction of duplicate seals prior to certifying a part for shipment. This is one potential area that adds to the total cost of procurement incurred by the military. Understanding the fundamental properties for military applications of G/M seals will reduce the statistical requirement for samples necessary to ensure performance of mission critical parts, thus contributing to the overall cost savings of military CAD manufacturing.
Present and future designs have resulted in smaller volume allowances for CAD devices. In the past, seals were simply over-designed with high safety factors so failure was not a primary concern. However, volume restrictions push the envelope and stretch design stress levels to the limit of empirical knowledge. A recent example from a Naval supplier for a torpedo application directly required a small volume seal that withstands a high order explosive, or shock-load driven response, rather than pressure driven, and was required to maintain seal integrity adjacent to shock loading. There was no existing data on shock load performance of a G/M seal for this contractor to utilize other than past knowledge of over-design conditions.

SECTION 1.2 OVERALL PROJECT GOAL AND OBJECTIVES

Collective goals of the project include the documentation of impact and shock loading failure events of G/M seals.[2] Subsequently, perform a root-cause investigation, aided by Finite Element Analysis (FEA) to produce stress plots and substantiate mechanical design. Finally, the culmination of this work is to produce a compressive definition of the failure sequence of CAD units during G/M seal overload events.

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[2] Impact loading is a dynamic load resulting from the motion of energy waves below the acoustic range. Shock loading produces energy waves that potentially cause changes in microstructure and irreversibly alter material properties.
SECTION 1.3 METHODS

The methods used to determine the weakness of G/M seal design include mechanical dynamic impact, finite element analysis, and chemical or pyrotechnic shock loading. FEA, static mechanics of material method, was used to model the stress state of the G/M seal. G/M seals during production have large accumulations of residual stresses. Literature was surveyed to use principal closed form solutions for these values and incorporated into the initial model. The stresses calculated for the interface pressures were applied to the assembled model and radial and tangential stresses were solved. Meshes of the assembled G/M seal were analyzed in Solidworks® Simulation. The FEA models included static stress with linear material responses and mechanical event simulation.

Dynamic tests were accomplished by loading with a blunt pin on the face of the glass seal. The pin was slightly undersized to the diameter of the glass to isolate loading to the G/M interface. A high speed video recorder was positioned perpendicular to the G/M seal axis to produce sequential frames during overload failure.

Chemical pressure response shock load tests were conducted in an isolated detonation chamber capable of withstanding the explosive force upon ignition. Again a high speed camera was positioned, behind a protective shield with a view port, perpendicular to the G/M seal axis. Seals were pyrotechnically loaded within a solid housing designed to insure that complete overload failure occurs at the seal only.
SECTION 1.4 EMBODIMENT OF DESIGN

Many different design configurations exist for both G/M seals and housing designs, based on component geometry, materials, and CAD performance requirements. The components and dimensions of the initiator under consideration in this work are represented in Table 1 and Figure 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Alloy 52</th>
<th>9010 Glass</th>
<th>303 S.S.</th>
</tr>
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<tbody>
<tr>
<td>$\alpha$ (1/°C)</td>
<td>10.2 X 10^{-6}</td>
<td>10.2 X 10^{-6}</td>
<td>16.6 X 10^{-6}</td>
</tr>
<tr>
<td>$K$ (W/m-°C)</td>
<td>100.0</td>
<td>1.09</td>
<td>16.4</td>
</tr>
<tr>
<td>$C_p$ (W-sec/Kg)</td>
<td>0.385</td>
<td>0.8</td>
<td>0.46</td>
</tr>
<tr>
<td>$\rho$ (Kg/m$^3$)</td>
<td>8500</td>
<td>2200</td>
<td>8030</td>
</tr>
<tr>
<td>$E$ (MPa)</td>
<td>206.9 X 10^3</td>
<td>67.57 X 10^3</td>
<td>193.1 X 10^3</td>
</tr>
<tr>
<td>ET/E</td>
<td>---</td>
<td>---</td>
<td>0.1</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.3</td>
<td>0.21</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sigma_y$ (MPa)</td>
<td>344.7</td>
<td>---</td>
<td>241.3</td>
</tr>
<tr>
<td>$\sigma_T$ (MPa)</td>
<td>---</td>
<td>34.5</td>
<td>---</td>
</tr>
<tr>
<td>$\sigma_C$ (MPa)</td>
<td>---</td>
<td>275.8</td>
<td>---</td>
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Table 1. Thermal and Mechanical Properties

Figure 1. Dimensions and Materials of G/M Seal Initiator
The seal was selected based on its previous empirical knowledge in this application and observed limitations. Figure 2 shows how the initiator fits into a CAD, and also a representation of the sequence of events during successful detonation.\textsuperscript{[3]} For the purpose of this thesis, failure occurs when the G/M seal breaks. Failure of other components is not considered. As long as the “outer burst disc” ruptures, failure has not occurred even though the G/M seal may have burst. Ideally, the G/M seal remains intact and all energy is transferred into the rupture of the burst disc, according to the sequence of Figure 2.

The effective life of a CAD is based on the hermeticity and stability of the pyrotechnic components. During static state, the effective life of a CAD, or shelf life, is the length of time given before the entire unit is considered unsuitable for use. For man-rated or mission essential CAD units, it is the regulated time the units can be stored without use, during which, the defined quality of the unit remains acceptable under expected conditions of service. Many of the chemical components of the pyrotechnic materials are highly corrosive and act to degrade the overall hermeticity of the G/M seal. Once seal integrity has been compromised, the CAD is no longer deemed safe for use and must be replaced and disposed of properly.

\textsuperscript{[3]} A deflagration event is characterized by a subsonic flame propagation velocity. In contrast, a detonation event is characterized by supersonic flame propagation velocities.
**Static State:** Pyrotechnic contained in hermetic seal.

**Initiation:** Bridge-wire ignites pyrotechnic.

**Energy release:** Thermal or mechanical primary energy release.

*Figure 2. CAD Assembly and Sequence of Failure*
During initiation, the bridge wire connecting electrical pins and housing burns, and the pyrotechnic material is ignited. Sudden explosion of the material ruptures the inner burst disc, subsequently transferring heat into the gas mixture. Finally, after enough temperature and pressure have built up, the outer burst disc is ruptured and energy is released thermo-mechanically with a flier-plate or pressure release work delivery system.

SECTION 1.5 RESULTS

This work defines the failure sequence of a G/M seal during pressure overload failure. It shows that, during detonation of a chemical initiator, sufficient tensile stresses develop around the pin interface to lead to total failure. Several mechanical properties are characterized to support empirical findings. Furthermore, it reveals how the G/M interface responds during shear loading isolated to the interface region. It is advised that sufficient design considerations of this sequence be observed in future CAD use of G/M seals to increase overall reliability.

SECTION 1.6 STRUCTURE OF THIS THESIS

The following chapter contains a literature review, subdivided on topical basis, pertaining to traditional academic achievements in the field of materials engineering relevant to material selection and environmental concerns. Chapters
3 through 5 describe mechanical impact loading of the G/M interface, finite element analysis, and shock load testing, respectively. Each chapter will contain distinct sections on design approach, method details, and results. Chapter 6 will cover conclusions and future recommendations.
SECTION 2.1 OVERVIEW/ORGANIZATION

For many years, glasses have been used by the electronics industry as a sealing and insulating medium, especially when hermetic needs arise. However, a joint interface consisting of elastically differentiable materials, subjected to impact or high-strain rate loading, is largely undocumented. As Selcuk’s work on determining mechanical strengths for G/M seals notes, “there have been no measurements reported of mechanical properties of seals, nor any discussion of methods by which these properties can be measured.” Much less is there a seemingly present knowledge of shock loading for these interface mechanics. Traditionally, investigators were only interested in residual stresses and differences in thermal expansion between the sealing material and components being sealed. However, this leaves a gap in the armaments industry when such seals are used in the production of CADs.

