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Use of Polymer Rapid Tools as Functional Injection Mold Tooling

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USE OF POLYMER RAPID TOOLS AS FUNCTIONAL INJECTION MOLD TOOLING

by

Sean Derrick

A Thesis submitted to the Graduate College in partial fulfillment of the requirements for the degree of Master of Science in Industrial and Manufacturing Engineering
Western Michigan University
December 2013

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Conventional tool making for injection molded plastics is expensive, time consuming, and generates a great deal of waste. Presently, industry is waiting for what is commonly referred to as Rapid Tooling (RT). The greatest opportunity for RT implementation would be the use of Additively Manufacturing (AM) technology. Specifically, AM techniques which use a high strength polymer resin substrate.

The following research is an initial feasibility study to determine if Polymer Rapid Tools (PRTs) could be used as functional injection mold tooling. The objective of the research was to determine if a PRT could mold a variety of features to a given dimension, within conventional tolerance limits, and do so repeatedly. Initially, simple geometric shapes, which represent commonly molded features, were molded and studied. This was followed by molding more complex and commercially available plastic components. In this study, conventionally produced aluminum tools were used as a control for dimensional comparison.
DEDICATION

This paper is dedicated to my parents and family who stood by me throughout every step of this project. They continuously challenge me to improve and to become better at all facets of life. Without them this paper would not have been completed.
ACKNOWLEDGEMENTS

I would like to acknowledge the contributions and support of the following people and organizations. Without them this project would not have been possible:

From industry I would like to thank Jason Reznar from Rayce for providing various PRT molds as well as supporting polymer rapid tools at Western Michigan University. Chicago Miniature Lighting (CHML) for providing materials and industrial test cases for comparison. DASI Solutions for providing additional sample molds and material data for study.

From Western Michigan University I would like to acknowledge and thank Dr. Paul Engelmann, Dr. Betsy Aller, Jay Shoemaker, Dan Switzer, Mike Konkle, and John Jager. Their support, guidance, equipment, expertise, and general help were critical for completing this research. I would also like to acknowledge fellow classmates Nate Christensen and Matthew Johnson for continually reminding me I wasn’t done yet and to keep working. Also, I would like to acknowledge my committee members Dr. Pavel Ikonomov and Dr. Mitchel Keil for serving on my committee and providing me guidance and education through the years.

Lastly, I would like to acknowledge my advisor Dr. Jorge Rodriguez. His guidance, patience, and time were vital.
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CHAPTER 1: INTRODUCTION

Injection molding is one of the most widely used and accepted processes in modern manufacturing. The process begins with the heating of a thermoplastic material which is then forced into a mold cavity under pressure. Inside of the mold cavity the material cools, solidifies, and is then extracted as a formed product. Molds, which are also referred to as tools, form the resin into the desired shape and are typically machined from metals such as aluminum, steel, and various copper-based alloys.

Conventional tool making is expensive, time consuming, and generates a great deal of waste. Tools can take weeks to produce and cost thousands, even millions of dollars. They require highly skilled labor to fabricate and in many cases are produced far away from where they are intended to be used, thus requiring expensive and lengthy transportation. Compounding these problems, in the early phases of manufacturing a new product, the design of the mold might experience changes. These changes can be due to alterations in the product’s shape or due to refining the mold to better meet desired product specifications. Regardless of the reason for the change, each modification requires lengthy and costly rework. In some cases the changes are so severe that the mold must be rebuilt from scratch.

In the case of short production run components, such as prototypes or in mold verification, the cost of the mold is the single highest driving cost of the component's production. An alternative to conventional tooling in those instances is called Rapid Tooling (RT). A Rapid Tool is a mold which can produce the same components as a conventional tool, at comparable quality, but be produced at a fraction of the time and expense. Rapid tools are not intended to fully replace conventional tooling nor would
they be used in high volume production. Instead RTs are ideal for prototyping, quoting, proofing, and short batch run applications which require the most flexibility.

There are different approaches to create rapid tools. One of the best and most recent approaches involves the Additive Manufacturing (AM) process. Typically the AM process has been used indirectly to create the injection mold. However, the most ideal use for AM-produced rapid tools is their direct use as a functional injection mold. Specifically, the most ideal use of AM rapid tools is the direct use of the far less expensive polymer-based AM techniques. With advancements in AM materials and techniques it may now be feasible to create plastic molds and use them as functional tools. The following research details an initial feasibility study to determine if polymer-based rapid tools are feasible as injection mold tools by determining if they can hold specified dimensions over multiple cycles.

1.1 BACKGROUND

A brief overview is provided next to orient the reader to the subject matter and terminology used within this research. The subject matter covered includes additive manufacture, injection molding, and the use of rapid tools within the injection molding industry. Additional information for each section, with increased specificity, can be found in Appendix A.

1.1.1 ADDITIVE MANUFACTURING

Additive Manufacturing (AM) involves the construction of physical objects from computer models by automatically and systematically adding material until a real object is fabricated. These generated objects can be used in a variety of ways and be produced in
various materials. Typically AM techniques work by splitting a computer model into various cross-sections or layers. Those cross-sections are then laid down successively as layers of material. The buildup of layers slowly generates the desired component; see Figure 1 below for reference. The field is referred to additive manufacturing because material is added to produce the product, versus subtracted, in process like turning, milling, or grinding.

![Figure 1: Additive manufacturing methodology](image)

Figure 1: Additive manufacturing methodology [A] computer-generated base geometry [B] sectioned geometry (3D Printing)

AM technologies have three common traits: resolution, porosity, and material strength. The amount of each of these traits is directly related to the production method used. Resolution is directly affected by the layer thickness of each cross-section. The thinner the layers the more defined curves become. Thicker cross sections obscure curvature leading to a phenomenon known as stair stepping. This phenomenon can be seen in the highlighted area Figure 1.

The amount of porosity within an AM component is again determined largely by the fabrication method. Typically porosity is caused in one of two ways: gaps within successive layers of the material and incomplete adhesion/cohesion between the fabrication materials. Some AM methods do not bond the material in one continuous
cross-section. They instead lay the material in beads or in uneven layering. This can cause air entrapment or voids to occur. Additionally, improper bonding of one layer to another can lead to additional pores within the material. As a result, large amounts of pores would make the final product brittle.

Material strength is typically derived due to three factors: AM material, bonding method, and porosity. Several rapid prototyping methods use soft and weak base building materials such as cellulose, powdered and even flowered minerals. Typically methods which use softer base materials rely on stronger bonding materials, such as epoxy, for strength. Other AM methods use stronger base materials: such as plastics, metals, and ceramics bound through fusing their base constituents together through heat. Some of the stronger materials are also bonded using resins.

Currently there are five additive manufacturing methods which are widely available: Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Polymer Jet Deposition (PolyJet©), and 3D printing (3DP). Other AM techniques exist but are unsuitable due to cost, availability, or material strength. Additional information regarding each technique, including their pros, cons, and why they were not selected for this experiment, can be found in Appendix A.

One of the newest methods for rapid prototyping is PolyJet© Deposition, which involves spraying a UV curable polymer onto a surface. As the resin is sprayed into place a UV light, tracing behind the spray head, cures the polymer immediately following its adherence to the surface plate. An example of the described process can be seen in Figure 2 (Objet Geometries). This method, marketed as PolyJet© by the Objet® company, yields a solid polymer model. Due to the thin mist of polymer the printing process
produces extremely high detail and high strength models. Out of all the current polymer-based AM technologies this process generates the strongest, least porous, and highest detail models. These attributes make it optimal for this research.

![Diagram of Objet® Polyjet® printing](image)

**Figure 2: Objet® Polyjet® printing diagram**

### 1.1.2 INJECTION MOLDING

Injection molding is defined as a cyclic process for producing identical articles from a mold, and is one of the most widely used polymer processing operations. The main advantage of this process is the capacity for repetitively creating parts having complex geometries at high production rates (Zheng, 2011). Polymer resins are first melted and then forced, or injected, into a mold cavity. Once inside of the mold cavity the polymer cools and solidifies into the shape of the cavity. Once solidified, the mold is then opened and the form is ejected.

The injection molding process forms parts used within every facet of life. Examples of injection molded components can be found in the automotive, aerospace,
and consumer goods markets. The process can be used to mold product from a wide variety of polymer resins such as Polypropylene, Polyethylene, Nylon, and polycarbonate. Examples of the diverse nature of injection molded parts can be seen below in Figure 3. For readers unfamiliar with injection molding, additional information regarding the injection molding process, including a step by step walkthrough of the molding cycle, is presented in Appendix A.

![Figure 3: Injection molded parts (NingBo ALA Packing Co., LTD)](image)

### 1.1.3 Rapid Tooling

Rapid Tooling (RT) describes a process that is the result of combining Additive Manufacturing (AM) techniques with conventional tooling practices to produce a mold in less time at a lower cost relative to traditional machining methods (DLG, 2012). There are two divergent schools of thought in regards to Rapid Tooling. One school uses the AM model as a pattern for creating either a more permanent mold or to create a mold which would be consumed during the manufacturing process. This practice is known as Indirect Rapid Tooling. When an AM model is used directly as the mold or tool, this is known as Direct Rapid Tooling.
1.1.3.1 *Indirect Rapid Tooling*

Indirect rapid tooling is a classification of rapid tooling composed of first creating the desired component using an additive manufacturing technique. Then the AM component is used to create a negative mold from a chosen medium. Therefore, the AM process indirectly creates a molding tool instead of directly creating a tool. Typical mediums include Room Temperature Vulcanizing (RTV) rubber and epoxy. Indirect rapid tooling has been used for many years and has become a well-established practice. Some examples of indirect tooling include urethane castings, aluminum filled epoxy tools, and lost form metal casting.

1.1.3.2 *Direct Rapid Tooling*

Direct rapid tooling is regarded as one of the next great technological leaps for the manufacturing world. Direct rapid tooling is the direct creation of a fully functional tool from additive manufacturing. This process differs from indirect tooling because the tool itself is what the AM technology produces. Ideally these tools would require little or no post-processing after creation and could move straight from the AM machine to the production floor to create product. Like indirect tooling there are several forms of direct tooling which are closely linked with the AM technology being employed. Each form has its benefits and drawbacks; however to date there has been no large scale adoption of direct tooling by industry.

The primary benefit of direct rapid tools are that they can be used to produce a subgroup of injection molds called “Firm” or “Bridge” tools (Jacobs, 1996). Injection mold tools are classified based upon the amount of components they can produce in their life. Soft tooling describes a mold which produces 25 or fewer components. These types
of tools are typically made using indirect RT methods. Hard tools are heavy production tools which yield hundreds and even millions of components during their life cycles.

Firm tooling is used to fill, or bridge, the gap between soft and hard tooling. They are tools capable of short prototype runs, approximately 50 to 100 parts (Pham, 2001). Firm tools are molds produced from less expensive materials using less expensive methods. These tools are designed with shorter lead times and appropriate for part verification. Jacobs (2000) describes firm tooling as a mold which produces fewer than 50 cycles while Bridge Tooling was inferred to be less than one hundred cycles.

1.2 LITERATURE REVIEW

Since the early 1990's there have been multiple published attempts at creating a feasible Direct RT for plastic injection molding. All of the previous attempts can be grouped into one of two categories: metallic or polymer-based rapid tools. Both sets of previous research have met with success; however, neither has yet to be adopted by industry. The issues preventing adoption will be discussed in the following sections.

1.2.1 METALLIC-BASED RAPID TOOLS

Tools created using a metallic-based material are one of the largest and most experimented forms of rapid injection mold tooling. There are dozens of documented research projects and it is by far one of the most successful techniques (Levy, Schindel, & Kruth, 2003), (Rosochowski & Matuszak, 2000). Examples of past research include the use of a Direct Metal Laser Sintering (DMLS) additive manufacturing machine to sinter layers of powdered metal. The sintered component is then further sintered in an oven to increase the strength of the components by further bonding the metallic powder
together (Dalgarno & Stewart, 2001). In essence these machines produce real metallic tools. Equipment exists to create components in various alloys of aluminum, steel, zinc, and even titanium (Barlow, Beaman, & Balasubramanian, 1996). This RT technique allows for the production of “Hard Tools” which can be used for limited to full production. According to various publications, DMLS metallic tools are capable of creating 250 to 100,000 parts, with mold fabrication taking two to four weeks (Pham, 2000).

Using similar techniques metallic powders can first be sintered together in a loose sponge. Once sintered the sponge-like matrix can be permeated with a desired alloy using a vacuum process. This method yields tools which are confirmed to produce firm tooling capabilities or better (Ravi & Mukherjee, 2006). However, this process requires the secondary post-process operation of permeating the original prototyped mold in metal. This typically adds additional lead time and expense.

Another popularly experimented method uses sprayed highly energized metal particles similar in methodology to ink jet printers (Krunakaran, 2004). This method yields very rigid and thermally conductive tools of firm to bridge tooling capabilities. Depending on the size of the tool and the complexity of the mold hard tooling status could be achieved

All of these methods have two chief drawbacks. First, the additive manufacturing machines, which build components in metal, are far more expensive and less accessible than those which build their products in plastics. Machines which can create metallic parts can cost two to ten times the amount of an alternative machine. An additional
drawback is that metallic-based AM technologies have very limited build volumes. This limits the size of a tool which can be produced.

1.2.2 POLYMER-BASED RAPID TOOLS

The largest opportunity for RT implementation would be the direct use of a polymer rapid prototype as an injection mold tool. Polymer-based additive manufactured parts are not only a fraction of the cost of metallic methods but require far less training and have become readily accessible for a variety of industries. Due to this several research areas have been dedicated to its development.

1.2.2.1 ACES™ Inject Mold (AIM™)

The Accurate Clear Epoxy Solid (ACES) style of rapid tooling uses a modified Stereolithography (SLA) technique (Jacobs, 1996). The typical SLA technique uses a laser which cures a liquid photopolymer. The ACES™ replaces the typical photopolymer with a high temperature epoxy solution. The epoxy’s increased heat deflection temperature allows it to survive a greater number of injection molding cycles compared to conventional SLA resin.

The AIM™ process of rapid tooling consists of several steps. First the mold is printed using the ACES method (Kenney, 1996), (Jacobs & Hilton, 2000). Only the shell of the mold is produced using the ACES™ SLA machine. Copper tubing is then added to the mold to help with thermal conductivity and reduce cycle times. In the final step of the process, the bulk of the tool is filled with a metal filled epoxy. During the molding process compressed air is blown onto the tool between molding cycles to help cool the mold face. This process is capable of molding between 20 to 200 components, depending
on the resin being injected, at a cycle time between 3 to 4 minutes (McLaughlin, 1997). Additionally this process takes about a week to yield a fully functional tool (Saurkar, 1998), (Decelles & Barritt, 1996).

The largest detractor to ACES™ tooling is the time required to fabricate a single tool (Nagahanumaiah, Subburaj, & Ravi, 2008). The tool takes multiple post-processing steps along with lengthy curing times between steps. A further attribute to ACES™ tooling is the length of time between injection mold cycles which the tools require. The average cycle time for this type of tooling is ±5 minutes per shot. This means that producing a great number of molded parts requires substantial time investment. Additionally studies have found that the tooling, especially the core, would begin to show wear around 50 cycles (Jacobs, 2000).

1.2.2.2 Laminated Object Manufactured (LOM) Tool

Attempts have been made at modifying the Laminated Object Manufactured (LOM) process for use as direct functional injection mold tooling (Glozer & Brevich, 1993). The first attempts used the conventional LOM machines which utilized laminated layers of paper. The molds, post manufacture, have the same look and consistency as wood. Unfortunately, it was found that unless the molds are coated in at least a thin metallic layer they would not survive the injection molding process (Pak et al., 1997). This process was found to take one to two days to produce a tool without coating.

However, additional attempts have been made using laminated sheets of high temperature polymers and ceramics. The polymer sheets were composed of glass and ceramic fibers in B-staged epoxy matrix. After manufacture the plastic LOM technique creates a tool capable of handling injection mold temperatures of 175°C (Klosterman et
This process is reported to take between two and four days to yield a production ready tool. A final attempt to refine LOM tooling was made by using two ceramic materials that would undergo a post-process sinter. The sintering process bonds the ceramic layers creating a laminated ceramic composite. Little data is available on this process other than it takes up to three days to create a workable tool and requires a polymeric binder (Klosterman, 1996).

1.2.3 **DIRECT POLYMER RAPID TOOLS (PRTs)**

Unlike the previously described methods, direct Polymer Rapid Tools (PRTs) is dedicated to creating a polymer rapid tool without any post-processing. Attempts were made in the late 1990s using the Stereolithography (SLA) process to create functional injection mold tools out of stock SLA plastic resin (Dickens, 1997), (Jacobs P. F., 1996). This research proved it was possible to create injection mold tools using plastic-based rapid prototypes without any post-processing (Jacobs P. F., 1996), (Dickens, Rahmati, & Philip, 1997).

However, it was found that SLA resin was too soft to resist the high amount of pressure and heat of the injection molding process (Dickens, P., 2000). The polymer molds were not able to hold a great enough degree of dimensional tolerances to be reliably used for multiple shots (Dawson, 1998). The research also found that parts of the mold would shear and fail depending on the directionality of the resin as it filled the mold cavity (Palmer & Colton, 2000). It was concluded that although possible, the use of SLA-created molds as an injection mold tool was not feasible for industrial use.
With advances in build materials over the last ten years, it is now possible to create polymer models with high strength and low heat deflection properties (Ilyas, Taylor, Dalgarno, & Gosden, 2010). With this advance in materials along with the now easy access and low cost plastic-based-AM equipment, direct use Polymer Rapid Tools (PRTs) would be a far more advantageous option in creating injection molds for low and highly flexible production.

In early 2011 the Industrial and Manufacturing Engineering Department at Western Michigan University conducted a pilot proof of concept study using the stronger polymer material (Crouch, DeMenter, Guenther, & VanEeuwen, 2011). During this pilot study it was confirmed that PRTs could be used as injection mold tools using this stronger material. As this study was only a proof of concept it did not fully test the capability of the material or its potential feasibility. What is needed is to determine if the newer PRT materials result in a process which is feasible for larger use and study.

1.3 OBJECTIVE

The goal of this research was to study the feasibility of using Polymer Rapid Tools (PRTs) as functional injection mold tooling. For a part molded using PRTs to be feasible it must be able to meet chosen physical dimensions within acceptable tolerance limits, which imply that the mold must be stable and robust to remain within the acceptable limits over multiple short run cycles. Two factors affecting dimensional stability were the focus of this study:

- Mold complexity, referring to geometric features within in the mold
- Mold degradation over time
The primary objective of this study was to study feasibility by determining if PRT molds could meet desired physical dimensions, within tolerance limits, over a range of geometries and complexities. Specifically, the research evaluated if the dimensional stability observed on an object with simple features could be held consistently in components with a higher degree of geometric complexity. Concurrently, dimensional stability of PRT molds was evaluated by cycling the molds until failure and tracking changes and variance over time. Furthermore, PRT mold degradation was studied by using conventionally fabricated aluminum molds as a basis for comparison.

Additionally, information was collected during the course of experimentation to aid in future research and feasibility determination. The differences in process parameters between PRT molded components and aluminum tooling was tracked. The identification and location of PRT mold failures were recorded as well.

1.4 SCOPE

The scope of this research was limited to determining if PRT molds were feasible for use as injection mold tools. Specifically, the experiments focused on the use of direct rapid tools produced using the PolyJet© technique, without post-processing. Feasibility was deemed acceptable if parts molded via PRT could meet the same dimensional constraints as parts molded using conventional means, and do so repeatedly.

For ease and reduction of variables all molds were made using a two plate mold design with no actions or ejection systems. Additionally, the molds did not contain any cooling systems. In place of cooling systems, the surface temperature of the mold was monitored between shots. This narrowed the study to compare only the cavities of the molds by simplifying the tool to its most basic and fundamental components.
Similar research using Stereolithography and filled epoxy tooling found it possible to inject low temperature resins such as Polypropylene (PP) and waxes (Jacobs, 2000). Likewise an exploratory study, using the PolyJet® process found mixed results using low-to-mid temperature resins such as Nylon and PP (Crouch et. al., 2011). This research used high temperature Polycarbonate (PC) resin. The benefit of using Polycarbonate would be to demonstrate an improvement over past SLA research while expanding prior PRT results.

As the purpose and objective of the research was only to determine feasibility, the end molded parts were examined and analyzed rather than the molds. Further analyses on mold wear, molding improvements, and economics were commented on but were not analyzed, as they fell outside the scope of this research. Full analysis of each factor could be studied in further research once feasibility is established.
CHAPTER 2: METHODOLOGY

This chapter describes the specific steps and methodology which were used to construct this project. First, the experimental method is described and explained. This is followed by the experimental protocol used for the experimental phases as well as data collection. Lastly, the various equipment and materials used for the experiments are discussed and described.

2.1 EXPERIMENTAL METHOD

As defined earlier, for a PRT mold to be deemed feasible for use it must be able to mold product that meets specified geometry and do so repeatedly and within tolerance limits. This implies that the mold must be stable and robust. For the purposes of this research mold stability refers to a mold which meets given dimensions over multiple cycles, yielding dimensionally acceptable components. Robustness refers to a mold’s resistance to degradation and therefore the limitation of dimensional variation from part to part.

To study the robustness and stability of PRT molds, parts were selected and molded using both PRTs and conventional metallic tools. Each molded part contained several critical features. After molding, the preselected features were measured, compared with the designed dimensions, and evaluated for accuracy. The measurement data was then tracked from shot to shot to determine the behavior and robustness of the parts being produced. The measurement data from the molded parts would then be analyzed to determine:
• if the parts met the desired dimension (within a specified tolerance),
• if the components met the dimensions for the majority of the components produced,
• the rate at which the parts dimensionally changed as a function of the number of shot cycles the mold experienced.

As mold stability and robustness are directly affected by feature geometry and mold complexity, it was necessary to separate these factors. Therefore, two different experiment phases were developed. Phase I consisted of parts with low levels of mold complexity, while Phase II consisted of parts with high levels of complexity. The two phases were linked using similar feature geometries whose behavior and performance would be evaluated.

The geometric features evaluated were wall thickness, overall length, and overall width. Diametrical features were also studied but to a lesser extent. The feature which was focused on the most was wall thickness. The rational for focusing on wall thickness was that regardless of the component’s shape and function all injection molded components will contain at least one specified thickness. Although overall length and width are not necessarily geometric features, it is a simple way to compare a molded component regardless of overall complexity. To a lesser extent diameters were also examined to represent nonlinear features such as cylinders, bolsters, rounds, and fillets.

2.1.1 **Phase I (Simple Components)**

Three simplified geometric shapes were selected which contain at least two of the previously described features to be studied. The selected shapes were a cylinder, a
rectangle, and a flat angular feature. Each of the shapes selected would have different thicknesses to compare behavior over a wide range.

A cylinder was selected to represent circular molded features such as bolsters, fillets, and rounds. The features to be studied in this geometry were a specified diameter and overall part thickness. The rectangular component represented parts of rectangular construction such as plates or box shapes. The features studied in this geometry include overall length, width, as well as part thickness. The last component consisted of a simple angular feature with a radius. The purpose of this component would be to study a non-rectangular part with a specified length, width, and part thickness. This component also contained a specified diameter in order for comparative purposes. An example of each shape, with its corresponding measurements, can be seen below as Figure 4.

![Figure 4: Phase I simple shapes [A] cylinder, [B] rectangle, and [C] angular feature with radius](image)

2.1.2 **Phase II (Complex Components)**

To represent the complex geometric components in Phase II, two commercially produced components were selected. The first component was a lens for an overhead
dome light. This part consisted of a rectangular shape with multiple wall thicknesses, radii, and tapered surfaces. Three areas of the component, with different thicknesses, were selected. The behavior of the part’s thicknesses in these areas would be compared to the thickness behavior of all three Phase I components. For additional comparison, the length and width of the rectangular shape would be compared to the length and width measurements of the non-circular Phase I designs.

The second Phase II component selected was the interior housing of a rear tail light. This part was also rectangular in shape and contained multiple radii, including several cylindrical bolsters, ribs, and various wall thickness differences. As with the first Phase II component, three areas of differing wall thickness were selected. These three areas were measured and used for comparison with all three Phase I inserts. One of the tail light housing’s cylindrical bolster features was also measured for diametrical comparison. Lastly, the overall length and width of the part was measured for comparison with Phase I components as well the Phase II lens. Examples of the Phase II components can be seen as Figure 5.

Figure 5: Phase II complex shapes [A] dome light lens and [B] tail light housing
2.2 PROTOCOL

For all of the mold designs the following experimental protocol was used:

1. A component with known geometry and tolerances was designed.
2. An injection mold was then engineered to produce the desired component.
3. The mold was produced in both metallic and PRT forms. (Four PRT inserts created for Phase I. One PRT insert for Phase II molds.)
4. The metallic mold was used to establish injection molding parameters and create control specimens for analysis.
5. Once the best parameters were found, and the control specimens molded, the aluminum tool was removed and replaced with a PRT mold. As many components would be created as possible, until PRT mold failure.
6. Once PRT mold failure occurred the failed mold would be replaced with a new PRT mold and cycled until failure. This step would continue until all PRT mold samples have failed.
7. The molded specimens measured and checked against the desired dimensional requirements.
8. The collected measurement data would then be analyzed.

2.1.1 INJECTION MOLDING SETUP PROCEDURE

For all cases, once a mold design was finalized, an aluminum 6061-T6 insert was machined and PRT inserts were printed using the Polyjet© process. First, for a given mold set, the aluminum insert was placed into an injection mold press and used to
establish the processing conditions according to Bryce (1996). The following procedural steps were used to establish processing conditions:

1. Five cycles were taken using the shot size determined via CAD model
2. Packing pressure and time was set to zero
3. Varying shot size in ± 0.05 in\(^3\) increments
4. Cycle mold three times
5. Repeat steps 2 and 3 as needed until part was fully filled
6. Packing pressure set to 1000 psi, packing time set to 1 second
7. Cycle mold three times
8. Vary packing pressure in ± 500 psi increments
9. Repeat steps 6 and 7 until part was fully packed
10. Vary packing time in ± 0.5 second interval
11. Cycle mold three times
12. Repeat steps 9 and 10 until surface defects were minimized
13. At the conclusion of step eleven the process parameters were recorded and the press’s setup was completed.

2.1.2 INJECTION MOLDING EXPERIMENTAL PROCEDURE

Immediately after the processing conditions were established the following experimental procedure was followed:

1. The aluminum tool, used to establish the processing conditions, remained installed in the press
2. Before a subsequent molding cycle began, the mold insert’s surface temperature was measured. The surface temperature of the mold was not allowed to exceed 180°F (82°C).

3. If the mold’s temperature exceeded 180°F the mold was allowed to cool in the open position until its surface temperature was acceptable.

4. The mold insert was cycled then recycled
   a. If a successful part was created, the component was manually extracted, observed for defects, and the part’s identification number was recorded on the runner system.
   b. If the component failed due to short shot or excessive flash, the component was manually extracted and the defect recorded.
   c. If the component failed due to mold failure, the failure location was photographed, recorded, and experimentation discontinued.

5. Steps 2, 3, and 4 were repeated until mold failure or 100 specimens were produced.

6. Once the aluminum tool failed or completed 100 specimens the injection mold press was inspected and the aluminum tool replaced with a PRT insert.

7. Steps 2, 3, and 4 were repeated until the PRT insert failed or 100 specimens were produced.

8. Experimentation was complete once all PRT inserts for the given mold design finished the experimental protocol.
Insert failure was classified as a defect or fracture of the insert which would prevent further molding or compromise the safety of the molding equipment. Traditional part defects, such as excessive flash or the rounding of mold details, were not deemed as a failure as long as the defect did not directly affect the structural integrity of the insert or compromise a critical part dimensions.

In the event of three consecutive short shots, or other defects due to improper process parameters, the process parameters would be modified. Any modifications would be noted and detailed for comparison. In the event that a process parameter required a change larger than 10% of the original condition, the molding sequence would be stopped and the aluminum insert would be reinstalled. The aluminum process parameter procedure would begin again.

2.1.3 **MEASUREMENT PROCEDURE**

Two measurement procedures were needed based on the accessibility of the component’s feature. The primary measurement method would be the use of a Mitutoyo height gauge. This primary measurement method was used for all external dimensions. The secondary measurement method used was a Mitutoyo micrometer. This secondary method was employed for dimensions which were inaccessible or impractical for measurement on the height gauge. Such measurements included internal wall thicknesses, ribs, and bolster features.

2.1.3.1 *Height Gauge Procedure*

Before any measurements were taken, both the granite measurement surface and gauge was cleaned using 99% isopropyl alcohol. Once cleaned the gauge was calibrated
using a 0.005, 0.050, 0.10, 1.00, and 2.00 inch gauge block. The gauge blocks used were all grade 0. After calibration and accuracy were confirmed the following measurement procedure was used. Steps 1 through 7 were repeated for each desired measurement.

1. The height gauge zeroed on the granite surface.
2. The part placed onto the granite surface with its primary reference surface in contact with the granite.
3. If necessary a secondary reference surface would be fixed in place via gauge block, to prevent misaligned measurement.
4. The gauge was then touched off onto the surface to be measured and the measurement recorded.
5. Steps 2 to 4 were then repeated until three measurements were recorded.
6. All three data points were then averaged to form the final recorded measurement.

2.1.3.2 Micrometer Procedure

Before any measurements were taken, the measurement surfaces of the micrometer were cleaned using 99% isopropyl alcohol. Once cleaned the gauge was calibrated using a 0.10 and 0.50 inch gauge block. After calibration and accuracy were confirmed the following measurement procedure was used. Steps 1 through 8 were to be repeated for each desired measurement.

1. The micrometer was collapsed and zero position confirmed.
2. The feature to be measured was placed between the micrometer’s measuring surfaces.
3. Micrometer’s measurement surfaces were then closed until the surface of the object was lightly touching.

4. The object was then rotated to confirm proper alignment of the measuring surfaces with the part’s feature.

5. Using the fine adjustment barrel the micrometer was then tightened into position.

6. The measurement was then read from the micrometer and recorded.

7. Step 2 to 6 would be then be repeated until three measurements were recorded.

8. All three data points were then averaged to form the final recorded measurement.

2.3 EQUIPMENT

The injection mold press used for all of the experiments was a Miltronic Roboshot-110R 110Ton injection molding press, housed in the plastics laboratory at Western Michigan University’s College of Engineering and Applied Sciences. All of the resin used was dried to 0.02% $^{+0.02\%}_{-0.005\%}$ using a Motan Luxor resin dryer. The resin’s percent moisture was checked pre-and post-drying using a Computrac Max 2000 Moisture Analyzer. A Mitutoyo 192-151 height gauge and Mitutoyo 103-259 micrometer were used to acquire the measurement data. Weather-related data was recorded from a Fluke 971 Temperature and Humidity monitor. Images of the equipment used can be seen as Figures 88 to 90 in Appendix B.
2.3.1 Master Unit Die (MUD)

A Master Unit Die (MUD) was designed and fabricated in order to hold the various inserts and mold cavities. A MUD unit was selected because it offers the largest amount of flexibility with a minimal amount of tooling. Due to sizing constraints and economics, the MUD was designed and built at Western Michigan University’s student machine shop. The tool was designed to be a simple two plate design which consisted of an “A” half and “B” half. No ejection system or cooling was to be used for this set of experiments. Therefore the design did not include an ejection housing, support plate, support pillars, or ancillary equipment such as ejector pins or cooling plugs.