This review develops a basic understanding of interface issues for mismatched joints and seeks to provide an understanding of problematic areas. Secondly, it begins to show a basic understanding of shock loading for elastic-plastic materials, based on the development of dislocation mechanics.
Additionally, this review presents an understanding of adiabatic properties, which are extremely significant when attempting to understand energy transfer within the matrix due to extremely high energy inputs. Finally, it presents information specifically focused on mechanical construction of G/M seals.

SECTION 2.2 MECHANICAL STRUCTURE OF G/M SEALS

The adherence, or bonding, of glass to metal is extremely important in producing a quality G/M seal. Primarily, two bonding mechanisms are present: mechanical wetting of an irregular or “rough” metal interface by the glass and chemical interaction with a tenacious surface oxide. Most chemical theories rely on the metal ions forming a tight bond on both sides as a result of oxidation. M. Hida et al. points out, in recent years, that strong joining of two materials depends on both chemical and physical joining. Meaning, the development of bonding at the interface to produce chemical adhesion and the development of mechanical stress distributions and gradients across the interfacial zones, are both necessary. Thus, redox reactions in the interfacial zone are necessary, not only for forming chemical bonds, but also for producing an interlocking structure because wetting is required for the latter.

The general absence of contemporary widespread developments in the field of G/M seal research originates largely from the lack of computational modeling technologies and an overall appeal to modern researchers, as evidenced by the difficulty in finding extensive modern-day sources. Marcus Borom, during the 1960’s, provided primary definitions of the physical chemistry of glass sealing
and characterization of oxides. Borom studied porcelain enamel structures and redox reactions present during manufacturing. At the time, due to a lack of high resolution microscopes, his observations were based on weight with respect to oxidizing time data.⁴

To this day, the guiding body of research for construction and design of G/M seals remains the work conducted during the early 1980’s at Sandia National Laboratories by S.N. Burchett et al.¹ Burchett reports the design and manufacturing considerations for a coaxial compression G/M seal with a particular material combination. The goal of the work was to couple the design with manufacturing guidelines to yield a mechanically optimized G/M coaxial compression pin seal. For the forming of a seal, a metal pin is surrounded by a collar of glass (insulator) which is inserted into a hole in the metal housing (header). The temperature is then increased until the glass flows and fuses to the metal pin and housing. Finally, the most crucial step is initial cooling to service temperature. During this stage, if the materials’ expansions are not properly understood, stresses develop.

The seal must survive many different environments, and survival is based largely on the stress state of the seal. Proper design requires either zero stress or compressive stress state in the glass at room temperature. Tensile stresses will lead to micro-cracking and loss of hermeticity.¹ Burchett’s work focused on geometric configurations, thermal cycling, and the effect of multiple pin seals in a metal housing.
In 1993, Bruchett provided an extension of the publication “Some Guidelines for the Mechanical Design of Coaxial Compression Pin Seals.” The extension stated that, during heat treatment for sealing, the temperatures reached were capable of annealing the Alloy 52 pins. This research focused on the increase in ductility and lowering yield strength of the pins. Thermal residual stresses were then computed with annealed pins, and the improved results were used to reconstruct the previous set of guidelines that originated from his initial study. Bruchett found that annealing of the pins significantly narrows the optimal design range. Also of importance, the presence of excessive pin wetting was shown to greatly impact the glass’s residual stress state.

SECTION 2.3 MODELING DEFORMATION OF INTERFACES

An interface can be described as a collection of strains and several constitutive elements. Strains within an interface allow for discontinuous moment stresses to develop and are either stored and/or dissipated. To assist in understanding this, Gudmundson proposed a mechanical analogy of an interface, shown in Figure 3. Higher-order moment stresses and plastic strains are analogous to tractions and displacements. The constitutive behavior can be described by stiffnesses, viscous and frictional elements, etc, represented as K.
C.W. Lau et al., in work conducted at Drexel during the early 1990’s, sought to understand two cases of interfacial stresses of seal-bonded elastic materials and seal-bonded plastic materials. Work concluded stress induced interfacial debonding is the most frequently encountered mode of damage in seal-bonds. Lau’s work developed cases for a range of plastic strain hardening: linearly plastic, power-law strain hardening, and finally, perfectly plastic materials. Secondly, stress states at the interface of two elastic materials was presented with a resulting eigenvalue numerical solution.

According to Lau’s work, when looking at seal-bonded brittle materials which fracture before substantial local plastic deformation occurs, it is desirable to see a solution for stresses expressed in a separable power series. The solutions Lau presents are valid for a wide spectrum of material combinations: “these results for bonded linear elastic materials are directly applicable for bonded viscous materials, if one interprets displacements and strains as their time rates.”

To this end, N. Chandra et al. of Florida State University seeks to apply a cohesive zone model (CMZ) to simulate strain response in several in-
homogeneous systems. As compared to Lau’s modeling, Chandra’s work starts with a primary understanding of interfaces based upon a narrowly graded region of continuum properties, and evolves to an infinitely thin surface separated by springs which are represented as cohesive zones with specific traction relations. This research seeks to establish traction equations for Ceramic-Metal interfaces. In general, CMZs are defined as boundary-value problems, in which quantities such as displacements, velocities, stresses or temperatures are the input values; however, strain response rate is omitted.

In 2006, Fredriksson et al. of the Royal Institute of Technology completed a CMZ model for plastic deformation at the micron scale. However, this work was limited to isotropic materials. In his first model, motivated by dislocation theory, interface energy was accumulated as linear plastic strain. In his second model, plastic energy was completely dissipated at the surface.

Understanding of dislocation theory at interfaces arises from Ashby’s work during the early 1970’s. Ashby et al. stated, “geometrically necessary dislocations are generated for compatibility reasons when plastic deformation is heterogeneous.” One type of gradient theory seeks to preserve the form of standard plasticity equations but does not involve additional boundary conditions.

The concept of interfacial energy dependent on the plastic strain state at the interface, implies a vanishing strain energy at the interface; however, no plastic strain on the elastic side of the interface can exist. In order to develop a gradient equation, Fredriksson assumed all interfaces were of the same type, either elastic or elastic-plastic, and could contribute to strain gradient plasticity energy.
Fredriksson also theorized that as a strain moves toward an interface, it behaves as a free surface and allows for strain energy to propagate across the interface. Conceptually, these strains function as a slip system, causing an accumulation of edge dislocations at the interface.

Alternately, another type of interface, presented by Gudmundson, can be visualized as surface energy vanishing and work dissipating. This interface condition is similar to plastic deformation and would include creep in the bulk material, but speculatively remains of limited use to the focus of pure elastic interfaces at high-strain rates such as shock loading.

In 2004, Gudmundson presented a general discussion on the formulation of conditions seen by a strain gradient, based upon interface descriptions by Fredriksson. In Gudmundson’s unified theory, the interface can be considered a mechanical structure made of Hookean springs, see Figure 3. Forces are able to move across the mechanical system and strains are accumulated and dissimulated accordingly.

The development of the above interface models allow for the study of energy transfer across interfaces. The ability to completely model the mechanics of interfaces, provide FEA models the ability to accurately transfer energy across dissimilar boundaries, thereby contributing to enhanced design capabilities.
SECTION 2.4 INTERFACE DIFFUSION

When considering sealing technology, diffusivity is a crucially important aspect for the collection of dislocation strains along the interface, which in turn promote failure of the interface. Additionally, it is important to understand the effects of residual stresses upon the interface, which arise from differences in thermal expansion. Work conducted by Raj et al. at the University of Colorado presents interfacial ion exchange and subsequent vacancies and point defects. Raj proved the occurrence of ion exchange across a metal-ceramic interface.\textsuperscript{11} In earlier studies of soda-lime glass, large ions of potassium were exchanged to create compressive stresses. As the stresses increased, the effective fracture strength of the glass magnified.\textsuperscript{12} An additional variable considered during this defining study was influence of particle size on thermal diffusively. Raj hypothesized that thermal diffusivity would decrease with smaller particles because of thermal resistance of the interface.