The tool was constructed primarily from aluminum 6061-T6 due to ease of machinability and availability. The MUD was designed so that only the surfaces of the insert came into contact while the mold was closed. This was done to insure adequate compression of the parting line. The only section of the MUD unit which came in contact while the mold was closed was a support column. Contained within the support column was the sprue which feeds the insert cavity. Due to the support column acting as a compressive load bearing member, the column was made from P20 tool steel for strength.

As seen in Figure 6 the mold contained two halves. The “A” half consisted of a top clamp plate, “A” plate, sprue bushing, retaining ring, support column, and leader pins. The “B” half of the mold consisted of a “B” plate, rear clamp plate, support column and leader pin bushings.
Both the A and B plates were machined symmetrically to each other and contained two pockets. These pockets acted as mold insert locations. Although not utilized during this project, the MUD was designed so that with a change of support columns two molds could be injected simultaneously. Attached to the A plate was a top clamp plate, also made from 6061-T6. This top plate contained a recessed pocket for a locating ring. The A plate additionally contained a channel for the stainless steel sprue bushing and pocket location for the main support column. Technical drawings outlining the MUD’s design can be seen as Figures 91 to 99 in Appendix C.1.

2.3.2 INSERT DESIGN AND CONSTRUCTION

The MUD unit was designed to allow for two mold insert sets to be used at one time. For the purposes of this experiment, only one mold set was used. A mold insert measures 8 inches long by 4 inches wide as seen in Figure 7 and Figure 8. The sprue utilized within the MUD base allows for two primary runners 0.125 inches in diameter.
Therefore the largest primary runner which could feed a single mold insert was 0.125 inches in diameter.

![Figure 7: Moldable area of MUD insert](image)

As the parting line could change, based upon the requirements of the mold, two design constraints for the mold were created. First, the P20 support pillars had to be machined in accordance with the position of the insert’s parting line and primary runner. Therefore if the parting line of the insert was not equal distant, a specifically made support pillar was fabricated. Second, in order not to disrupt the sprue’s function the combined thickness of both inserts needed to be 3.750 ± 0.002 inches. If the combined thickness of the inserts was above this tolerance range, then the inserts would prevent the support column from compressing. This would divert the flow of resin in the sprue. If the inserts were below this range, excess flash would occur within the mold due to lack of clamping force.

Two recesses were machined within each insert cavity to allow for alignment between the insert blocks. Furthermore, two different corner radii were selected to make
the inserts uni-directional. This prevents loading of a mold insert in the wrong orientation which could damage the mold or the machine.

Each insert was mounted to the MUD unit via socket head cap screw. To prevent the cap screws from coming into contact with each other, four recessed areas were placed in the corner of each insert. If the screws were to collide during molding the collision could damage the mold or press and pose a safety concern. Due to these locations, and the recessed areas for alignment, the moldable footprint allotted was 26.71in², which is illustrated in Figure 7. The nominal plate thickness for a mold insert set was 3.375 inches. An example of a complete mold insert set can be seen in Figure 8.

![Figure 8: MUD unit inserts (assembled)](image)

2.3.3 **INSERT ADAPTER DESIGN AND CONSTRUCTION**

Due to the small size of the Phase I components, printing and machining inserts that were the entire size of the moldable area was impractical. Therefore, smaller mold inserts were selected. The Phase I molds were designed to fit within an insert which measured 3 inches by 4 inches by a combined thickness of 1.5 ± 0.002 inches. An example of the smaller insert can be seen in Figure 9.
The smaller inserts nest within an adapter insert which mounts into the MUD unit as seen in Figure 10 below. The smaller inserts mount into the adapter block, seen in blue, via socket head cap screws. Finally, the adapter assembly was mounted into the MUD unit, seen in green. Due to the recessed areas, required for the cap screws, the overall footprint of the inserts was reduced to 11.26in$^2$. In the case of the more complex Phase II components, no adapter was required. Instead only a one piece mold insert was manufactured. Technical drawings used to produce all of the discussed mold inserts can be seen as Figures 100 to 102 in Appendix C.2.
2.4 PHASE I (SIMPLE MOLD GEOMETRIES)

The following section discusses the rationale behind the part shape, mold, and experimental design for each of the three Phase I mold components. All of the Phase I mold inserts were constructed from the smaller insert described in the previous section. The primary runner configuration, selected for all Phase I inserts, was a half round runner 0.125 inches in diameter. A half round runner was selected due to its ease of manufacturing via conventional milling. The diameter of the runner was selected because it was the largest diameter of runner leading to the adapter from the sprue.

2.4.1 MOLD 1: TWO CAVITY CIRCULAR CHIP MOLD

The first mold design for Phase I testing was designed to study change in diameter along with constant part thickness. For the purposes of this experiment the first mold design was referred to as Phase I Mold 1 (PIM1). For this first mold design two identical cylindrical "chips" were molded simultaneously using a two cavity mold. The chips measure 1 inch in diameter by 0.125 inches thick. An example of the form being molded in this section can be seen below in Figure 11. A technical drawing, including inspection locations, can be found as Figure 103 in Appendix C.2.

![Phase I Mold 1 “chip” design](image)
2.4.1.1 Mold Purpose

The primary purpose of the first mold set was to track changes in diameter and part thickness over the amount of cycles. The secondary purpose was to compare the behavior of diameter and part thickness between components created in the same shot cycle.

2.4.1.2 Mold Design

A two cavity mold was selected in order to optimize the allotted space of the mold insert and to compare components molded during the same cycle. The mold creates two 1 inch diameter by 0.125 inch thick discs per shot. Due to the relatively short length of the runner system both the primary and secondary runners were sized to the same diameter. The primary runner was 1.50 inches long while each of the secondary runners were 0.285 inches before terminating at the gate.

![Figure 12: Phase I Mold 1 (PIM1) insert design](image)

Once the mold was analyzed the following mold inserts, seen in Figure 12 above, were finalized. The dimensions of the mold cavity were increased by x1.005 to account for the 0.005 inches per inch shrinkage of polycarbonate. Additional technical information, specifications, and inspection dimensions for the mold design can be found as Figure 104 in Appendix C2.
2.4.2  **MOLD 2: THREE CAVITY RECTANGLES OF VARYING THICKNESS**

The second mold design for Phase I testing was designed to study rectangular components as well as part thickness. For the purposes of this experiment this mold design was referred to as Phase I Mold 2 (PIM2). The part design for the second mold consisted of three “plates” with identical lengths and widths. Each plate being created was 0.50 inches wide by 1.75 inches long and each has a different thickness. The thicknesses selected were 0.05, 0.10, and 0.15 inches. The plates were molded in parallel allowing for the shortest runner system as well as allowing three components to be molded per shot. The designed part can be seen below in Figure 13. The technical drawing for this component can be found as Figure 105 in Appendix C.2

![Figure 13: Phase I Mold 2 “plate” design](image)

2.4.2.1  **Mold Purpose**

The primary purpose, of the second mold set, was to track behavior in part thickness. The secondary purpose was to compare the behavior of width and length measurement between components created in the same shot cycle.
2.4.2.2 Mold Design

Due to the relatively short length of the runner system both the primary and secondary runners were sized to the same diameter. The primary runner was 1.50 inches long while each of the secondary runners were 0.285 inches before terminating at the gate.

For this part a three cavity mold was selected in order to optimize the allotted space of the mold insert by creating three plates of varying thickness at the same time. Each plate was separated by a 0.325 inch thick wall of mold material. Once the molds were analyzed the following mold inserts, seen in Figure 14 below, were finalized. The technical specifications for the mold design can be found as Figure 105 in Appendix C2.

![Figure 14: Phase I Mold 2 (PIM2) insert design](image)

2.4.3 Mold 3: One Cavity Single Part with Angular Surface

The third and final mold design for Phase I testing was designed to create a component which linked the two previous components. Therefore a component which contained a known length, width, thickness, and diameter was designed. The component was also designed to create a tapered profile. For the purposes of this experiment this mold design was referred to as Phase I Mold 3 (PIM3).
The part was designed to be a single cavity “Plate”. This was in contrast to the two and three cavity molds from the previous Phase I insert designs. This component was designed with a 1 inch diameter and set to 0.125 inches thick similar to PIM1. The insert geometry did not allow for the component to match the length of PIM2’s component. Therefore, the component was set to 1.5 inches long by 1.09 inches wide. The designed part can be seen below in Figure 15. The inspection print for this component’s design can be found as Figure 106 in Appendix C2.

![Figure 15: Phase I Mold 3 part design](image)

2.4.3.1 Mold Purpose

The primary purpose of the third mold set was to track changes in part thickness over the life of the tool. The secondary purpose of the mold set was to act as a comparative part between PIM1 and PIM2.

2.4.3.2 Mold Design

Due to the mold being a single cavity only a primary runner was used to deliver resin to the part cavity. The primary runner was 0.95in long. Once the cavity was analyzed the following mold insert, seen in Figure 16, was finalized. The technical drawing for this mold’s construction can be found as Figure 107 in Appendix C2.
2.5 PHASE II (COMPLEX MOLD GEOMETRY)

The following section discusses the methodology behind the part shape selection, mold design, and experimentation for each of the Phase II mold components used during experimentation. Again, the purpose of the Phase II parts was to mold more complex and commercially available components for more realistic comparison. The study of the more complex components would serve two purposes. First it would confirm and substantiate that PRT molds could yield the same commercially viable components as metallic molds. Second, after additional analysis they could be used to determine if trends found in the simplest geometries scaled to a more complex mold environment.

2.5.1 MOLD 1: LENS

The first component used for Phase II was a prototype part that was provided by a sponsoring body. The provided part was an optical lens cover for the U502 Ford Explorer. The part was selected due to its relatively simple external geometric shape. The original design was simplified to remove extremely complex molding features, such as optical facets and a magnifying lens. The external surfaces of the lens were unmodified.
from the original design. An example of the part before and after simplification can be seen below in Figure 17 and Figure 18 respectively.

Figure 17: Optical lens (before simplification)

Figure 18: Optical lens (after simplification showing runner system)

Although the part was designed to be optically clear at a full production level, optical clarity was not requested nor required for the purposes of this study. Though not deemed critical for the purposes of this test, the sponsoring body requested that the snap features, designed within the part, remain during the simplification process for their own use. The snap features consisted of a single barbed snap on one end of the component as shown in Figure 19. The second snap feature was composed of a double barbed U-shaped snap. This feature, seen in Figure 20 below, was located on the opposite side of the part from the first snap feature.
2.5.1.1  *Lens Mold Purpose*

For this section the primary purpose was to determine if it is possible to mold a complicated shape, such as the lens, using a PRT and if dimensions in key areas would remain within specified tolerances. The secondary purpose was to compare the behavior of the part’s wall thicknesses, overall length, and width against the data from Phase I to determine trends in feature behavior.

2.5.1.2  *Mold Design*

Due to the size of the Lens and its runner system the use of an entire MUD insert was required. This would result in a larger mold runner system and a larger amount of PRT material usage. Figure 21 below shows a size comparison between the Phase II Lens and a single PIM1 chip along with a single PIM2 plate for scale.
The part allowed for a flat parting line which followed the perimeter of the component. To accommodate for the undercut created by the barb snap features the parting line was raised to follow the perimeter of the particular feature. The part geometry came included with a standard draft angle of 2.5 degrees.

A single runner was selected which would pass into a single edge gate. Due to the extra material fed into the double barb feature the gate was shifted slightly off center to allow for a balanced fill. Upon the request of the sponsoring body a trapezoidal gate runner was used. The primary runner measured 0.125 inches wide by 0.0625 inches deep. Examples of both mold halves can be seen as Figure 22. An inspection print for this component can be found as Figure 109 in Appendix C2.
2.5.2 Mold 2: Tail Light Housing

The second mold design used for Phase II was again a prototype part that was provided by the sponsoring body. The selected part was the rear tail light housing from a 2012 Ford F150. This part contains multiple bolsters and ribs for use in an ultrasonic welding process. It also contains varying part thicknesses, a generally rectangular construction, and several tapered ribs for reinforcement.

As with the lens, to remove variables the part was simplified, removing extremely difficult and overly complex features. Deleted features include a mounting tab, to prevent an undercut which would require a mold action. Also, unnecessary geometry such as lettering and mounting orientation grooves were eliminated. This geometry was removed because the geometry would not be measured and was not critical for analysis. A digital example of the part before and after simplification can be seen below in Figure 23 and Figure 24 respectively. The inspection print, for the simplified part, is seen as Figure 110 in Appendix C2.

![Figure 23: Tail light housing (before simplification)](image-url)
2.5.2.1 Housing Purpose

For this section the primary purpose was to determine if it was possible to mold a complicated shape, such as the housing, using a PRT and if dimensions in key areas would remain within specified tolerances.

2.5.2.2 Mold Design

Due to the size of the part a single cavity mold was selected. The complex curved shape of the part prevents a flat parting line. A curved parting line was used which followed the outer flanged perimeter of the part. After simplification there were no longer any undercut surfaces. Therefore no additional mold inserts or actions would be required to mold this component. The part geometry came included with a standard draft angle of 2.5 degrees to facilitate part release after molding.
The Housing component was substantially larger than all previous experimental components. The component requires the entire MUD insert and orienting the component within the MUD insert to maximize insert wall thickness. An example of the housing’s size relative to all other experimental components can be seen above in Figure 25.

A single runner was selected which would pass into a single edge gate. The gate was positioned near the outer most edge at the parts center to facilitate a balanced fill pattern. Again a trapezoidal gate and runner was requested by the sponsor. Once the molds were analyzed the following mold inserts, seen in Figure 26, were finalized.
2.5.3 TEST PROCEDURE

The molding test procedure for Phase II was identical to the procedure outlined in section 2.2.2 with two slight modifications. During Phase I it was found that creating 100 components was excessive. The number of samples created was then changed to 75 components. The second change made to the testing procedure was the amount of PRT molds created for testing. The increased size of mold cavities, required for the Phase II, dictated that the amount of PRT molds was reduced from four molds to two molds. The reason for this change was due to budgetary constraints.

2.6 MATERIALS

The following section discusses specifics on the various materials used for these experiments. This includes the resin being molded as well as technical information on the aluminum and PRT mold materials. More specific information on these materials can be found in Appendix D.
2.6.1 Resin

The resin selected for all of the following experiments was a clear unfilled Lexan 940 Polycarbonate (UL IDES Data Sheets). The resin was dried to 0.02% ± 0.02 moisture before being processed. Additional information on the material can be found on GE’s technical specifications located in Appendix D. This particular resin was selected due to its high injection temperature and its commercial use in the Phase II components.