For example, Raj suggested changes in particle size would lead to a change in relative values of thermal conductivity between the fine particles and coarse particles when the temperature was increased. Materials that are dissimilar and have a highly diffuseable matrix are especially vulnerable. Secondly, in contrast to a dissolution-precipitation reaction, ion exchange requires only that the cations of the ceramic should have significant mobility.\textsuperscript{11} If a dissolution type reaction occurs, it requires a significant interfacial energy among the particles with an added chemical driving force. In G/M seals, the interface relies heavily on the
chemical adhesion and stability. Ion exchange during forming acts to achieve adhesion by altering the driving force toward chemical equilibrium.

Ronald Loeman’s work at Sandia National labs focused on mapping the stresses that induce microstructural changes, resulting from chemical interfacial reactions of G/M seals. Ideally, thermal coefficients of the metal and final glass seal should be comparable. Loeman’s work shows that crystallization of a high-thermal-expansion lithium silicate glass-ceramic differs in the presence of a metal substrate than in bulk and forms a reaction zone. The presence of a reaction zone probably suggests that both the glass-ceramic’s thermal expansion and thermal conductivity vary across the interface. The expansion coefficients infer that the interlayer of the glass-ceramic will have significant implications on residual stresses. Normally, the seal is assumed to be stress-free or in compression. The results of this study proves the glass-metal reactions required for bonding alter the crystallization of the glass-ceramic near the interface. Significant interfacial stresses may develop and must be accounted for in design.

SECTION 2.5 SHOCK DEFORMATION

Normally, materials are subjected to forces at speeds in the regime of sub-acoustic waves. A shock wave is a force that propagates through a material faster than the speed of sound, causing changes in a material’s state variables. Traditional force waves will produce isentropic alterations in state variables, while the passage of a shock wave typically produces irreversible changes in the same
values. Shock energy is able to produce extremely high-strain rates which induce adiabatic viscous effects. Grujicic, of Clemson, has significantly studied modeling of such waves within soda-lime glass.\textsuperscript{14} Grujicic’s shock wave work attempted to advance the application of computational modeling for glasses under high-pressure/high-strain rate loading. According to the research, glass is traditionally treated as a continuum whose properties become degraded by nucleation, growth, and coalescence of cracks.\textsuperscript{14} Additionally, unlike the metal housing, glass is amorphous and lacking of long-range order. This lack of order gave rise to a second modeling approach based on the bonding sites of a random network. At high pressures, the network formers can change, resulting in phase changes based on geometric alterations.

Gaining an understanding of materials for higher strain testing is also significant to dislocation theory. Once diffusion is omitted from the interface, energy transfer must be understood. Recent work at the Naval Surface Warfare Center by R. W. Armstrong et al. seeks to describe dislocation mechanics constitutive equation analysis for fcc and bcc materials.\textsuperscript{15} Armstrong’s work begins with a fundamental Hall-Petch pile-up basis and moves to strain hardening and dynamic recovery. In 1988, a simple dislocation formula for constitutive equations for metals was introduced, based on thermally activated motion of dislocations. Armstrong’s associate F. Zerilli promoted that, for bcc metals, the motion of dislocations was governed primarily by their interaction with the lattice potential (Peierls-Nabarro stress).\textsuperscript{16} Meaning, dislocation motion is
essentially temperature and strain-rate independent. The von-Mises equation was used to define yielding with respect to average grain diameter, with constants to account for thermally activated dislocation interactions. For testing on copper, Armstrong’s initial equations show theoretically the flow stress acted to diminish the ductility, comparative to experimental results by K. J. Frustchy. Experimental results showed a strongly increased strain hardening behavior for copper at high-strain rates, most likely due to dislocation drag and deformation twinning stress.$^{17}$

Twinning, in materials, shows a strong dependance on grain size. For iron twinning, flow stresses can produce strain rates on the order of $10^4$ per second and has been shown to occur in fcc metals, but generally at very high stress levels.$^{18}$ In 1995, Armstrong’s work produced a constitutive model for twinning based on the idea that a threshold amount of twinning will occur in a single grain. This threshold is responsible for accommodation of the excess strain, by which the von-Mises effective stress exceeds the twinning stress. Thus, the results indicate that twinning hardens these metals by reducing the material’s grain size and the microstructure within the grain as well. In very small grain size materials, little to no twinning was observed, as well as little to no shock hardening was found.$^{18}$ However, strain hardening can be seen with a susceptibility to shear instability, translating to enhanced ductility. Additionally, L. Murr’s work observed profuse twinning in shock deformed tantalum, thus endorsing the shock hardening theory based on the Hall-Petch grain size refinement basis.$^{19}$ At shock
rates, adiabatic conditions are present, as proposed by Zener and Hollomon in 1944, the shear instability develops and the rate of thermal softening overcomes the rate of work hardening.\textsuperscript{20}

In 1998, Drumheller produced a collective work based on modern nonlinear waveforms. Drumheller outlined the only constitutive model for an elastic material and detailed formation and decay of a shock wave. The principles of shock waves was unified based on pressure and thermodynamics. Both temperature and entropy, as well as force and motion, govern the constitutive model of materials.\textsuperscript{21}

**SECTION 2.6 CONCLUDING THOUGHTS**

The idea of G/M seals has existed for many years, and application is largely based on empirical experience. When conducting literature searches for mechanical properties, little information can be located. This is especially true when looking at extremely high-strain rate loading conditions. This literature survey sought to illustrate a basic understanding of several potentially underlying issues, which are expected to aid this thesis. However, due to the field of high-strain rate loading of elastically mismatched interfaces being largely unexplored, the connection between many of the above detailed concepts is disjoint. Future development of interface mechanics will conceivably unify these foundational concepts, in order to reveal application-oriented usefulness of the academic premises for production engineering.
SECTION 3.1 INTRODUCTION

Construction of G/M seals produces many forms of residual stresses, and depending upon loading, different failure sequences will result. One possible indication of cracking susceptibility is the location of maximum residual stresses. Predominantly, the maximum residual stresses are seen at the sealing interface due to accumulation of compressive stresses and CTE mismatch. The goal of this impact or dynamic loading experiment was to measure the maximum push-out force of a G/M seal during overload failure and empirically record the resulting failure sequence.

SECTION 3.2 G/M SEAL DESIGN

To aid in understanding the observed impact failure sequence, several commonly encountered internal stresses were defined. Definition of the internal stresses was followed by a root-cause analysis supported by a number of characteristics of G/M seals pertaining to the findings.
Section 3.2.1 Internal Stress

Below the annealing point of the glass, no significant stress relief by internal flow can take place.\textsuperscript{23} Consequently, strain due to differential expansion becomes permanent and three principal stresses are produced in G/M seals. These stress states were represented in Figure 4.

![Figure 4. Stress States in G/M Seals](image)

Axial stresses act in the longitudinal direction, perpendicular to the diameter of the seal and parallel the primary pin/header axis. Generally, these stresses develop when the seal expands or contracts, from being cooled below the annealing point, in the axial direction of the header. Radial stresses in the glass develop as the glass is constricted by the header. These compressive stresses act perpendicular to the axis of the seal and inward from the header. Finally, tangential or circumferential stresses act as a tangent plane to the outer radius of the seal or much like a hoop stress.