2.6.2 Mold Materials

Two different materials were used to create molds inserts for the experiments. The metallic control molds were made from aluminum 6061-T6. The PRT molds would be constructed from Objet’s RGD515 (PolyJet Materials Data Sheet)

2.6.2.1 Aluminum Mold Material

The particular grade of Aluminum was selected due to its higher strength and ease of machinability. It is also used extensively in tooling making for prototype mold cavities. The material properties for AL6061-T6 can be seen below in Table 1.

Table 1: AL6061-T6 material properties

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2.6.2.2  *PRT Material (Objet's RGD515)*

The PRT molds were made using a Objet Connex 500 printer from RGD515 “ABS-Like” Digital Material (Objet 3D Printers, 2012). At the time of this research RGD515 was the strongest material with the highest heat resistant offered by Objet for use in there PolyJet© process. The material properties for RGD515 can be found in Table 2.

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<th>Property</th>
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<td>Tensile Strength</td>
<td>D-638-03</td>
<td>8,000-8,700 psi</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>D-638-04</td>
<td>375,000-435,000 psi</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>D-638-05</td>
<td>9,500-11,000 %</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>D-790-03</td>
<td>245,000-320,000 psi</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>D-790-04</td>
<td>1.22-1.50 psi</td>
</tr>
<tr>
<td>Izod Notched Impact</td>
<td>D-256-06</td>
<td>1.22-1.50 ft lb/in</td>
</tr>
<tr>
<td>HDT @ 0.45MPa</td>
<td>D-648-06</td>
<td>136-154 °F</td>
</tr>
<tr>
<td>HDT at 0.45MPa <em>after post curing</em></td>
<td>D-648-06</td>
<td>180-194 °F</td>
</tr>
</tbody>
</table>

2.7 TESTING AND MEASUREMENT CONDITIONS

According to injection molding standards, tolerances of ±5% could be held for a part thickness 0.020in (±.001in), and ±1% for components 0.050in (±.0005in). Lengths and diameters have standard tolerances of ±0.5% for lengths under 1.0 inches (±.005) and ±0.25% up to 5 inches (±0.0125in) (Rosato, D.V., Rosato, M., 2000).

To simplify the measurements and to examine a worst case scenario dimensions less than 2 inch were assigned a tolerance of ± 0.005 inches. Measurements over 2 inch were assigned a tolerance limit of ± 0.010 inches.
The test parameters describe the equipment and the conditions under which the experiment was conducted or the measurement that was taken. The test parameters were important to understand the implications of the results. In order to attain the same results when the benchmark was repeated, the test parameters have to be mentioned along with the benchmark results. Table 3 below includes the common test parameters which all of the following mold evaluation experiments were conducted in.

Table 3: Common test parameters and default values

<table>
<thead>
<tr>
<th>Test Parameter</th>
<th>Recorded Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environment (Molding)</strong></td>
<td></td>
</tr>
<tr>
<td>Temp. (F)</td>
<td>82.3 ± 10.0</td>
</tr>
<tr>
<td>Humidity %</td>
<td>53.0 ± 5.0</td>
</tr>
<tr>
<td>Atmospheric Pressure (in Hg)</td>
<td>30.25 ±10</td>
</tr>
<tr>
<td><strong>Environment (Specimen Measurement)</strong></td>
<td></td>
</tr>
<tr>
<td>Temp. (F)</td>
<td>79.4 ±5</td>
</tr>
<tr>
<td>Humidity %</td>
<td>44 ± 3</td>
</tr>
<tr>
<td>Atmospheric Pressure</td>
<td>30.25 ± 10</td>
</tr>
</tbody>
</table>
CHAPTER 3: RESULTS

This chapter details the data which was gathered during experimentation. Phase I data is presented first, followed by Phase II. A summary for each phase is presented at the end of each section. Included with these summaries are additional statistical information on the overall performance and acceptability of the components produced.

For each mold design statistical information has been provided. Included within the statistical tables are the amount of samples produced per mold, the nominal measurement value, minimum and maximum values, mean, and the amount which the mean varied from the nominal assigned dimension. In addition to the tables, run charts are presented to track the observed behavior of each feature. The purposes of the run charts are to study the behavior of the mold insert over the life of the tool. The run charts show the nominal dimension, maximum and minimum tolerance allowances, and data set trends.

For reference, the assigned tolerance for all measurements fewer than 2 inches was ± 0.005 inches. For measurements over 2 inches a tolerance limit of ± 0.0625 inches was assigned. The length of Phase II Mold 2 was specified to ± 0.125 due to its length being over 6 inches. Inspection dimensions and tolerances for each part can be found in the technical drawings, located in Appendix C.2.

Lastly, as stated in the protocol, insert failure was classified as a defect or fracture of the insert which would prevent further molding or compromise the safety of the molding equipment. Traditional part defects, such as excessive flash, the rounding of mold details, and components not meeting tolerances, were not deemed as a mold failure as long as the defect did not directly affect the structural integrity of the insert or
compromise a critical part dimensions. The first instance a measurement did not meet its tolerance zone is recorded within the statistical data.

3.1 PHASE I RESULTS

The following section describes the results collected during Phase I experimentation. For ease of comparison a summation of Phase I experimental results is located in section 3.1.4 of this chapter.

3.1.1 MOLD 1: TWO CAVITY CIRCULAR CHIP MOLD

During experimentation, all of the Phase I Mold 1 PRTs yielded product which met tolerance standards. The PRT molds yielded an average of 39.5 shots per mold. A total of 158 components were molded using four PRT inserts. As each component contains two chips, a total of 316 individual cylindrical features were molded and measured. In the case of the conventional aluminum tool, used as a control group, the mold reached the maximum of one hundred shots without failure. This translates into 100 components with a total of 200 individual chips.

An example of a component molded via PRT insert, along with its corresponding PRT tool, is seen as Figure 27 and Figure 28. Additional pictures of experimentation, produced samples, and mold failures can be referenced as Figures 231 to 240 in Appendix G.1.

Once the ideal process parameters were established the inserts yielded components with very few observable defects. For reference, the process parameters used for each PIM1 mold can be found within Appendix E. It should be noted that after roughly twenty cycles, parts molded using a PRT insert, began to display an increasing
amount of flash at the parting line. The flash described is highlighted in Figure 27. For all experiments flash was not deemed as part or mold failure. The rational being: flash from prototype level components are typically expected and trimmed from the component. The parts are deemed acceptable as long as the inspected part met dimensional requirements.

Figure 27: PIM1 molded specimen

Figure 28: PIM1 insert installed in molding press (after 2 cycles)

Figure 29: PIM1 insert after mold failure (40 cycles)
During the Phase I Mold 1 experiments the cause of PRT mold failure, in all instances, was due to the part adhering to the mold cavity’s surface preventing part extraction. Regardless of the application of release agent, the part would become fused to the mold in such a way that the part could not be extracted without destroying the mold cavity. During the extraction process the mold would typically chip and fracture the gate, or surrounding parting line, rendering the insert unusable. An example of such a failure is shown in Figure 29.

An observation made during experimentation was a visual discoloration of the PRT mold prior to mold failure. The cavity surface of the PRT insert would lighten in color roughly 10 to 20 shots prior to mold failure. The discoloration typically presented itself in conjunction with the observed parting line flash. The described yellowing is also highlighted in Figure 29.

3.1.1.1 Diameter

Statistical information regarding the diametrical feature can be found in Table 4. This table represents all diameter measurements taken from Phase I Mold 1 inserts. Out of the 200 individual components molded using an aluminum tool, all of the measured diameters fell within acceptable tolerance limits. In contrast, out of the 316 components molded using PRT inserts, 298 were dimensionally acceptable. This equates to 94.3% of the diameters produced from a PRT insert being dimensionally acceptable. The table also shows that in all but one instance the data’s range fell below the established tolerance zone of ±0.005 inches. In all cases, but one, the calculated range of the data was 0.010 inches which is equivalent to the tolerance range.
Table 4: PIM1 – diameter measurement statistics

<table>
<thead>
<tr>
<th></th>
<th>Aluminum Control</th>
<th>PRT Mold 1</th>
<th>PRT Mold 2</th>
<th>PRT Mold 3</th>
<th>PRT Mold 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dia. 1</td>
<td>Dia. 2</td>
<td>Dia. 1</td>
<td>Dia. 2</td>
<td>Dia. 1</td>
</tr>
<tr>
<td>Samples</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td># Within Tolerance</td>
<td>100</td>
<td>100</td>
<td>22</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>Exceeded Tolerance</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Nom.</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Max</td>
<td>1.003</td>
<td>1.004</td>
<td>1.006</td>
<td>1.005</td>
<td>1.006</td>
</tr>
<tr>
<td>Min</td>
<td>0.997</td>
<td>0.996</td>
<td>0.999</td>
<td>1.000</td>
<td>0.997</td>
</tr>
<tr>
<td>Range</td>
<td>0.006</td>
<td>0.008</td>
<td>0.007</td>
<td>0.005</td>
<td>0.009</td>
</tr>
<tr>
<td>Mean</td>
<td>1.000</td>
<td>1.000</td>
<td>1.003</td>
<td>1.003</td>
<td>1.002</td>
</tr>
<tr>
<td>Median</td>
<td>1.000</td>
<td>1.000</td>
<td>1.002</td>
<td>1.004</td>
<td>1.003</td>
</tr>
<tr>
<td>StdDev.</td>
<td>0.0014</td>
<td>0.0020</td>
<td>0.0021</td>
<td>0.0015</td>
<td>0.0021</td>
</tr>
<tr>
<td>Nom. Vs. Mean</td>
<td>0.0001</td>
<td>-0.0001</td>
<td>-0.0026</td>
<td>-0.0033</td>
<td>-0.0022</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100.0%</td>
<td>100.0%</td>
<td>88.0%</td>
<td>100.0%</td>
<td>95.0%</td>
</tr>
</tbody>
</table>
Two charts depicting diameter feature behavior are presented as Figure 30 and Figure 31. These figures specifically show diameter measurements from the left cavity of the mold. Figure 30 depicts diameter measurements from the second PRT insert while Figure 31 depicts data measured from the aluminum control tool.

The data shows the aluminum tool remains stable around the desired nominal dimension with little variation. The PRT’s chart shows that the first molded parts are within tolerance limits and acceptable. However, as the tool is used the feature’s size steadily increases. Eventually the parts surpass the upper tolerance limit before mold failure occurs. In this particular case two of the molded specimens fall outside of the desired tolerance range before mold failure. Similar behavior is observed in all four PRT inserts. Likewise similar behavior is observed in parts molded in the right cavity of all PRT inserts. For reference, the remaining collected data can be found as Figures 111 to 120 in Appendix F.1.

![Phase I Mold 1: PRT Mold Dia 2-1](image)

Figure 30: PIM1 Run Chart – PRT mold #2 diameter measurements
3.1.1.2 Thickness

Statistical information regarding the thickness of the molded features can be found as Table 5 on the next page. This table represents all thickness measurements taken from Phase I Mold 1 inserts. Out of the 200 individual components molded using an aluminum tool, 100% of the measured thicknesses fell within acceptable tolerance limits. By comparison, out of the 316 features molded using PRT inserts, 308 of the features met acceptable limits. This equates to 97.5% of PIM1 thicknesses molded from PRT inserts being acceptable. Individual cavity acceptability ranged from 92% to 100%. Lastly, the aluminum’s range was less than the established tolerance. By comparison the PRTs’ range was equal to or slightly greater than the tolerance of 0.010 inches.

Two range charts depicting PIM1 thickness feature behavior are presenting as Figure 32 and Figure 33. These figures specifically show thickness measurements recorded from the left mold cavity. Figure 32 shows the thickness of parts molded from the third PRT insert. Figure 33 depicts the measured thickness of parts molded from the aluminum control tool. For reference, the remaining run charts are Figures 121 to 130 in Appendix F.1.
Table 5: PIM1 – thickness measurement statistics

<table>
<thead>
<tr>
<th></th>
<th>Aluminum Control</th>
<th>PRT Mold 1</th>
<th>PRT Mold 2</th>
<th>PRT Mold 3</th>
<th>PRT Mold 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THK. 1</td>
<td>THK. 2</td>
<td>THK. 1</td>
<td>THK. 2</td>
<td>THK. 1</td>
</tr>
<tr>
<td>Samples</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td># Within Tolerance</td>
<td>100</td>
<td>100</td>
<td>23</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td>Exceeded Tolerance</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Nom.</td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
</tr>
<tr>
<td>Max</td>
<td>0.128</td>
<td>0.129</td>
<td>0.134</td>
<td>0.131</td>
<td>0.13</td>
</tr>
<tr>
<td>Min</td>
<td>0.121</td>
<td>0.122</td>
<td>0.121</td>
<td>0.122</td>
<td>0.12</td>
</tr>
<tr>
<td>Range</td>
<td>0.007</td>
<td>0.007</td>
<td>0.013</td>
<td>0.009</td>
<td>0.010</td>
</tr>
<tr>
<td>Mean</td>
<td>0.125</td>
<td>0.125</td>
<td>0.127</td>
<td>0.127</td>
<td>0.126</td>
</tr>
<tr>
<td>Median</td>
<td>0.125</td>
<td>0.125</td>
<td>0.127</td>
<td>0.126</td>
<td>0.125</td>
</tr>
<tr>
<td>StdDev.</td>
<td>0.0022</td>
<td>0.0020</td>
<td>0.0030</td>
<td>0.0022</td>
<td>0.0024</td>
</tr>
<tr>
<td>Nom. Vs. Mean</td>
<td>-0.0002</td>
<td>-0.0003</td>
<td>-0.0018</td>
<td>-0.0019</td>
<td>-0.0006</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100.0%</td>
<td>100.0%</td>
<td>92.0%</td>
<td>96.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
The data shows the trends found in the diameter measurements continued with the collected data for part thickness. The aluminum tool remains stable around the desired nominal dimension. However, compared to the diameter features, the thicknesses of each cylinder experienced a greater degree of variation from shot to shot.

Figure 32: PIM1 Run Chart – PRT mold #3 thickness measurements

Figure 33: PIM1 Run Chart - Aluminum mold thickness measurements

The PRT run chart shows the first molded parts are within tolerance limits. As the tool is used the feature’s size steadily increases. Eventually the parts surpass the upper tolerance limit before mold failure occurs. In this particular case only one of the molded specimens fell outside of the desired tolerance range before mold failure. Similar behavior is observed in all four PRT inserts.
3.1.1.3  Mold I Summary

Out of the 316 PRT specimens parts molded 289 were acceptable both in thickness and diameter. From those that failed to be acceptable only one component failed to meet both the diameter and thickness specification. The remaining unacceptable components failed only a single specification. By comparison, out of the 200 parts molded with the control tool, all 200 specimens met both specifications. A breakdown of each tool’s performance by cavity is shown below in Table 6.

Table 6: PIM1Summary - total part acceptability

<table>
<thead>
<tr>
<th>Cavity 1 (# Acceptable)</th>
<th>AL</th>
<th>PRT1</th>
<th>PRT2</th>
<th>PRT3</th>
<th>PRT4</th>
<th>PRT Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>20</td>
<td>38</td>
<td>32</td>
<td>55</td>
<td></td>
<td>145</td>
</tr>
<tr>
<td>Cavity 2 (# Acceptable)</td>
<td>100</td>
<td>24</td>
<td>33</td>
<td>33</td>
<td>54</td>
<td>144</td>
</tr>
<tr>
<td>Total Acceptable</td>
<td>100</td>
<td>44</td>
<td>71</td>
<td>65</td>
<td>109</td>
<td>289</td>
</tr>
<tr>
<td>Total Produced</td>
<td>200</td>
<td>50</td>
<td>80</td>
<td>70</td>
<td>116</td>
<td>316</td>
</tr>
<tr>
<td>Cavity 1 (%) Acceptable</td>
<td>100.0%</td>
<td>80.0%</td>
<td>95.0%</td>
<td>91.4%</td>
<td>94.8%</td>
<td>91.8%</td>
</tr>
<tr>
<td>Cavity 2 (%) Acceptable</td>
<td>100.0%</td>
<td>96.0%</td>
<td>82.5%</td>
<td>94.3%</td>
<td>93.1%</td>
<td>91.1%</td>
</tr>
<tr>
<td>Mold Average (%) Acceptable</td>
<td>100.0%</td>
<td>88.0%</td>
<td>88.8%</td>
<td>92.9%</td>
<td>94.0%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PRT Unacceptable Features</th>
<th>AL Unacceptable Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 out of 2</td>
<td>26</td>
</tr>
<tr>
<td>2 out of 2</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
</tr>
</tbody>
</table>

Mold Performance

<table>
<thead>
<tr>
<th>PRT Cavity Average</th>
<th>Al Cavity Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>91.5%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PRT Mold Avg.</th>
<th>AL Mold Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.9%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

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3.1.2 *Mold 2: Three Cavity Rectangles of Varying Thickness*

During experimentation, all of the Phase I Mold I PRTs yielded product which met tolerance standards. The PRT molds yielded an average of 34 shots per mold. This was a smaller average life than PIM1’s average life of 39.5 shots. A total of 102 components were molded using four PRT inserts. As each component contains three rectangles, a total of 408 individual rectangular parts were molded and measured. In the case of the conventional aluminum tool the mold reached the maximum of 100 shots without failure. This translates a total of 300 individual rectangles molded.

For reference an example of a PIM2 insert, along with a component molded from a PRT insert, are presented as Figure 34 and Figure 35. Once the ideal process parameters were established, the inserts yielded components with very few observable defects. The most noted defects were substantial amounts of internal shrinkage and flashing in the center and edges of the rectangular parts. This could be attributed to the design of the mold and location of the gate. Slight amounts of flash could be seen at the farthest distance from the gate in the opposing two rectangles. This flash only became present in PRT molds which had experienced an excess of 15 cycles. An example of these defects can be seen below in Figure 34.
The most common cause of mold failure was excessive deflection in the mold wall between the center and right rectangle. This deflection eventually became large enough that fractures occurred in the center rectangle’s cavity. An example of the described fracture can be seen below in Figure 36. An additional cause of mold failure
was a strong adhesion between the part and the mold, similar to the failures found during PIM1. This adhesion would become strong enough that part extraction resulted in the destruction of the mold. As with the Phase 1 Mold 1 experiments the PRT mold cavities began to observably lighten in color after multiple cycles. In this particular instance a yellowing of the center most mold cavity was observed prior to mold failure in all PRT cases.

Figure 36: PIM2 failure in mold 2

3.1.2.1 Thickness

Out of the 300 individual components molded using an aluminum tool, 298 of the measurements fell within acceptable tolerance limits. That equates to 99.3% of the components, molded using the control tool, as being acceptable. In contrast, out of the 408 components molded using PRT inserts, 368 were dimensionally acceptable. This is equivalent to 90.2% of the PRT thicknesses being dimensionally acceptable. Information regarding the various thickness features, within Phase I Mold 2, is presented as Table 7 on the next page. This table represents all thickness measurements taken from Phase I Mold 2 inserts.
Table 7: PIM2 - thickness measurement statistics

<table>
<thead>
<tr>
<th></th>
<th>Aluminum Control</th>
<th>PRT Mold 1</th>
<th>PRT Mold 2</th>
<th>PRT Mold 3</th>
<th>PRT Mold 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THK.1</td>
<td>THK.2</td>
<td>THK.3</td>
<td>THK.1</td>
<td>THK.2</td>
</tr>
<tr>
<td>Samples</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td># Within Tol.</td>
<td>98</td>
<td>100</td>
<td>100</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Exceed Tol.</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Nom.</td>
<td>0.100</td>
<td>0.150</td>
<td>0.050</td>
<td>0.100</td>
<td>0.150</td>
</tr>
<tr>
<td>Min.</td>
<td>0.102</td>
<td>0.15</td>
<td>0.05</td>
<td>0.102</td>
<td>0.151</td>
</tr>
<tr>
<td>Max.</td>
<td>0.106</td>
<td>0.154</td>
<td>0.055</td>
<td>0.110</td>
<td>0.158</td>
</tr>
<tr>
<td>Range</td>
<td>0.004</td>
<td>0.005</td>
<td>0.006</td>
<td>0.008</td>
<td>0.007</td>
</tr>
<tr>
<td>Mean</td>
<td>0.104</td>
<td>0.153</td>
<td>0.053</td>
<td>0.105</td>
<td>0.154</td>
</tr>
<tr>
<td>Median</td>
<td>0.103</td>
<td>0.153</td>
<td>0.053</td>
<td>0.105</td>
<td>0.154</td>
</tr>
<tr>
<td>StdDev.</td>
<td>0.0007</td>
<td>0.0008</td>
<td>0.0009</td>
<td>0.0018</td>
<td>0.0019</td>
</tr>
<tr>
<td>Nom. Vs. Mean</td>
<td>-0.0035</td>
<td>-0.0026</td>
<td>-0.0027</td>
<td>-0.0047</td>
<td>-0.0044</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>98.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>72.0%</td>
<td>80.0%</td>
</tr>
</tbody>
</table>
In the following pages, Figures 37 thru 42 display run chart data collected from the aluminum control tool and second PRT insert. These figures represent plate thicknesses for all three plates created from each insert. All of the run charts related to PIM2 plate thickness can be found as Figures 131 to 145 in Appendix F.2.

Figures 37 and 38 display the thicknesses of the rectangle located to the left of the primary runner, referred to as Plate 1 THK. Figure 37 details data collected from the aluminum control tool while Figure 38 describes data collected from the third PRT insert.

Both charts show that the average part thickness lies on the higher end of the tolerance limit. In the case of the aluminum control tool the collected data has a very small negative trend with low deviation from shot to shot. By contrast the PRT tool has a large amount of variation from shot to shot tool. This trend is evident in the remaining PRT run charts.

Both the aluminum and PRT run charts show that several components exceeded the maximum tolerance limit. However, the aluminum tool appears to exceed the limit during a brief and abrupt shift. After which the aluminum tools behavior returns to its previous performance. The failures from the PRT insert appear to be caused due to a high standard deviation between shots. The parts exceeding tolerances do not appear to be attributed to any sudden shifts in process performance.
Figures 39 and 40, the thicknesses measured off of the plate centered on the primary runner, referred to as Plate 2, are presented. Figure 39 depicts data from the aluminum tool while Figure 40 shows data from the third PRT insert. Plate 2 is the thickest plate of the three molded.

Based upon the run charts the data from the aluminum has a low standard deviation and a gradual negative slope. All of the thicknesses measured from the aluminum tool were dimensionally acceptable. Despite the negative slope the components being created by the aluminum tool are approaching the more ideal nominal dimension.
Out of the PRT inserts created a consistently high standard deviation is found from shot to shot. The PRT mold depicted below shows the greater amount of deviation, especially when compared to the aluminum tool. The remaining PRT tools contained little slope, with Figure 40 showing the greatest amount. Likewise, all of the components are dimensionally acceptable.

![Phase 1 Mold 2: AL Mold Plate2 THK](image)

**Figure 39:** PIM2 Run Chart - Aluminum mold plate 2 thickness measurements

![Phase 1 Mold 2: PRT3 Plate2 THK](image)

**Figure 40:** PIM2 Run Chart - PRT mold #3 plate 2 thickness measurements

Finally, Figures 41 and 42 show the thinnest of the plate cavities, which was located to the right of the primary runner, referred to as Plate 3. Figure 41 displays data collected from the aluminum tool while Figure 42 shows data from the third PRT insert. The behavior of the aluminum tool is again similar to the prior aluminum produced thicknesses. The data appears low in deviation with only a small positive slope.
The data recorded from the PRT appears to start low in deviation. As the amount of shots increases, the amount of dimensional deviation also increases. Likewise the PRT insert has a greater positive slope compared to the aluminum control tool. Both trends are found in two of the additional PRT insert specimens.

![Figure 41: PIM2 Run Chart - Aluminum mold plate 3 thickness measurements](image1)

![Figure 42: PIM2 Run Chart - PRT mold #3 plate 3 thickness measurements](image2)

### 3.1.2.2 Length

Out of the 408 parts molded using the PIM2 PRT inserts all had acceptable lengths. Likewise, all 300 parts molded with the control tool had acceptable lengths. The data reveals that not only are the parts acceptable but there was only a 0.001 inches difference between parts molded with an aluminum tool and those from the PRT tools.
This data along with other information can be found in Table 8. Run charts showing the part’s behavior are found in Figures 43 thru 46.

Figure 43 displays the measured lengths for plates 1, 2, and 3 molded from the first PRT tool. This chart shows that despite each part being molded in its own individual mold cavity, the dimensional behavior of components is very similar over time. The lengths of all three components have a generally large positive slope. This translates into the parts becoming longer as mold use increases. This trend is present in all of the parts molded using PRTs. The run charts for the remaining PRT molds can be referenced as Figures 146 to 150 in Appendix F.2.

Due to the fact that all of the measurements share the same nominal dimension and are molded within the same shot, the data for the three plates can be averaged together to better show the behavior of the tool. Figure 44 graphs the data presented in Figure 43 by averaging the three plates. This data further substantiates the observed trend. The chart shows that the parts from the second PRT tool grew an average of 7E-5 inches per shot.
<table>
<thead>
<tr>
<th></th>
<th>Aluminum Control</th>
<th>PRT Mold 1</th>
<th>PRT Mold 2</th>
<th>PRT Mold 3</th>
<th>PRT Mold 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L 1</td>
<td>L 2</td>
<td>L 3</td>
<td>L 1</td>
<td>L 2</td>
</tr>
<tr>
<td><strong>Samples</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong># Within Tol.</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong>Exceeded Tol.</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Nom.</strong></td>
<td>1.75</td>
<td>1.75</td>
<td>1.75</td>
<td>1.75</td>
<td>1.75</td>
</tr>
<tr>
<td><strong>Min.</strong></td>
<td>1.747</td>
<td>1.747</td>
<td>1.747</td>
<td>1.746</td>
<td>1.746</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>0.006</td>
<td>0.006</td>
<td>0.006</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>1.750</td>
<td>1.750</td>
<td>1.750</td>
<td>1.749</td>
<td>1.749</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>1.750</td>
<td>1.750</td>
<td>1.750</td>
<td>1.749</td>
<td>1.750</td>
</tr>
<tr>
<td><strong>StdDev.</strong></td>
<td>0.0015</td>
<td>0.0013</td>
<td>0.0013</td>
<td>0.0018</td>
<td>0.0019</td>
</tr>
<tr>
<td><strong>Nom. Vs. Mean</strong></td>
<td>0.0000</td>
<td>0.0001</td>
<td>-0.0003</td>
<td>0.0008</td>
<td>0.0006</td>
</tr>
<tr>
<td><strong>% Acceptable</strong></td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 8: PIM2 – length measurement statistics
For comparative reference Figure 45 and Figure 46 present the data collected from the control tool. A very different observation is made when evaluating the individual components from the aluminum tool. There appears to be little to no slope present in all three of the lengths being molded. This is further corroborated when the average performances, seen in Figure 46, is studied. The slope of the averaged aluminum length data is -3E-06 inches.
3.1.2.3 Width

Table 9 shows data collected from the measured widths of the molded rectangles. The data within this table reflects all molded parts from both PRT and Aluminum inserts. In several instances parts were successfully molded but fell outside of established tolerance limits. Out of the 300 individual components molded using an aluminum tool, 100% of the measurements fell within acceptable tolerance limits. In contrast, out of the 408 components molded using PRT inserts, 331 were dimensionally acceptable. This is equivalent to 81.1% of the PRT widths being dimensionally acceptable.
Table 9: PIM2 – width measurement statistics

<table>
<thead>
<tr>
<th></th>
<th>Aluminum Control</th>
<th>PRT Mold 1</th>
<th>PRT Mold 2</th>
<th>PRT Mold 3</th>
<th>PRT Mold 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width. 1</td>
<td>Width. 2</td>
<td>Width. 3</td>
<td>Width. 1</td>
<td>Width. 2</td>
</tr>
<tr>
<td>Samples</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td># Within Tol.</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>Exceed Tol.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Nom.</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Min</td>
<td>0.495</td>
<td>0.497</td>
<td>0.496</td>
<td>0.482</td>
<td>0.500</td>
</tr>
<tr>
<td>Max</td>
<td>0.502</td>
<td>0.502</td>
<td>0.502</td>
<td>0.504</td>
<td>0.507</td>
</tr>
<tr>
<td>Range</td>
<td>0.007</td>
<td>0.005</td>
<td>0.006</td>
<td>0.024</td>
<td>0.007</td>
</tr>
<tr>
<td>Mean</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.501</td>
<td>0.504</td>
</tr>
<tr>
<td>Median</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td>0.502</td>
<td>0.504</td>
</tr>
<tr>
<td>StdDev.</td>
<td>0.0012</td>
<td>0.0013</td>
<td>0.0012</td>
<td>0.0044</td>
<td>0.0021</td>
</tr>
<tr>
<td>Nom. Vs. Mean</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0001</td>
<td>-0.0013</td>
<td>-0.0038</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>92.0%</td>
<td>80.0%</td>
</tr>
</tbody>
</table>
Width measurements from the aluminum and PRT molded parts are located in Figures 47 thru 50. Similar to the length features, each insert molds three components with the same nominal and tolerance specifications. Due to this, the run charts show all components produced for a given shot for reference. Figure 47 displays the measured lengths for Plates 1, 2, and 3 molded from the second PRT tool. For further comparison the three individual components, molded per same shot, are averaged and graphed in a separate run chart. Figure 48 displays the average behavior of part width within the second PRT insert.

Based upon the two run charts an immediate phenomenon is evident. All of the components, that are first molded, have relatively low deviation and little to no slope. The parts that are first created are nominally high on the tolerance range but are more consistent than other data groups presented. However, after the twenty fifth shot, parts molded in the second part cavity begin to grow rapidly. Simultaneous the remaining two cavities began to shrink in width. For orientation, the second part cavity is the thickest cavity and located in line with the primary runner.

![Phase 1 Mold 2: PRT 2 Width Measurements](image-url)

Figure 47: PIM2 Run Chart - PRT mold #2 width measurements
The noted data trend was apparent in all four PRT inserts. A distinctive change occurs within the mold without the insert completely failing. This pattern is further seen within the averaged data run chart. The parts being created appear stable for the first half of the tool’s life. However, nearing the end of tool life, the rate of change between shots increased sharply. For comparison, the remaining run charts can be found as Figures 156 to 165 in Appendix F.