The particular design of the seal tested utilized a mis-matched CTE compression design.\textsuperscript{4} The header had a higher contracting CTE than the glass and during forming shrunk more than the glass. Header contraction created

\textsuperscript{4} Compression design indicates the glass seal is under compression by the header assembly.
radial and axial compressive forces that produced compressive residual stresses in the glass. The pin retained the balance of forces by employing a matching CTE, which sustained the compressive stresses from the header.

A model FEA seal consisting of a glass seal and metal header, with the material properties of Table 1, was constructed to illustrate the stress accumulation at the G/M interface which resulted from forming. The seal was assumed stress free at the annealing temperature of 445°C and cooled over 850 seconds to a steady state 25°C, which was represented in Figure 5. The FEA modeled maximum principal stresses and showed how primary tensile forces developed along the G/M interface. Figure 5 demonstrated that the interface is the most likely region to propagate failure of a glass seal with no feed-through pins.

![Figure 5. Example Tensile Stresses in G/M Seal](image)
Section 3.2.2 Hermeticity

Hermeticity of a G/M seal is measured by the quality of being impervious to air and corrosive chemicals. One indication of the quality of hermeticity is proper formation of the meniscus, which also indicates correct forming procedures. Proper wetting of the pin and header by the glass is necessary to enhance chemical and mechanical bonding. The wetting of a pin by a viscous glass upon forming was illustrated in Figure 6.

![Figure 6. Meniscus Wetting Conditions](image.png)

With good wetting the glass will climb up the pin, signifying a correct glass melt density (a positive meniscus). Contrastingly, poor wetting can signify a G/M seal production problem, such as too much oxidation of the metal. Proper oxidation prohibits excessive roughening of the substrate or excessive mechanical bonding that compromises chemical equilibrium.
SECTION 3.3 IDENTIFICATION OF TEST METHOD

The test methodology that was developed to accomplish impact loading placed a sudden impact on a stationary mounted CAD seal assembly. The outer housing or header was supported on the axis of the G/M seal on a double edge clamp where a push-out pin rested on the inner face, according to Figure 7. This testing followed a similar approach as Thompson performed in his master's work at University of Idaho, where he recorded the displacement of pins relative to loading. His work was used as a reference for general test procedure and loading.24

![Diagram of G/M seal for push-out test](image)

**Figure 7. Loading of G/M seal for push-out test**

Loading of the exterior and entire flat interior surface of the glass seal by a flat push-out pin produced shear conditions on the G/M interface, which was equal to
the normal stress. Assuming uniform loading this stress is described by Equation [1].

\[ \sigma = \frac{P}{\pi ld} \]  

[1]

where,

\( \sigma \) - Normal Stress  
\( P \) - Load Applied  
\( l \) - Thickness of G/M Interface  
\( d \) - Diameter of Seal

The normal stress, \( \sigma \), was a function of the load, \( P \), and the structural dimensions of the interface under a fixed resistance load, \( l \). Recall from Figure 1 the diameter of the glass seal was 0.25"; it was necessary for the push out rod applying load, \( P \), to be undersized to 0.2" diameter. Undersizing the push rod, to the diameter of the seal, aided in accommodating misalignment of load frame and seal. The equipment used to collect the force data was a 5000 pounds high frequency load cell and drop weight impact test machine detailed in Appendix A. A weight of fifteen pounds was dropped 60 inches.

The impact test measured the resistive forces exerted on the load cell by the G/M interface. Tests were conducted at two temperatures: room temperature and 300°F. Due to expense and scarcity of components, and comparable results produced by Thompson, only one G/M seal was tested at each temperature.[5]

The introduction of shear push out force with respect to time was recorded in Figure 8. The production of tensile stresses result in an increase of micro-

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[5] Coaxial with Alloy 52 pin of 1mm \( \phi \), 304L SS Header, 8061 Glass with 2 mm \( \phi \), and seal thickness 2.150 mm. Load-720 pounds. Stress-430 MPa.
cracking along the interface and a higher overall probability of a fracture of the glass bond, resulting in failure.\textsuperscript{24} Table 2 showed the maximum loads seen during failure at test temperatures for this material combination and design. Equation [1] was used to calculate the stress at failure and assumed to be the strength of the interface, recorded in Table 2. Additionally, the curves were integrated and recorded as impulse. The area under the curves represented the change of momentum upon failure of the G/M seal, or rather the absorption of force with respect to time.

![Figure 8. Load Curve for Impact at RT and 300°F](image)

<table>
<thead>
<tr>
<th>Test</th>
<th>Load [lbf]</th>
<th>Load [N]</th>
<th>Stress [MPa]</th>
<th>Impulse [Ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temp 72°F</td>
<td>2412</td>
<td>10,729</td>
<td>117</td>
<td>879.45</td>
</tr>
<tr>
<td>300°F</td>
<td>1456</td>
<td>6476</td>
<td>71</td>
<td>417.60</td>
</tr>
</tbody>
</table>

**Table 2. Load and Stress for Impact Test**
To collect video data, a high speed video camera was placed perpendicular to the load axis of Figure 7.\textsuperscript{6} High speed video data was collected at 14,000 frames per second at room temperature. Selected frames were presented in Figures 9-12 and documented the failure sequence of a G/M seal undergoing impact loading. The selected frames will be analyzed in detail in section 3.4.

This high speed video data portrayed how design characteristics contribute to failure. To the knowledge of the author, high speed video of overload failure sequence has never been recorded nor is there any existing in literature. In the future, design engineers will be able to use this failure sequence to gain a true understanding of G/M seal construction and implementation.

\textbf{Figure 9. Impact High Speed Photo-Time Stamp 0.392194 s}

\textsuperscript{6} Camera: Manufacture-Redlake Imaging, Model-Motion Pro X3, Image Array-1280x1024, Frame Rate (fps)-2000 to 128,000, Electronic Start/Stop Record Trigger
Figure 10. Impact High Speed Photo-Time Stamp 0.396051 s

Figure 11. Impact High Speed Photo-Time Stamp 0.398622 s
SECTION 3.4 FINDINGS

Loading profiles, displayed in Figure 8, created at room temperature (RT) and 300°F show a marked difference in peak strength as a function of temperature. The author speculates this is likely the result of a loss of adhesion at the interface. As the temperature increases the adhesion lowered, as evidenced by the initial discontinuity during loading of the elevated sample.

Furthermore, the derivative or slope of the curves from peak force to approximately 500 pounds suggested the response was not completely elastic, marked by an abrupt release of linear energy, but rather an elastic-plastic with a measured yielding and unloading of energy. Conjecturally, an elastic-plastic response indicated energy is potentially transferred minutely across the interface, and the metal housing provided plastic yielding that assisted in absorbing energy.
Additionally, gagged inflections exhibited by the elevated temperature sample during unloading advocated a loss of adhesion followed by traction resistance as the seal slips and then regains adhesion and slips again. Consequently, the majority of the applied force went into fracturing the material. Thus, the strains that were developed upon instantaneous loading were not uniquely determined by the stresses elastically, but depended upon the history of loading or how the stress state was reached.

The area under the curve was measured and represented the impulse of the strain response that was exhibited during impact loading. Impulse provided the comparative tool in determining the difference between the qualitative responses and also described the change in momentum the load cell experienced upon impact. Impulse was considered due to the inseparable nature of both force and duration of an impact event during dynamic loading. The impulse produced throughout impact loading at room temperature was two times greater than that which was produced at 300°F. In other words, at room temperature the G/M seal absorbed twice as much momentum from impact forces as the G/M seal that was tested at an elevated temperature.

Analysis proceeded from the load curves to the selection of frames from the high speed video, presented in Figures 9-12. Several hypotheses existed for the observed failure sequence and remained speculatively based on empirical data. However, as discussed earlier, it was assumed that the interface of the glass being investigated was placed in pure shear: the maximum tensile stress equaled the shear stress that occurred at the interface.
The following were applications of traditionally encountered problems, seen during manufacturing of G/M seals, which were extrapolated for this case study. Cracks in glass tend to be (move) perpendicular to the largest stress. Radial cracks would indicate the CTE mismatch of the glass was higher than the pin selection. Upon cooling, the pin would contract and cause radial tensile forces in the glass. Under this failure-mode, cracks propagate outward from the pin structure. Ideally, in a compression seal, the pin should exert a small compression force on the glass/pin interface, and the header should not allow the contraction of the glass to develop radial tensile stresses. Figure 12 disproved this; the face was unaltered and the pin structure remained intact. Tangential cracks would indicate the CTE of the glass was much lower than the pin and the glass was pulling away from the pin and header. Again, Figure 12 proved the structure did not separate as a result of CTE mismatch. Finally, if the seal exhibits a planner crack at the seal mid-point, the design is too long and the CTE too large. Once more, Figure 12 showed the seal structure remained intact.

Root-cause analysis eliminated manufacturing and material selection problems for potential CAD malfunctions. Failure determination proceeded to impact loading conditions. Figures 9, 10, and 11 portrayed a very clear sequence of failure during the initial stages of breakdown. Figure 9 revealed a primary ejection of particulate glass initiating from within the header body of the CAD's interior side (upper most side of seal with respect to loading position of figure) and formation of the unzipping of the meniscus. As time proceeded to Figures 10 and 11, the full evolution of meniscus separation was observed; and primary
glass particle expulsion transitioned from the upper/inner face to the lower/outer interface of G/M seal and flowed out over the header assembly. Finally, Figure 12 characterized the ejection of the glass seal. The glossy lower exterior surface of the seal remained intact and the surface condition remained in initial forming state. The face condition further proved the glass expulsion, recorded in Figure 9, as being ejected from the lower side of the seal, did not originate from the break down of the face of the seal. The only remaining possible location of failure was isolated to the meniscus region. Figure 12 supported this failure hypothesis, in that it completely lacked the meniscus and showed deterioration along the outer ring where the meniscus should be attached, and also exhibited cracking along the entire axial G/M interface.

From the sequence of Figures 9, 10, and 11, it is speculated that failure originated along the G/M interface within the meniscus zone. Several possible loading scenarios explain meniscus cracking. First, too much wetting occurred and produced an excessive meniscus, and when coupled with high compression forces from the metal housing, failure resulted. Second, if the glass preform weight was too high and the melt density was lower than normal, excessive wetting might occur, but was unlikely in this case as materials selection was well documented. Most likely, compressive stresses were overloaded, and due to the forming state of the meniscus, it was the weakest link for this form of loading and design.

It was proposed: failure propagated from the impact zone along the interface toward the opposite end of the seal and was focused at the meniscus/header
interface. As stresses were constrained axially along the seal interface, the compressive forces were overcome in the radial and tangential directions. After initial failure of the meniscus, material was ejected from the top seal surface, axial traction forces provided resistance and held the glass seal in place. Once the interface traction forces along the G/M interface, resisting the impact in the axial direction, were overcome the glass seal slipped; as evidenced by the initial glass particulate being ejected from the inside lower face in Figure 9. The meniscus “unzipped” around the circumference and peeled away. Finally, all axial friction forces were completely overcome and seal structure was expelled.

SECTION 3.5 CONCLUDING THOUGHTS

The sequence and phenomena of “unzipping” of the meniscus was observed and documented during interfacial overload. Furthermore, the impact force at two temperatures was measured and resulting stresses calculated. The rate of change of momentum as energy was conveyed by impact forces into the G/M seal was measured as impulse. At an elevated temperature, the seal absorbed less impulse energy and failed at a lower peak load.

It is recommended additional statical testing be performed to determine with one hundred percent certainty what the root causes were that initiated failure. However, it was clear the breakdown of the G/M interface and meniscus was the mode of failure. Although it is not clear if failure occurs in the metal/oxide, glass/oxide, or oxide alone as no mechanical testing, as of now, is developed to show which interface deteriorates.
SECTION 4.1 INTRODUCTION

Traditionally, the maximum residual stresses are seen at the sealing interface of a G/M seal. Finite Element Analysis (FEA) provided one method for predicting potentially susceptible regions for accumulation of high levels of stresses. A two-dimensional closed-form maximum principal stress solution provided a basic understanding of the design. A fully assembled three-dimensional model, processed computationally, fully mapped the complete stress state of the G/M seal upon loading. The goal of the three-dimensional FEA model was to isolate the most prone regions that lead to potential failure.

SECTION 4.2 CLOSED FORM SOLUTIONS

The design parameters necessary to produce a “good” G/M seal were outlined in J.D. Miller and S.N. Burchett’s work at Sandia National Laboratories and was used to conduct a two-dimensional initial design study. The G/M seal dimensions and material properties studied with the Miller-Burchett approach were outlined in Figure 1 and Table 1.
Design considerations for a single coaxial compression pin seal in a metal header, along with assumptions for the Miller-Burchett’s approach, were presented as follows. Residual stresses were determined by assuming the stress-free temperature occurred at the annealing temperature of the glass. As the structure cooled, stresses developed linearly, and at room temperature, the material properties of the respective materials were used to calculate the residual stresses. Also, the glass was assumed to respond as a linear elastic with the header and pin in an elastic-plastic manner with von-Mises criteria.

The closed-form approach used was a two-dimensional maximum principal stress model which compared $\sigma_{\text{max}}$ to an estimated tensile load limit based on material properties. It was assumed for $\sigma_T$ values between 6.9 MPa (1000) psi and 34.5 MPa (5000 psi), potential cracking could initiate, and above 34.5 MPa (5000 psi), cracks occur. The compressive stress limit was assumed to be 8 times the tensile limit, or $\sigma_c=8.0\sigma_T$. Using the stress limit model, a Glass Geometry Ratio (GGR) was calculated. Figure 13 outlined the GGR calculation and dimensions from Figure 1 were used to calculate a GGR. $R_2$ was the radius of the G/M interface and $R_1$ was the radius of the G/M interface minus the radius of the pin structure. The Miller-Burchett model only predicted stress distribution of a coaxial G/M seal with a single pin construction. For the purpose of applying this model to the three pin structure, it was assumed the three pins acted as one solid pin and the effects of stresses inside the pin placement radius were neglected.
The GGR, according to the method of Figure 13, was calculated to be 0.319. The Miller-Bruchett model specified that values below 0.2 produced a high tensile principal stress in the element adjacent to the pin-glass boundary at the surface of the glass. Likewise, for values calculated above 0.33, the highest maximum principal stress was exceeded by the element adjacent to the glass-header boundary at the surface of the glass. According to Figure 14, a GGR of 0.319 meant the maximum principal stress was safely within the design of the seal structure and not exceedingly isolated to an interface region.
Furthermore, the GGR was considered to limit the shear radial and axial component stresses, which weighed heavily in calculating the degree to which the principal stress, $\sigma_{\text{max}}$, was tensile. At a GGR value of 0.25, the radial and axial stresses produced the lowest principal stress level.
Tekna Seal®, LLC prescribed for a multi-pin single glass bead seal, the minimum distance between adjacent pins or housing should be greater than or equal to $\phi d$, with optimum spacing $\phi G > 3d$, defined in Figure 15.²⁶

![Figure 15. Multiple Pins in Single Glass Bead Design](image)

The $G$ value was calculated according to Figure 15. For the CAD design of Figure 1, it was found $\phi G = 0.177$ and $3d = 0.09$, so Tekna Seal® conditions were satisfied.