Figure 48: PIM2 Run Chart – PRT mold #2 average width measurements

Figure 49 and Figure 50 display the raw and averaged data collected from the aluminum control tool. All of the data collected from the aluminum tool fell within acceptable specifications. Unlike the PRT samples the data is consistent from shot to shot with very little deviation. Apart from the very first shots the recorded data is very close to the nominal specified dimension. This observation is further corroborated when the average data is reviewed. The trend of rapid part change, found in the PRT inserts, is not found within the aluminum tooling.
3.1.2.4  Mold 2 Summary

Out of the 408 PRT specimen parts molded 297 had acceptable thicknesses, length, and width, 105 PRT components failed only one feature and 6 components failed two features. By comparison, out of the 300 parts molded with the control tool, 298 specimens met all three specifications. The two remaining components only had one unacceptable feature each. A breakdown of each tool’s performance by cavity is shown below in Table 10.
Table 10: PIM2 Summary - total part acceptability

<table>
<thead>
<tr>
<th>% Acceptable</th>
<th># Acceptable</th>
<th>PIM2 Acceptability</th>
<th>PRT Unacceptable Features</th>
<th>AL Unacceptable Features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PRT1</td>
<td>PRT2</td>
<td>PRT3</td>
</tr>
<tr>
<td>Cavity 1</td>
<td>98</td>
<td>17</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>Cavity 2</td>
<td>100</td>
<td>15</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Cavity 3</td>
<td>100</td>
<td>21</td>
<td>26</td>
<td>37</td>
</tr>
<tr>
<td>Total Produced</td>
<td>298</td>
<td>53</td>
<td>60</td>
<td>86</td>
</tr>
</tbody>
</table>

Mold Average:

- PRT Cavity Average: 72.8%
- PRT Mold Avg: 72.4%
- % Acceptable: 99.3%
- AL Unacceptable Features: 105
- PRT Unacceptable Features: 6
- Total: 111
- Total: 2

Upon further review of data with high amounts of unacceptable measurements, it was noticed this data appeared to have an overall range smaller than the specified tolerance limit. The data visually appeared to fail due to an average value which was larger/smaller than the specified nominal value, rather than excessive standard deviation or range. To review this, two data sets were selected. The tolerance range was offset based upon the difference in the data’s mean value and the specified nominal value.

One of the selected sets was the width measurement from the third PRT insert. Using the original tolerance range five components failed to fall within the acceptable range. The mean value of the data differed from the nominal dimension by 0.0018 inches. The maximum and minimum tolerance was then adjusted to reflect the difference in
nominal value. After the adjustment the number of unacceptable components is only one component, the last shot when failure occurred. This change represents an increase in acceptability from 86.5% to 97.3%. This data along with the adjusted tolerance range can be seen as Figure 51 below.

![Figure 51: PIM2 Run Chart - PRT 3 with adjusted tolerances](image)

The second selected data set, seen in Figure 52, consisted of the width measurement from the fourth PRT insert. With the original tolerance range the data contained five components outside of the given limit. The tolerance range was then adjusted by 0.0024 inches to compensate for the difference between nominal and mean values of the width dimension. After the adjustment was done, only two components did not fall within the tolerance limits. This adjustment represented an increase in acceptability from 88.9% to 95.6%.
These two studies show that there are various reasons for why certain data sets have larger numbers of failures than others. One reason might be caused in part by an insert manufactured with a nominal dimension different from the specified nominal dimension. This observation has been found in both PRT as well as aluminum inserts.

It should be noted the PRT inserts have not undergone any secondary processes after their initial additive manufacture. In this study the feasibility of an acceptable final product is being evaluated, based on having acceptable PRT inserts. The cause of the differences within nominal value could be due to variation in the additive manufacturing process. The purpose and scope of this research is to study direct rapid tooling without secondary processing. With this scope in mind these finding are noted for future studies and research.

### 3.1.3 Mold 3: One Cavity Single Part with Angular Surface

The following section details the results collected from the Phase I Mold 3 experiments. The PRT molds yielded an average of 30 components per mold which was a smaller average life then Phase I Mold 1 which had an average life of 39.5 cycles. The average mold life was skewed for this mold design due to a premature mold failure in the
third PRT insert. The gate on the mold failed due to excessive force required for part extraction. However, at the time of failure the mold was not fully discolored and did not show similar signs of mold wear that were displayed in previous Phase I PRT mold insert. In the case of the conventional aluminum control group tool, the mold reached the maximum allotted one hundred cycles and failure of the tool was not achieved.

A total of 100 components were molded using the aluminum control tool. Using four PRT inserts a total of 122 parts were molded and measured for data. Examples of a PRT mold insert as well as PRT molded components can be seen as Figure 53 and Figure 54 on the following page. Once the most preferable process parameters were found the PRT tools yield components with little observable defects. Unlike the other Phase I molds, flash was only apparent upon the failure of the molds. Flash was never present in parts molded via the aluminum control mold.

Figure 53: PIM3 PRT molded specimen
Similar to Phase 1 Mold 1 the most common cause of PRT mold failure was the adherence of the part to the mold cavity. Regardless of the application of mold release the molded part adhered to the mold cavity walls. The force required to remove the component from the mold cavity would eventually lead to the failure of the mold’s gate. As previously observed, a yellowing of the PRT mold material would occur prior to mold failure. An example of the observed yellowing can be seen above in Figure 54. The mold depicted in Figure 54 was the second PRT insert prior to its 29th cycle.

3.1.3.1 Diameter

Table 11 below shows diameter data collected from all inserts and shows all molded diameter features within acceptable tolerances. The table shows that the deviation in measurements is very similar between the PRTs and control tool. The standard deviation for the second and third PRT tool is lower than the control tool.
Table 11: PIM3 – one cavity mold diameter measurement statistics

<table>
<thead>
<tr>
<th>Mold 3. Diameter Data</th>
<th>Aluminu m</th>
<th>PRT Mold 1</th>
<th>PRT Mold 2</th>
<th>PRT Mold 3</th>
<th>PRT Mold 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dia. 1</td>
<td>Dia. 1</td>
<td>Dia. 1</td>
<td>Dia. 1</td>
<td>Dia. 1</td>
<td>Dia. 1</td>
</tr>
<tr>
<td>Samples</td>
<td>100</td>
<td>23</td>
<td>33</td>
<td>25</td>
<td>41</td>
</tr>
<tr>
<td># Within Tol.</td>
<td>100</td>
<td>23</td>
<td>33</td>
<td>25</td>
<td>41</td>
</tr>
<tr>
<td>Exceeding Tol.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nom.</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Min</td>
<td>0.997</td>
<td>1.001</td>
<td>0.999</td>
<td>0.997</td>
<td>0.998</td>
</tr>
<tr>
<td>Max</td>
<td>1.000</td>
<td>1.004</td>
<td>1.005</td>
<td>1.002</td>
<td>1.003</td>
</tr>
<tr>
<td>Range</td>
<td>0.003</td>
<td>0.003</td>
<td>0.006</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Mean</td>
<td>0.999</td>
<td>1.002</td>
<td>1.002</td>
<td>0.999</td>
<td>1.001</td>
</tr>
<tr>
<td>Median</td>
<td>0.999</td>
<td>1.002</td>
<td>1.002</td>
<td>0.999</td>
<td>1.001</td>
</tr>
<tr>
<td>StdDev.</td>
<td>0.0008</td>
<td>0.0011</td>
<td>0.0017</td>
<td>0.0011</td>
<td>0.0013</td>
</tr>
<tr>
<td>Nom. Vs. Mean</td>
<td>0.0013</td>
<td>-0.0024</td>
<td>-0.0015</td>
<td>0.0006</td>
<td>-0.0009</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Figure 55 depicts diameters measurement behavior from the fourth PRT mold while Figure 56 shows data measured from the aluminum tool for comparison. In the case of the PRT insert, the data shows a very distinctive positive slope. This trend is observed in all but the first PRT’s data. In the first PRT insert’s data, the measured diameters were constant with little to no slope. By comparison the aluminum control tool has little slope. For reference see Figures 166 to 170 in Appendix F.3 for the remaining run charts.
3.1.3.2 Thickness

Statistical information regarding the various molded thicknesses, within the Phase I Mold 3, can be found below in Table 12. The data within this table shows that all molded parts, except from the first PRT mold insert, fell within established tolerance limits. Out of 122 PRT samples 120 were acceptable. This means 98.4% of the samples were acceptable. By comparison the aluminum tool produced a total of 100 acceptable samples out of 100.
Table 12: PIM3 – one cavity mold thickness measurement statistics

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>PRT Mold 1</th>
<th>PRT Mold 2</th>
<th>PRT Mold 3</th>
<th>PRT Mold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THK. 1</td>
<td>THK. 1</td>
<td>THK. 1</td>
<td>THK. 1</td>
<td>THK. 1</td>
</tr>
<tr>
<td><strong>Samples</strong></td>
<td>100</td>
<td>23</td>
<td>33</td>
<td>25</td>
<td>41</td>
</tr>
<tr>
<td><strong># Within Tol.</strong></td>
<td>100</td>
<td>21</td>
<td>33</td>
<td>25</td>
<td>41</td>
</tr>
<tr>
<td><strong>Exceeding Tol.</strong></td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Nom.</strong></td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>0.125</td>
<td>0.126</td>
<td>0.126</td>
<td>0.126</td>
<td>0.125</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>0.128</td>
<td>0.131</td>
<td>0.130</td>
<td>0.129</td>
<td>0.129</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>0.003</td>
<td>0.005</td>
<td>0.004</td>
<td>0.003</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>0.126</td>
<td>0.128</td>
<td>0.128</td>
<td>0.128</td>
<td>0.127</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>0.126</td>
<td>0.129</td>
<td>0.128</td>
<td>0.128</td>
<td>0.127</td>
</tr>
<tr>
<td><strong>StdDev.</strong></td>
<td>0.0008</td>
<td>0.0015</td>
<td>0.0011</td>
<td>0.0010</td>
<td>0.0009</td>
</tr>
<tr>
<td><strong>Nom. Vs. Mean</strong></td>
<td>-0.0014</td>
<td>-0.0033</td>
<td>-0.0031</td>
<td>-0.0026</td>
<td>-0.0023</td>
</tr>
<tr>
<td><strong>% Acceptable</strong></td>
<td>100.0%</td>
<td>91.3%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Figures 57 and 58 below show selected run charts from the collected thickness data. Figure 57 depicts the measured thicknesses of parts molded from the fourth PRT mold insert. In this chart a progressive thickening of the parts from shot to shot was evident. This trend is also evident in the remaining three PRT run charts found as Figures 171 to 175 in Appendix F.3.

Figure 57: PIM3 Run Chart – PRT mold #3 thickness measurements
In contrast Figure 58 shows part thicknesses measured from the aluminum control tool. In this chart the parts are remain steady from shot to shot. The slope found for the data is two hundred times less than that of the largest PRT insert. Likewise the chart shows that there is less deviation from shot to shot. This observation is also evident in the table.

3.1.3.3  **Length**

Like the thickness measurements 98.4% of PRT and 100% of aluminum specimens were acceptable. This data can be seen as Table 13. Figure 59 displays the measured lengths for from the fourth PRT mold insert and Figure 60 shows data control tool for comparison. The trends noticed in these charts are very different than the thickness measurements from the previous section. The aluminum tool has a small slope; however the amount of deviation from shot to shot is much higher. In contrast, the PRT components have a deviation closely matching the control tool. The slopes of the PRT run charts are also greatly reduced compared the trends from PIM3. For comparison the remaining run charts can be found as Figures 177 to 180 in Appendix F.3.
Table 13: PIM3 – one cavity mold length measurement statistics

<table>
<thead>
<tr>
<th>Mold 3. Length Data (inch)</th>
<th>Aluminum</th>
<th>PRT Mold 1</th>
<th>PRT Mold 2</th>
<th>PRT Mold 3</th>
<th>PRT Mold</th>
<th>L. 1</th>
<th>L. 1</th>
<th>L. 1</th>
<th>L. 1</th>
<th>L. 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>100</td>
<td>23</td>
<td>33</td>
<td>25</td>
<td>41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># Within Tol.</td>
<td>100</td>
<td>21</td>
<td>33</td>
<td>25</td>
<td>41</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exceeding Tol.</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nom.</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>1.498</td>
<td>1.501</td>
<td>1.500</td>
<td>1.500</td>
<td>1.498</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>1.502</td>
<td>1.506</td>
<td>1.505</td>
<td>1.504</td>
<td>1.504</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
<td>0.004</td>
<td>0.006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.500</td>
<td>1.504</td>
<td>1.502</td>
<td>1.502</td>
<td>1.501</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>1.500</td>
<td>1.504</td>
<td>1.502</td>
<td>1.503</td>
<td>1.502</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>StdDev.</td>
<td>0.0014</td>
<td>0.0015</td>
<td>0.0013</td>
<td>0.0010</td>
<td>0.0017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nom. Vs. Mean</td>
<td>0.0003</td>
<td>-0.0040</td>
<td>-0.0020</td>
<td>-0.0024</td>
<td>-0.0012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100.0%</td>
<td>91.3%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 59: PIM3 Run Chart - PRT mold #4 length measurements
3.1.3.4 Width

Statistical information regarding the various molded widths within the Phase I Mold 3 parts can be found below in Table 14. The data within this table shows all molded parts, in several instances parts were successfully molded but fell outside of established tolerance limits. Out of all samples molded via aluminum tool 100% of the width measurements fell within acceptable tolerance limits. Whereas 98.4% of the parts molded from PRT were acceptable.

Table 14: PIM3 - width measurement statistics
Width measurements from the aluminum and PRT molded parts are located below in Figures 61 and 62. Figure 61 displays the measured width for the fourth PRT mold insert. Figure 62 shows the measured widths molded from the aluminum control insert. Additional run charts for the remaining inserts can be seen as Figures 181 thru 185 in Appendix F.3.

![Chart](image)

Figure 61: PIM3 Run Chart - PRT mold #4 width measurements

![Chart](image)

Figure 62: PIM3 Run Chart - Aluminum mold width measurements
3.1.3.5 Mold 3 Summary

Out of the 122 PRT specimen parts molded 116 had acceptable thickness, diameter, length, and width specifications. The average performance of each insert was 94.1% acceptable components per mold. All six of the remaining components were unacceptable in only one specified feature. By comparison, out of the 100 parts molded with the control tool, all 100 specimens met specifications. A breakdown of each tool’s performance by cavity is shown below in Table 15.

Table 15: PIM3 Summary - total part acceptability

<table>
<thead>
<tr>
<th>Cavity (# Acceptable)</th>
<th>AL</th>
<th>PRT1</th>
<th>PRT2</th>
<th>PRT3</th>
<th>PRT4</th>
<th>PRT Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>19</td>
<td>31</td>
<td>25</td>
<td>41</td>
<td>116</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cavity (% Acceptable)</th>
<th>PIM3 Acceptability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AL</td>
</tr>
<tr>
<td></td>
<td>100.0% 82.6% 93.9% 100.0% 100.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PRT Unacceptable Features</th>
<th>AL Unacceptable Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 out of 4</td>
<td>6</td>
</tr>
<tr>
<td>2 out of 4</td>
<td>0</td>
</tr>
<tr>
<td>3 out of 4</td>
<td>0</td>
</tr>
<tr>
<td>4 out of 4</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mold Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRT Average per Mold</td>
</tr>
<tr>
<td>PRT Total Average</td>
</tr>
</tbody>
</table>
3.1.4 Phase I Summary

Table 16, seen on the next page, shows the average standard deviation for a given feature type. Except in the case of width measurements the difference between the average PRT’s deviation and the control was $7 \times 10^{-4}$ inches. In the case of case of width, the difference in deviation was $2.4 \times 10^{-3}$ inches. The width measurement experienced a significant outlier in its data. As explained earlier this can be contributed to a weakening of the mold wall, and therefore a large amount of wall deflection, prior to mold failure. This outlier also affects the difference between the specified nominal value and the mean value. The largest difference again occurred in the width measurements. The difference between the average measurement and the specified normal value was $2.6 \times 10^{-3}$ inches.

Table 16 also shows a composite comparison of the data’s range. The range of the aluminum tools falls between 0.005 to 0.0057 inches. The range of the PRT falls between 0.0064 to 0.0193 inches. Based on a tolerance range of $\pm 0.005$ this data shows that the aluminum tools will meet an acceptable tolerance range as long as the median value is within 0.0043 inches of nominal. This is also true of the PRT inserts except in the case of width.

For comparative purposes, similar feature behaviors have been combined in Table 17. This table shows that 2,195 features were successfully created out of 2,344 total features molded and measured from a PRT tool. Likewise the data shows that 1,698 features were acceptable out of 1,700 features created from a control tool. This table also shows that the feature which experiences the largest difference between the PRT and control were width measurements. The remaining features varied from the control tool less than 6%.
Table 16: Phase I standard deviation and deviation from nominal comparison

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>PRT</th>
<th>Difference</th>
<th>Nom. Vs. Mean</th>
<th>Aluminum</th>
<th>PRT</th>
<th>Difference</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.0014</td>
<td>0.0021</td>
<td>-0.0007</td>
<td>0.0040</td>
<td>0.0008</td>
<td>0.0048</td>
<td>0.0078</td>
<td>-0.0021</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.0015</td>
<td>0.0020</td>
<td>-0.0005</td>
<td>-0.0030</td>
<td>-0.0010</td>
<td>-0.0020</td>
<td>0.0050</td>
<td>0.0079</td>
</tr>
<tr>
<td>Length</td>
<td>0.0014</td>
<td>0.0010</td>
<td>0.0004</td>
<td>0.0000</td>
<td>-0.0010</td>
<td>0.0010</td>
<td>0.0055</td>
<td>0.0064</td>
</tr>
<tr>
<td>Width</td>
<td>0.0011</td>
<td>0.0037</td>
<td>-0.0026</td>
<td>0.0002</td>
<td>-0.0024</td>
<td>0.0026</td>
<td>0.0055</td>
<td>0.0193</td>
</tr>
</tbody>
</table>

Table 17: Phase I acceptable feature summary

<table>
<thead>
<tr>
<th></th>
<th>Samples (Total)</th>
<th># Within Tol.</th>
<th>% Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum</td>
<td>PRT</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Diameter</td>
<td>300</td>
<td>438</td>
<td>300</td>
</tr>
<tr>
<td>Thickness</td>
<td>600</td>
<td>846</td>
<td>598</td>
</tr>
<tr>
<td>Length</td>
<td>400</td>
<td>530</td>
<td>400</td>
</tr>
<tr>
<td>Width</td>
<td>400</td>
<td>530</td>
<td>400</td>
</tr>
<tr>
<td>Total</td>
<td>1700</td>
<td>2344</td>
<td>1698</td>
</tr>
</tbody>
</table>

Table 18: Phase I acceptable part summary

<table>
<thead>
<tr>
<th></th>
<th>Aluminum Control Tool</th>
<th>PRT Inserts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PIM1</td>
<td>PIM2</td>
</tr>
<tr>
<td>Total Parts</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Acceptable Parts</td>
<td>200</td>
<td>298</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100.0%</td>
<td>99.3%</td>
</tr>
</tbody>
</table>
Finally, Table 18 shows 846 individual components were created during Phase I using a PRT insert. Out of those components, 702 met all the required dimensions. This means that 83% of PRT components met at all criteria. By contrast, 600 individual components were created with a control tool. Out of those components, 598 met all establish tolerances. This equals 99.7% of aluminum molded components being acceptable.

3.2 PHASE II RESULTS

The following section describes the results collected during Phase II experimentation. As with the previous section a summary of each individual mold type is provided. A summation of the entire Phase II experimental results is located in section 3.2.3 of this chapter. The process parameters used for the Phase II inserts can be found Appendix E.

3.2.1 MOLD 1: LENS PROOF OF CONCEPT

The aluminum control was able to reach its maximum 75 allotted cycles without failure. The PRT insert was only able to mold 25 parts before mold failure. Once the most preferable process parameters were found, both the aluminum control and PRT tools yield components with little to no observable defects. Some flashing occurred in the PRT insert once it had experienced an excess of 20 cycles which was roughly 80% of its mold life.

The cause of mold failure was a rupture of the gate caused by strong adhesion of the part to the mold preventing part release, similar to Phase I components. During part ejection the PRT insert’s gate failure due to excessive force required to remove the
component. The pronged snap feature was the second most common location of adhesion after a mold cycle. As observed with the Phase I inserts, the PRT mold began to visually yellow with use. This discoloration occurred after the 19th specimen was molded.

Figure 63: PIIM1 lens mold (pronged snap feature)

Figure 63 above shows an example of the aluminum lens mold and the described pronged snap feature. Figure 64 and Figure 65 show parts molded via the PRT insert and depict the finer detail features which were molded. It should also be noted that despite no surface finish treatments or specifications, parts molded using both the aluminum and PRT tools were clear with little clouding from surface imperfections. An additional example of the mold inserts, experimentation, and produced components can be referenced as Figures 263 to 270 in Appendix G.5.
3.2.1.1 Statistical Data

Table 19 on the next page shows statistical data collected during the Phase II Mold I Lens experiment. The standard deviation of both the aluminum and PRT mold averaged 0.001 inches. The recorded thicknesses for both types of mold inserts ranged between 0.001 and 0.003 inches. The largest standard deviations occurred in both inserts for the length measurement. For both aluminum and PRT inserts the difference between the nominal thickness values and the recorded mean was 0.002 inches less than the nominal.
Table 19: PIIM1 lens mold – measurement statistics

<table>
<thead>
<tr>
<th></th>
<th>Thickness 1</th>
<th>Thickness 2</th>
<th>Thickness 3</th>
<th>Length</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AL</td>
<td>PRT</td>
<td>AL</td>
<td>PRT</td>
<td>Al</td>
</tr>
<tr>
<td>Samples</td>
<td>75</td>
<td>25</td>
<td>75</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td># Within Tol.</td>
<td>75</td>
<td>25</td>
<td>75</td>
<td>23</td>
<td>75</td>
</tr>
<tr>
<td># Exceeds Tol.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Nom.</td>
<td>0.079</td>
<td>0.079</td>
<td>0.079</td>
<td>0.059</td>
<td>0.059</td>
</tr>
<tr>
<td>Min</td>
<td>0.079</td>
<td>0.077</td>
<td>0.079</td>
<td>0.059</td>
<td>0.055</td>
</tr>
<tr>
<td>Max</td>
<td>0.084</td>
<td>0.084</td>
<td>0.086</td>
<td>0.064</td>
<td>0.066</td>
</tr>
<tr>
<td>Range</td>
<td>0.005</td>
<td>0.007</td>
<td>0.010</td>
<td>0.005</td>
<td>0.011</td>
</tr>
<tr>
<td>Mean</td>
<td>0.081</td>
<td>0.081</td>
<td>0.081</td>
<td>0.062</td>
<td>0.061</td>
</tr>
<tr>
<td>Median</td>
<td>0.081</td>
<td>0.081</td>
<td>0.082</td>
<td>0.061</td>
<td>0.062</td>
</tr>
<tr>
<td>StdDev.</td>
<td>0.0013</td>
<td>0.0019</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0026</td>
</tr>
<tr>
<td>Nom. Vs. Mean</td>
<td>-0.0024</td>
<td>-0.0018</td>
<td>-0.0024</td>
<td>-0.0026</td>
<td>-0.0024</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100%</td>
<td>100%</td>
<td>92%</td>
<td>100%</td>
<td>88%</td>
</tr>
</tbody>
</table>
3.2.1.2 Run charts

Figures 66 to 70 show the run charts related to the Phase II Mold 1 experiment. For reference, the location of each measurement was shown in the part’s technical specifications. Figures 66, 67, and 68 detail the thicknesses recorded in three areas of the component. Each of the run charts contains measurements from the PRT insert as data collected from the aluminum tool for comparison.

Figure 66 shows data collected from the first thickness measurement location. The first thickness measurement was taken one inch left of the gate on the lens’s wall. The data collected from the PRT mold show an upward trend over time. The parts from the PRT tool originally start near nominal but slowly increase towards the top of the tolerance limit before insert failure. In contrast the aluminum tool has a very small slope and remains relatively constant.

Figure 66: PIIM1 Run Chart - Lens thickness 1 measurements for PRT and AL molds

Figure 67 depicts data measured from the same lens wall but located on the opposite side of the part from the gate. As observed in the last run chart, the PRT data begins near the desired nominal dimension. While the tool ages the measured wall thickness slowly increases. The wall thickness eventually exceeds the upper tolerance
limit prior to mold failure. The observed behavior of the aluminum tool is very similar to
the previous run chart. The aluminum tool remains relatively constant between the upper
tolerance and nominal dimension.

Figure 67: PIIM1 Run Chart - Lens thickness 2 measurements for PRT and AL molds

Figure 68 below shows the last of the thickness data from PIIM1. This chart
contains the measured thickness of the double barbed feature. The trends observed in
chart are again similar to the previous thickness run charts for PIIM1. The parts from the
PRT insert are first molded near the nominal dimension and progressive thicken as the
tool is used. The aluminum tool remains relatively constant.

Figure 68: PIIM1 Run Chart - Lens thickness 3 measurements for PRT and AL molds

Figure 69 shows the recorded length data. The length of the part was measured
from the top of the double barb feature to the rear of the lens wall. Figure 70 graphs the

93
width of the lens. This measurement was taken from the same locations of thickness one and two. In both graphs PRT and aluminum mold behavior is very similar to each other. There appears to be no large increases or decreased in measurement or deviations from shot to shot. In the case of part length the data recorded from the PRT inserts nearly matches the behavior of the aluminum tool.

![Phase II Mold 1 Comparison: Length](image)

**Figure 69:** PIIM1 Run Chart - Lens length measurements for PRT and AL molds

![Phase II Mold 1 Comparison: Width](image)

**Figure 70:** PIIM1 Run Chart - Lens width measurements for PRT and AL molds

### 3.2.1.3 PIIM1 Lens Mold Acceptability

Out of the 75 components molded from the aluminum control tool, all of the components met all five design specifications. In comparison, out of the 25 components molded with the PRT tool 22 were acceptable in all specifications. Two of the
unacceptable components were unacceptable in two specifications. The remaining component was acceptable in four of the five criteria.

3.2.2 Mold 2: Housing Proof of Concept

As with all previous aluminum inserts the Phase II Mold 2 housing mold was able to reach its maximum allotted 75 cycles without failure. The PRT mold insert was able to produce 23 components prior to mold failure. Unlike all other experimental inserts, flash was present in nearly all produced components from both the control and PRT tools. Despite extensive adjustment to process parameters flash was greatly reduced but not eliminated. Due to similar amounts of flash, as well as the relative location of the flash, it could be inferred that the mold design and not the processing parameters were inadequate. However, since both molds were manufactured to identical specifications and displayed similar flash in similar locations a rational could be made that the dimensional behavior of the molded parts was still valid and comparable.

The cause of mold failure within the PRT mold was a failure within the injection mold gate. During the unclamping of the mold halves the molded component partially adhered to the A side of the mold cavity. This limited adherence partially ejected the component from the B side of the tool prematurely instead of remaining with the B side until manual ejection. This partial ejection fractured the gate and deformed the runner system preventing additional cycles. As noticed in all other experiments the PRT insert visually began to discolor during use. The discoloration was first evident after the 18th molding cycle was complete. An example of the Phase II Mold 2 PRT housing mold insert, prior to use, can be seen below in Figure 71.
Figure 71: PIIM2 - PRT housing mold inserts

Figure 72 and Figure 73 below show components molded using the PRT mold insert. Figure 72 displays the cylindrical bolster as well as the T shaped bolster which were measured and recorded in the run charts.

Figure 72: PIIM2 - PRT molded housing bolster and T-rib
Figure 73 depicts an entire housing molded with the PRT insert. For comparison, Figure 74 shows an idealized housing produced from an Objet rapid prototyping machine. The PRT molded component matches the Objet component dimensionally and in the same detail. The Objet component was made from polystyrene like material whereas the PRT component has been molded from a production grade Polycarbonate resin. Therefore, the PRT component should behave in the same way as a production component. Additional images of the inserts, specimens, and experimentation can be seen as Figures 271 to 279 in Appendix G.6.
3.2.2.1 Statistical Data

Table 20 on the next page shows statistical data collected during the Phase II Mold 2 experiment. In the case of standard deviation both the aluminum and PRT mold averaged 0.001 inches. The largest standard deviations occurred in both inserts for the length and width measurements. For both aluminum and PRT inserts the difference between the nominal thickness values and the recorded mean was an average of 0.001 inches less than the nominal.

Prior to failure, the PRT tool yielded 23 individual components which yielded 138 individual measurements. Out of those measurements 136 features met acceptable tolerances. This equates to 98.6% feature acceptance among PRT features. By comparison, the aluminum tool produced 75 components with a total of 430 data points. 100% of these measurements were acceptable.

3.2.2.2 Run charts

Figures 75 to 80 show the run charts relating to the Phase II experiment. Figures 75, 76, and 77 detail the thicknesses recorded in three areas of the component. For each run chart the parts produced from the aluminum control tool, seen in blue, have been included for reference.