SECTION 4.3 COMPUTATIONAL SOLUTIONS

For the computational model according to the design of Figure 1, SolidWorks® FEA was used.⁷ Due to the initiator being analyzed, it was possible to use a three-dimensional model. The model employed the mesh shown in Figure 16. Appropriate material properties, according to Table 1, were input into SolidWorks®. Unlike the closed-form solutions which assumed the three pin

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⁷SolidWorks® Simulation 2010. Dassault Systèmes SolidWorks Corp.
structure acted as one pin, the size of the radius and three pin placement was completely modeled.

![Figure 16. Axisymmetric Mesh of G/M Seal Used for FEA](image)

Two different techniques were used to analyze the problem. The first technique used a combination of von-Mises deformation criteria and a fixed static stress linear materials model for the application of maximum pressure which produced deformation. The second setup modeled the maximum principal stresses. Analysis of cooling the CAD started from thermal load upon forming, and inputed a maximum pressure load distributed across the face of the G/M seal to perform a linear stress analysis. The maximum pressure load was estimated using empirical evidence and represented as 40,000 psi distributed across the inner face of the header and seal.\textsuperscript{25}

**Section 4.3.1 Deformation**

Figures 17 and 18 both detailed the resulting deformation, presented in millimeters, when a 40,000 psi load was applied to the interior face. However,
due to FEA software limitations, it was not possible to model the loads as shock loads. Rather, they were dynamically modeled as load rates in the impact regime. The most susceptible area predicted to deform upon loading was the center pin structure, not the G/M interface as originally hypothesized.
Section 4.3.2 Maximum Principal Stress

The Miller-Burchett model used finite element analysis to determine residual stresses due to manufacturing in G/M seals. In that research, it was assumed that the glass would fail when it reached its listed tensile strength. The assumption that breakdown of the component occurred at the maximum normal stress was applied to the principal stress model and used to calibrate the upper limit of endurance.

The maximum principal stresses accumulated on the exterior face of the G/M seal were modeled and presented in Figure 19. The G/M interface of the exterior face showed a significant accumulation of stresses when loaded to peak...
pressure on the interior face. As predicted by the closed-form solution presented in section 4.2, the model did not see significant stress accumulations in the region between the G/M interface and the pin radius. However, unlike the prediction of the closed-form solution, the pin-seal interface did see a significant increase in stresses on the exterior face.

Likewise, the interior face exhibited the same accumulations of principal stresses isolated to the G/M interface. In addition, the interior face revealed a particularly marked and noticeable accumulation in the center of the pin region. The principal stresses modeled of the interior face were represented in Figures 20 and 21.
Figure 20. Maximum Principal Stress-Interior Face and Axial Face

Figure 21. Maximum Principal Stress-Interior Face
SECTION 4.4 CONCLUDING THOUGHTS

By determining the correct design proportions through the closed-form solutions, and utilizing the deformation and maximum principal stress models, the likely path of failure was illustrated as not being isolated to the G/M interface, as originally hypothesized. The closed-form solution was limited to coaxial single-pin G/M seal models. When the pin structure was computationally modeled as three separate pins, the deformation model predicted a highly deformable region in the center of the pin structure. The maximum principal stress model also predicted the region that produced the most stresses was located in the central pin region.

Instead of failing at the G/M interface, it was anticipated, based on computational models, that as the seal deforms under the pressure, the center of the glass seal bulges and produces an area of increased tensile forces between the pin structure. As deformation intensified, the axial friction forces that hold the pin in place were overcome by the tensile radial forces along the pin, which resulted in the pin/glass interface cracking. Once the pin/glass interface cracked, deterioration of the entire G/M seal was imminent.
Chapter 5.
SHOCK LOADING

SECTION 5.1 INTRODUCTION

G/M seals that are used for the construction of CADs must meet very specific design criteria. They must provide sufficient hermeticity from the surrounding environment as well as maintain stable containment of highly reactive and corrosive materials used internally for detonation. The electrical properties of the seal must be sufficiently insulating to prevent the shorting of electrical feed-through components to the housing. The G/M seals used for CAD construction must be sufficiently strong to survive shock loading during detonation and compact enough to meet stringent size restrictions.

The goal of this chapter was to produce an understanding of the failure events of G/M seals that are exposed to shock loading or high-strain rate loading forces. Empirically, this was accomplished by high speed video recording overload failures of G/M seals during a detonation event. More specifically, shock loading is loading by a stress wave of energy that propagates through the medium at velocities higher than acoustic waves. The ability of a material system to respond to this form of loading is uniquely controlled by its stress-volume response or equation of state. Shock loading can even produce irreversible freezes in some of the microstructural changes.
SECTION 5.2 NONLINEAR SHOCK WAVE

Chapter 3 described mechanical testing of a G/M seal that produced impact energy below the regime of shock. The energy waves were in the acoustic range, limited by the speed of sound which travels at approximately 345 m/s through air. Acoustic waves produce a time lapse between the time the wave is generated and the instant the wave is detected, due to light traveling at $3 \times 10^8$ m/s and sound traveling at 345 m/s. This property is called the causality of the wave and the speed is termed the finite velocity of the wave. Laplace first understood that waves of energy in the acoustic range not only caused the pressure to oscillate, but the temperature as well. This is called the stress wave, where two forces act together upon a material environment.

The experiments of Chapter 3 produced energy waves that were linear. The waves did not interact with each other and could be represented by a linear system of equations. Yet, for the regime of shock loading the waves are nonlinear and contain powers of variables or products of one variable with another, rather than linear products of variables and constants. The waves interacted with one another to intensify or weaken the overall effect.

Simple mechanical understanding alone does not unify the response of these nonlinear waves. The principal form of a nonlinear wave is termed the simple wave and is a single non-linear compression wave, rarefaction wave or both and evolves into discontinuous jumps in velocity and stress due to material responses. The term shock wave was developed to include both the thermal field
and mechanical field produced by non-linear waves and energy is the unifying concept that connects these two fields.\textsuperscript{14}

The testing method developed in Chapter 5 produced a stark contrast to the form of energy exhibited during impact loading. Previously, weak waves caused changes in stress-strain and to a lesser extent temperature. These material changes were mostly small and reversible due to their elastic nature. In contrast, the shock waves in this chapter potentially caused irreversible changes in both properties and microstructure.\textsuperscript{14}

\textbf{SECTION 5.3 IDENTIFICATION OF TEST METHOD}

Test methodology was developed to direct the energy of a shock load from a pyrotechnic event into a G/M seal.

Units were constructed in typical fashion as CADs. They were loaded with a charge, bridge wire assembly, and G/M seal; the opposite end was sealed with an inner flier plate or burst disc. Figure 22 showed a typical brass burst disc on lower assembly and G/M seal with ignition wire protruding on upper assembly.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{image22.jpg}
\caption{Typical CAD Assembly}
\end{figure}
The CAD was fitted with an isolation cap on the operational or flier plate end. Immobilization of the operational end prevented the unit from functioning and releasing the burst disc energy. All energy, when detonated, was exerted equally in all directions, including against the G/M seal, with the exception of the minute amount of energy absorbed by the isolation cap. Typical CAD housing and isolation cap that was screwed onto housing were presented in Figure 23.

![Figure 23. CAD and Isolation Cap](image)

Tests were carried out within the solid containment chamber shown in Figure 24. CAD units were fixed to the bottom of the chamber and detonated parallel to the plywood observing window. A Motion Pro series high speed video camera was positioned perpendicular to the axis of CAD firing. The camera was electronically triggered to begin recording at 90,000 frames per second the moment the electrical signal triggered the CAD and several nano seconds before the unit detonated.
Figure 24. Detonation Test Chamber

Image data collected sequentially, Figures 25-28, documented the failure sequence of a G/M seal undergoing shock loading and analyzed in detail in section 5.4. The camera was aligned to capture movement starting on the left edge of view area advancing toward the right. Movement of one of the G/M seal pins was measured and recorded in Table 3. Additionally, pin-through-air displacements, velocity, and acceleration were calculated from the video time stamps and were recorded in Table 3.
Figure 25. Shock Load High Speed Photo-Time Stamp 0.000162 s

Figure 26. Shock Load High Speed Photo-Time Stamp 0.000187 s

Figure 27. Shock Load High Speed Photo-Time Stamp 0.000212 s
Figure 28. Shock Load High Speed Photo-Time Stamp 0.000237 s

Figure 29. Shock Load High Speed Photo-Time Pin Failure

<table>
<thead>
<tr>
<th>Figure</th>
<th>Time [s]</th>
<th>Displacement [m]</th>
<th>Velocity [m/s]</th>
<th>Acceleration [m/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.000162</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>26</td>
<td>0.000187</td>
<td>0.00279</td>
<td>110</td>
<td>-</td>
</tr>
<tr>
<td>27</td>
<td>0.000212</td>
<td>0.00914</td>
<td>250</td>
<td>5.69 x 10^6</td>
</tr>
<tr>
<td>28</td>
<td>0.000237</td>
<td>0.03302</td>
<td>955</td>
<td>28.04 x 10^6</td>
</tr>
</tbody>
</table>

Table 3. Pin Displacement, Velocity, and Acceleration
Pressure data was collected to determine the force produced from detonation of a CAD unit by means of a closed-bomb test.\[8\] The closed-bomb test consisted of a CAD unit which was detonated and a burst disc that released energy into a fixed chamber. The fixed chamber was of a known volume and fitted with a pressure sensor, shown in Figure 30. During the closed-bomb test, G/M seals were not tested to destruction and all survived. Shock energy exited the CAD through the burst disc and was recorded in the form of pressure data.

![Figure 30. Close Bomb Test Configuration](image)

Typical data collected was represented in Figure 31 and plotted as force [psi] with respect to time [s]. The lower portion of Figure 31 was enhanced to show time from 0.009s to 0.015s and better described the peak pressure recorded. Table 4 recorded the pressure test results from the CAD units: maximum pressure, time from electrical short to maximum load, time from maximum pressure to resonate pressure of 500 psi. Additionally, the force exerted against

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\[8\] Testing was performed by and results courtesy of Glen Stichling.
the G/M seal was calculated by multiplying pressure by the area of the glass seal and recorded in Table 4.

![Figure 31. Typical Pressure Trace of CAD Detonation](Courtesy of CAD Inc.)

<table>
<thead>
<tr>
<th>Test</th>
<th>Max Pressure [psi]</th>
<th>Time (0 to Peak Pressure) [s]</th>
<th>Time (Peak Pressure to 500 psi) [s]</th>
<th>Force on Seal [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4565.43</td>
<td>0.000203</td>
<td>0.2542</td>
<td>225.988785</td>
</tr>
<tr>
<td>2</td>
<td>3906.25</td>
<td>0.000258</td>
<td>0.454244</td>
<td>193.359375</td>
</tr>
<tr>
<td>3</td>
<td>6054.65</td>
<td>0.000203</td>
<td>0.4481</td>
<td>299.705175</td>
</tr>
<tr>
<td>4</td>
<td>6494.14</td>
<td>0.00018</td>
<td>0.45072</td>
<td>321.45993</td>
</tr>
<tr>
<td>5</td>
<td>4941.45</td>
<td>0.000086</td>
<td>0.54902</td>
<td>244.601775</td>
</tr>
<tr>
<td>6</td>
<td>4638.67</td>
<td>0.00015</td>
<td>0.4241</td>
<td>229.614165</td>
</tr>
<tr>
<td>7</td>
<td>5502.90</td>
<td>0.00016</td>
<td>0.5142</td>
<td>272.39355</td>
</tr>
<tr>
<td>8</td>
<td>4921.80</td>
<td>0.0002</td>
<td>0.289</td>
<td>243.6291</td>
</tr>
</tbody>
</table>

Table 4. Closed-Bomb Pressure Data (Courtesy of CAD Inc.)
The averages and standard deviation were calculated for Table 4 and are presented in Table 5.

<table>
<thead>
<tr>
<th>Max Pressure [psi]</th>
<th>Time (0 to Peak Pressure) [s]</th>
<th>Time (Peak Pressure to 500 psi) [s]</th>
<th>Force on Seal [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVG</td>
<td>STD</td>
<td>AVG</td>
<td>STD</td>
</tr>
<tr>
<td>5128.16</td>
<td>844.435</td>
<td>0.00018</td>
<td>0.00005025</td>
</tr>
</tbody>
</table>

Table 5. Average CAD Closed-Bomb Data

SECTION 5.4 FINDINGS

Data presented in Table 5 aided in gaining a clearer understanding of the forces the G/M seals can withstand during shock loading. Nevertheless, the column reported as ‘Force on Seal’ can be misleading. The value reported in Table 5 included the pressure inside the closed-bomb the instant after pressure was released from the inside the CAD. The maximum pressure seen by the G/M seal was therefore not 253.844 pounds as reported in Table 5. Instead, the maximum force was calculated the instant before rupture of the burst disc by Boyle’s Law according to equation [2].

\[ P_1 V_1 = P_2 (V_1 + V_2) \]  \[ [2] \]

Equation 2 was used to determine the correct pressure inside the CAD the instant before rupture and was found to be 46,360 psi ± 7,600 psi at 68% confidence interval. When the pressure was multiplied by the area of the G/M seal, it yielded a force of 2,290 pounds ± 370 pounds at 68% confidence interval, without failure of the seal.
Furthermore, the force load acquired when compared with the values obtained in Chapter 3 for impact loading were in close agreement. Notwithstanding, there were some limitations associated with extrapolating the method and results of Chapter 3 to those of the closed-bomb pressure test of Chapter 5. The major limitations were presented as follows.

Limitation (1). Mechanical impact testing performed with the methodology of Chapter 3 produced shear loading isolated to the interface. Under this loading method, it was impossible for the center of the seal to fail or bulge as predicted by the FEA model. Shock loading produced a pressure that acted equally across the entire exposed inner surface of the G/M seal.

Limitation (2). Shock waves produced thermal and pressure forces and were unified into an energy term. The test methodology of closed-bomb testing did not record thermal effects. In order to properly describe the entire event of shock loading, the thermal response must be established.

Limitation (3). The pressure recorded during closed-bomb testing is an indirect measurement of the event after actuation of the device. The pressures recorded do not reflect any losses due to ignition or the actual force inside the CAD prior to detonation. It was unknown the losses of energy that occurred between the instant prior to overload of the burst disc and after failure.

Limitation (4). The impact test prescribed in Chapter 3 was an overload test and complete failure of the G/M seal occurred. Closed-Bomb testing did not produce overload failure of the G/M seal. Instead, the CAD is loaded based on
industrial experience to a known threshold that did not produce pressures sufficient to result in failure of the G/M seal.

Limitation (5). The effect of the closed-bomb housing in which the CAD was inserted, acting as a thermal sink was unknown. The volume of the CAD unit in comparison to the closed-bomb chamber was significantly different. At shock loading rates, any significant expansion or limitation thereof could have produced major changes in the production and absorption of energy.

Although these limitations exist, the maximum load produced by pure shear impact loading approximated the total load recorded during shock loading. Nevertheless, a global assumption that mechanical impact loading results can be extrapolated to shock loading conditions was outside the scope of this thesis. Further extrapolation or comparison of the maximum measured loads between force load rate or untested conditions elsewhere are subject to error.

To the knowledge of the author, the exact duration of a CAD detonation has never been measured. From the video evidence, it was successfully found to go from initial electrical pulse to total release of energy in 0.82 μsec. This solitary value, coupled with the addition of even being able to collect video data, was an impressive finding and accomplishment. At first, it was hypothesized it would be impossible to capture any video data as the inertia of the G/M seal upon overload would be exceeded by the production of light energy and the video would be saturated and unable to visually record any data. Meaning, the inability to capture visual data would be limited by the causality of the wave, and the speed would overcome the finite velocity of the wave, much like the doppler effect. Yet data
was successfully collected and an initial velocity of the pin-through-air was recorded in Table 3 to be 955.04 m/s and accelerating at $28.04 \times 10^6 \text{m/s}^2$.

Perhaps the most crucial still frame collected occurred in Figure 29. Again, to the knowledge of the author, the exact failure mode of a G/M seal resulting from shock forces had never been recorded. Figure 29 provided concrete evidence for predictions of the FEA models, showing pin interface weakness. Both Figure 28 and 29 emulated the ejection of a pin the instant before total failure of the glass occurs. Testing of the G/M interface alone did not provide sufficient data to describe failure of G/M seals during shock loading.

Most likely the failure sequence is as follows. First, the bridge wire ignited the material as shock forces moved through the pyrotechnic. The equation governing density and volume is altered and a traditional explosion event occurs. Second, a massive amount of energy build-up occurred at the face of the G/M seal. The sudden change in pressure and thermal energy degraded the properties of the seal. In chapter 3, an increase of thermal energy lowered the overall strength. As for the case of shock loading, adiabatic changes in the material did not allow energy absorption as there was not sufficient time for a change in viscosity or nucleation of a phase transformation to occur. Third, due to an inability to absorb thermal energy, pressure became the primary driving force and bulged the glass outward. The sudden change in loading on the seal resulted in a change of stress state of the glass, and forces which were once compressive were overcome. Finally, when sufficient tensile forces along the pin developed axially and radially, the friction forces of the pin interface were overwhelmed and the pin
was ejected. This was also evidenced by the pressure response seen in the enhanced portion of Figure 31. The pressure trace exhibited a build up of force until the friction forces were first matched, followed a small sudden dip as the pin yielded, then increased again until maximum load and total failure occurred. Ultimate failure of the seal was imminent the instant after pins were compromised. During this form of loading, no materials remained for postmortem analysis and no glass remained bonded to the header.

SECTION 5.5 CONCLUDING THOUGHTS

High speed video data was successfully captured of a CAD during shock overload failure. Examination of high speed video yielded a qualitative understanding of the failure sequence of a G/M seal during a CAD overload event. Data proved the initial point of failure originated from the electrical pin and not the G/M interface. Closed-Bomb pressure test results were analyzed, and forces experienced by the G/M seal were found and compared to data collected during shear impact loading of the G/M interface.

The weaknesses predicted by the design FEA model of Chapter 4 were qualitatively confirmed. Furthermore, velocity and acceleration of a pin moving through air ejected from a G/M seal structure was calculated, as well as the duration of the overall event from electrical impulse to breakdown.

Overall, this work demonstrated the importance of understanding nonlinear phenomena and the effects caused during failure of a G/M seal. It is important that both event duration and energy magnitude be considered necessary for
defining the failure characteristics of CAD’s G/M seals. This work has provided evidence that future design considerations should not be based solely on simple static pressure overload testing.
Chapter 6.
CONCLUSIONS

Accomplishing the objectives presented in chapter 1 support the hypothesis that significant design considerations can be gained from the observed empirical failure sequence. As a result, the empirical study also sought to improve the overall structural performance of G/M seals used for CAD construction.

Impact testing performed in chapter 3 sought to examine the weaknesses of the G/M interface during shear loading. Typical design characteristics, stress states, and hermeticity were defined based upon industry prescribed standard practices. A standard glass seal, with no pins, was modeled which reflected the principal stress effect along the G/M interface when cooled below the annealing point upon forming.

The G/M interface was first theorized to be the most probable location of failure, due to the accumulation of stresses found as the metal header contracted upon cooling. Peak shear load, recorded from the mechanical drop weight impact test, at room temperature and 300°F was 2,412 pounds and 1,456 pounds, respectively. In addition, the resulting shear stress was calculated at room temperature and 300°F, resulting in 117 MPA and 71 MPA, respectively. Next, the resulting unload curves were integrated. The impulse or change in momentum upon overload failure was determined. The room temperature sample produced
two times the change in resulting momentum, or rather absorbed twice the impulse, upon overload failure as compared to the G/M seal tested at an elevated temperature. Finally, a high speed video was collected at 14,000 frames per second. Analysis of these still frames recorded the unzipping of the meniscus and empirically documented the failure sequence.

Closed-form Finite Element Analysis (FEA) solutions were evaluated in chapter 4 for the design configuration of the tested CAD G/M seal evaluated by impact and shock loading test. The three pin structure was modeled as a single coaxial pin with the radius of the coaxial pin sized to the radius of the three pin core structure. The CAD geometry investigated proved to satisfy the thickness and radial distances prescribed by the Glass Geometry Ratio (GGR) method, as well as the multiple pin placement guidelines provided by Tekna Seal®. Two fully computational models were completed utilizing both the von-Mises deformation criteria and maximum principal stress definitions. The generated three-dimensional models revealed a highly susceptible region in the axial core of the pin placement prone to bulging deformation with an extreme concentration of stresses.

Shock loading conditions were successfully high speed video recorded at 90,000 frames per second in chapter 5. During pressure overload, video analysis revealed that the G/M seal failed at the pin-seal interface; contrary to the original hypothesis that failure would occur at the G/M interface, which was tested in chapter 3. In addition, the total duration of a CAD detonation event was recorded as 0.82 µsec from initial electrical impulse to maximum pressure or overload
failure. Furthermore, the velocity and acceleration of the discharged pin-through-air were calculated as 955 m/s and \(28.04 \times 10^6\) m/s\(^2\), respectively. Shock load testing culminated with a defined breakdown sequence of a G/M seal during overload failure.

During shock loading, the total force seen was calculated as 46,000 psi or 2,250 pounds, and the peak pressure load was in close agreement with the impact test results. However, a global assumption that mechanical impact loading results can be extrapolated to shock loading conditions was outside the scope of this thesis and several limitations were outlined. Further extrapolation or comparison of the maximum measured loads between force load rate or untested conditions elsewhere are subject to error.

In order to develop an exact failure analysis, as well as completely confirm the exact path of failure, additional work is recommended to be focused at the G/M interface and glass-pin interface. These recommendations should be based on advanced interface characterization through the use of high power microscopy, X-ray diffraction, and electron backscatter diffraction. A complete quantitative characterization of the interface is needed in order to support the empirical findings of this thesis. Finally, further work is needed to determine if optimum mechanical and chemical adhesion was reached concerning the G/M seals in question of this thesis.


PLAN

PUSH BUTTON WEIGHT RELEASE

WEIGHT

2x2 STEEL TUBE

60°

PLUNGER ASSEMBLY

A36 PLATE

1\(\frac{1}{2}\)x1\(\frac{1}{2}\) STEEL TUBE

A36 PLATE

SIDE VIEW

SEE BASE DETAIL

FRONT VIEW
Load Cell:
Manufacturer-Omega Engineering
Model-DLC 101-5K
Interface-NI Labview Programable
Frequency Range-0-25 KHz

__BASE DETAIL__

PLUNGER ASSEMBLY
A36 PLATE
4" SCH. 40 PIPE
4" MALLEABLE IRON PIPE CAP
TEST CARTRIDGE SPECIMEN
1\(\frac{1}{2}\)x1\(\frac{1}{2}\) STEEL TUBE
A36 PLATE

SENSOR WIRE

G/M SEAL HOLDER
LOAD CELL
INDENTER PIN (HIGH TENSILE MATERIAL)

TOOL STEEL CONNECTOR SHAFT
A-36 PLATE
THREAD FOR LAD ASSEMBLY