Figure 75: PIIM2 Run Chart - Housing thickness 1 measurements for PRT and AL molds
Table 20: PIIM2 - housing measurement statistics

<table>
<thead>
<tr>
<th></th>
<th>Thickness 1</th>
<th></th>
<th>Thickness 2</th>
<th></th>
<th>Thickness 3</th>
<th></th>
<th>Length</th>
<th></th>
<th>Width</th>
<th></th>
<th>Diameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AL</td>
<td>PRT</td>
<td>AL</td>
<td>PRT</td>
<td>AL</td>
<td>PRT</td>
<td>AL</td>
<td>PRT</td>
<td>AL</td>
<td>PRT</td>
<td>AL</td>
<td>PRT</td>
</tr>
<tr>
<td>Samples</td>
<td>75</td>
<td>23</td>
<td>75</td>
<td>23</td>
<td>75</td>
<td>23</td>
<td>75</td>
<td>23</td>
<td>75</td>
<td>23</td>
<td>75</td>
<td>23</td>
</tr>
<tr>
<td># Within Tol.</td>
<td>75</td>
<td>23</td>
<td>75</td>
<td>22</td>
<td>75</td>
<td>22</td>
<td>75</td>
<td>23</td>
<td>75</td>
<td>23</td>
<td>75</td>
<td>23</td>
</tr>
<tr>
<td>Exceeds Tol.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nom</td>
<td>0.110</td>
<td>0.110</td>
<td>0.080</td>
<td>0.080</td>
<td>0.070</td>
<td>0.070</td>
<td>6.450</td>
<td>6.450</td>
<td>1.063</td>
<td>1.063</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td>Max</td>
<td>0.112</td>
<td>0.114</td>
<td>0.082</td>
<td>0.086</td>
<td>0.072</td>
<td>0.075</td>
<td>6.498</td>
<td>6.491</td>
<td>1.067</td>
<td>1.069</td>
<td>0.102</td>
<td>0.105</td>
</tr>
<tr>
<td>Min</td>
<td>0.108</td>
<td>0.109</td>
<td>0.078</td>
<td>0.079</td>
<td>0.068</td>
<td>0.068</td>
<td>6.406</td>
<td>6.401</td>
<td>1.058</td>
<td>1.060</td>
<td>0.098</td>
<td>0.099</td>
</tr>
<tr>
<td>Range</td>
<td>0.004</td>
<td>0.005</td>
<td>0.004</td>
<td>0.007</td>
<td>0.004</td>
<td>0.007</td>
<td>0.092</td>
<td>0.090</td>
<td>0.009</td>
<td>0.009</td>
<td>0.004</td>
<td>0.006</td>
</tr>
<tr>
<td>Mean</td>
<td>0.110</td>
<td>0.111</td>
<td>0.080</td>
<td>0.082</td>
<td>0.070</td>
<td>0.071</td>
<td>6.451</td>
<td>6.443</td>
<td>1.063</td>
<td>1.065</td>
<td>0.100</td>
<td>0.101</td>
</tr>
<tr>
<td>Median</td>
<td>0.110</td>
<td>0.111</td>
<td>0.080</td>
<td>0.082</td>
<td>0.070</td>
<td>0.072</td>
<td>6.450</td>
<td>6.450</td>
<td>1.063</td>
<td>1.065</td>
<td>0.100</td>
<td>0.101</td>
</tr>
<tr>
<td>StdDev</td>
<td>0.0012</td>
<td>0.0014</td>
<td>0.0012</td>
<td>0.0019</td>
<td>0.0011</td>
<td>0.0018</td>
<td>0.0204</td>
<td>0.0240</td>
<td>0.0024</td>
<td>0.0026</td>
<td>0.0013</td>
<td>0.0014</td>
</tr>
<tr>
<td>Nom. Vs. Mean</td>
<td>-0.0002</td>
<td>-0.0012</td>
<td>-0.0001</td>
<td>-0.0020</td>
<td>-0.0001</td>
<td>-0.0015</td>
<td>-0.0009</td>
<td>0.0073</td>
<td>-0.0004</td>
<td>-0.0025</td>
<td>0.0001</td>
<td>-0.0012</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>96%</td>
<td>100%</td>
<td>96%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Figure 75 shows the thickness measurements of the housing measured at the rear of the housing. The data shows that both the PRT and aluminum tool performed relatively similar for the first half of the PRT’s life. Both inserts had low amounts of deviation from shot to shot and were close to the nominal dimension. After half of the PRT tools life the average thickness, at this location, increased by two thousands of an inch. Despite this increase all of the measurements taken were acceptable and within limits. While the PRT insert grew slightly the aluminum tool’s behavior remained relatively constant around the nominal dimension.

Figure 76 graphs the measurements taken from the second reinforcing rib. For reference this rib is located in parallel with the gate. The behavior of the thickness is consistent with the observations from the first thickness. The first components molded, from both the aluminum and PRT inserts have low deviation. Likewise the first components are roughly the nominal dimension. However after nine shots the parts produced from the PRT tool begin to thicken with each shot. Eventually the thickness of the rib exceeds the maximum tolerance two shots prior to mold failure. In comparison the features from the aluminum tool begin to increase in deviation but are still within acceptable limits.

![Housing Comparison: Thickness 2](image-url)

Figure 76: PIIM2 Run Chart - Housing thickness 2 measurements for PRT and AL molds
The thickness data presented in Figure 77 represents the thickness of the T-shaped bolster feature, described earlier. The same trend found in the other two thickness measurement charts is present. The PRT and aluminum have similar performance during the first half of the tool’s life. After the tenth shot the bolster begins to thicken slowly as the mold experiences more shots while the aluminum tool continues to produce features with nominal dimensions.

Figure 77: PIIM2 Run Chart - Housing thickness 3 measurements for PRT and AL molds

Figures 78, 79, and 80 show measurement data for the overall part width, bolster diameter, and length respectively. In Figures 78 and 79 the behavior of both features is similar to that noted in the three thickness run charts. However another trend is evident in the length measurements shown in Figure 80. In this case the PRT and aluminum tool produce features that are both acceptable and relatively close to the nominal dimension for the duration of the insert’s life. There is no distinctive growth in the parts length during the life of the tool.
### 3.2.2.3 PIIM2 Summary

As with the lens mold, the control tool successfully molded 75 parts, all of which met all six specifications. The PRT insert molded 23 components before failure and all
but one met all dimensional specifications. The only component which was unacceptable overall failed in only one specification.

3.2.3 PHASE II SUMMARY

Table 21 on the next page summarizes important data collected from all Phase II experiments. Three key pieces of information are presented. First, the range of the collected data shows that the PRT tools fall below established tolerance areas. In certain instances, such as width, the range of the data is far below the tolerance. This means that as long as the median value is at or near the nominal dimensional value the aluminum tool will be acceptable. The data ranged from 0.006 to 0.079 inches. This means that given a nominal dimension a PRT part can hold a tolerance of ±0.04 inches or better.

Secondly, the table depicts the collective standard deviation for each geometric feature tracked during Phase II. This data shows that a PRT insert fluctuated 0.0006 to 0.005 inches per shot. Lastly, the table shows the average difference between a particular molded characteristic’s nominal value and the mean value of the measured data for that particular characteristic.

For reference, the total amount molded parts created during Phase II were presented in Table 22. Along with the amount of parts this able shows the amount of acceptable features. The percent of acceptable features molded during Phase II using a PRT ranges between 95.1% and 100% acceptability. It should be noted that in all cases the aluminum control tools exceeded their 75 cycle maximum record life. Finally, Table 23 breaks down the amount of overall acceptability of Phase II.
Table 21: Phase II standard deviation and deviation from nominal comparison

<table>
<thead>
<tr>
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<th>Std Dev.</th>
<th>Nom. Vs. Mean</th>
<th>Range</th>
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<td></td>
<td>Aluminum</td>
<td>PRT</td>
<td>Difference</td>
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<tr>
<td>Diameter</td>
<td>0.0013</td>
<td>0.0014</td>
<td>-0.0001</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.0013</td>
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<td>-0.0007</td>
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<tr>
<td>Length</td>
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<td>-0.0025</td>
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<tr>
<td>Width</td>
<td>0.0079</td>
<td>0.0063</td>
<td>0.0015</td>
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Table 22: Phase II acceptable feature

<table>
<thead>
<tr>
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<th>Samples (Total)</th>
<th># Within Tol.</th>
<th>% Acceptable</th>
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</thead>
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<td>PRT</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Diameter</td>
<td>75</td>
<td>23</td>
<td>75</td>
</tr>
<tr>
<td>Thickness</td>
<td>450</td>
<td>144</td>
<td>450</td>
</tr>
<tr>
<td>Length</td>
<td>150</td>
<td>48</td>
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<tr>
<td>Width</td>
<td>150</td>
<td>48</td>
<td>150</td>
</tr>
<tr>
<td>Total</td>
<td>825</td>
<td>263</td>
<td>825</td>
</tr>
</tbody>
</table>

Table 23: Phase II acceptable part summary

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>PRT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PIIM1</td>
<td>PIIM2</td>
</tr>
<tr>
<td>Total Parts Created</td>
<td>75</td>
<td>75</td>
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<tr>
<td># Acceptable</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td># Unacceptable</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
3.3 PHASE I AND II RESULTS COMPARISON

The following section compares the results taken from both Phase I and Phase II. Specifically, this section focuses on comparing the acceptability rates between the phases, the overall behavior of the insert, and the individual behavior of each feature.

3.3.1 TOTAL ACCEPTABILITY

A lower percentage of total acceptable parts were found with Phase I then in Phase II. Total acceptability for Phase I ranged between 72.8% and 95.1% while Phase II was 88% to 95.7%. One explanation for this could be due to the difference in life spans between the phases. The average number of components produced from a Phase I insert was 35.3 shots per mold with a standard deviation of 10 shots. By comparison the Phase II inserts averaged 23.5 shots per insert with a standard deviation of 1.3 shots. The extra components could skew the data. To better understand the behavior of Phase I in comparison to Phase II the data was condensed to reflect the first 23 shot cycles of each component. The number of cycles selected for this comparison was based on the lowest amount of cycles a PRT survived before failure, which corresponds to all the data having the same life span.

Presented in Figures 81 to 85 are run charts showing thickness data from each part type. Despite having differing nominal dimensions, the thicknesses for each part contain the same tolerance range allowing for direct comparison. Within the first 23 cycles, fewer components fall outside of the minimum and maximum tolerance range. In the case of PIM1’s first cavity, seen as Figure 81, no components fall outside of the tolerance range.
By comparison, PIM1 had four cavity one components out of tolerance during the life of the tool.

It can also be observed that the range and deviation of all four PRT inserts behaved similarly to the control tool. A similar trend is evident in PIM2’s abbreviated run chart, seen as Figure 82. Only four total failures occurred during this period in the lives of the PRT inserts. By comparison, a combined 26 failures occurred during the full lives of each insert. It should also be noted that the four failures in Figure 82 also appear to be isolated to the first PRT insert. The data from the first insert visually has a higher median value than the other PRT inserts and control tool.

![Figure 81: PIM1 - Cavity 1 thickness data showing first 23 shots only](image)

![Figure 82: PIM2 - Cavity 3 thickness data showing first 23 shots only](image)
The behavior of PIM3, PIIM1, and PIIM2, appear to behave similarly during the abbreviated time frame. In all three cases the data has a range which typically falls within 0.005 inches. PIM3 and PIIM1, seen as Figures 83 and 84 respectively, have average values above the nominal value yet below the maximum tolerance limit. PIIM2, shown as Figure 85, has a similar range but the average value for both the control and PRT inserts appear equal to the desired nominal value.

![PIM3 First 23 Shots (Thickness)](image)

Figure 83: PIM3- Thickness data showing first 23 shots only

![PIIM1 First 23 Shots (Thickness Location 1 & 2)](image)

Figure 84: PIIM1 - Thickness data from locations 1&2 showing first 23 shots only
Figure 85: PIIM2 Thickness data from location 1 showing first 23 shots only

3.3.2 Feature Comparison

By comparing both Phases a clearer picture of overall feature behavior can be seen. A comparison of all collected data by feature can be seen in Table 24. This table shows that the PRT feature which had highest percent of acceptable components was length. Width was the feature with the lowest percentage of acceptable measurements. Despite being the lowest, 86.3% of the measured widths were acceptable. By comparison the aluminum control tool was 100% acceptable for all features except thickness.

Table 24: Phase I and II comparison

<table>
<thead>
<tr>
<th>PRT Feature Behavior</th>
<th>Diameter</th>
<th>Thickness</th>
<th>Length</th>
<th>Width</th>
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</thead>
<tbody>
<tr>
<td>Total Specimens</td>
<td>461</td>
<td>990</td>
<td>578</td>
<td>578</td>
</tr>
<tr>
<td># Acceptable</td>
<td>443</td>
<td>909</td>
<td>566</td>
<td>499</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>96.1%</td>
<td>91.8%</td>
<td>97.9%</td>
<td>86.3%</td>
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</table>

<table>
<thead>
<tr>
<th>AL Feature Behavior</th>
<th>Diameter</th>
<th>Thickness</th>
<th>Length</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Specimens</td>
<td>375</td>
<td>1050</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td># Acceptable</td>
<td>375</td>
<td>1046</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>% Acceptable</td>
<td>100.0%</td>
<td>99.6%</td>
<td>100.0%</td>
<td>100.0%</td>
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</tbody>
</table>
CHAPTER 4: CONCLUSIONS

As defined earlier, for a PRT mold to be deemed feasible for use as an injection mold tool it must be stable and robust. Based on collected data, the following two conclusions were made:

i) Parts molded via Polymer Rapid Tools met desired dimensional requirements over a variety of simple and complex geometries.

ii) Based on the rate of dimensional change over mold life, PRT molds held desired tolerances for the majority of the tool’s life.

These two conclusions, along with other supported data, show that PRT molds are stable and robust. Therefore PRT inserts can be deemed feasible for use as functional short run injection mold tooling.

The first conclusion was made after it was found that parts molded with a PRT insert met desired dimensions within specified tolerances in 2,417 sample measurements for a total of 92.7% acceptance. Furthermore, 746 out of 894 components met all design specifications. This equates to 83.5% of all PRT molded components being acceptable to their corresponding specifications. This cumulative data shows that not only did the PRT components meet a single dimensional constraint, but they could maintain multiple constraints. Likewise, this data shows that the PRT tools could meet the specifications for the majority of components created.

For reference, parts molded with aluminum tooling met desired dimensions in 2,521 measurements for a total of 99.8% acceptance. Of the 750 total components that were molded, 748 of them met all specifications. This data comparison shows that
although the PRT inserts molded a dimensionally acceptable product, they did not perform as consistently as control tooling.

It was found that the amount of mold variability, over the course of a PRT’s life, was less than standard injection mold tolerances in all but one PRT measurement group. The largest variation in PRT molded samples was 0.012 inches for simple geometries with the specified tolerance being ± 0.005 inches. However, in this particular instance 94% of the samples fell within one standard deviation, ±0.003 inches, which was below the specified tolerance range of ±0.005. Furthermore, it was found that a PRT mold’s rate of dimensional change ranged between 0.005 to 0.006% per shot. This means on average a PRT part would result in 0.001 inches of dimensional change in a given measured dimension per 20 shots of mold use.

Lastly, despite a large number of the run charts having large slopes, the various PRT tools typically stayed within their specified tolerance limits for the majority of the tool’s life. The slopes show that the tools experience change over time which affects the components being created. This could also potentially mean that initially creating a PRT on the lower end of its tolerance zone could increase the overall life of the tool.
CHAPTER 5: RECOMMENDATIONS

This study represents a comprehensive set of experiments to investigate the feasibility of PRT for given geometries only. It is advised that additional experiments be conducted in this field to verify and validate the findings for these situations. Additional experiments are required to determine if finer tolerances are possible and if more complex geometries, such as splines and compound curves, could hold similar tolerances.

This research has also found that additional evaluations are required in order to fully determine PRT viability. First, an in-depth analysis is required to study the effects of mold degradation and wear. It is recommended that a research path begin with a detailed analysis of the mold material and its corresponding effects on the injection mold process. For example, studying the effects the PRT material has on a mold cavity’s thermal distortion and deflection under loading. A better understanding on how the mold material behaves during the molding process could be used to increase tool life.

A second recommended research path is an investigation into PRT mold cooling. It is believed that if additional cooling strategies (e.g., cooling lines, channels, air impingement) were utilized, a 25% increase in tool life, or greater, could be possible. The implementation of cooling strategies could also reduce or postpone the effects of excessive flash, which became common after multiple cycles of the tool.

Third, it was found during this research that it was necessary to optimize the allotted space of mold insert to reduce the expense of a PRT. It is recommended that a study be conducted to determine the minimum wall thickness required to yield a dimensionally stable component. The results of such a study could be used to optimize
and minimize the amount of polymer material needed to create a PRT. This in turn will allow for a greater cost and time savings.

Lastly, this research utilized the same processing parameters for PRT and aluminum tooling. It is highly recommended that research be continued to explore the differences in processing parameters required for PRTs. This information will increase mold life allowing more components to be produced per mold. In turn this information will further reduce the cost of components produced via PRT and thus increase PRT viability.
APPENDIX A: REFERENCE AND LITERATURE REVIEW

MATERIALS

A.1 RAPID PROTOTYPING

Currently there are five rapid prototyping methods which are widely available: Stereo Lithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Polymer Jet Deposition (PolyJet®), and 3D printing (3DP). Other techniques exist however they do not use polymer-based materials and far more expensive.

The 3D printing technique uses the same technology as inkjet printers. A printing head lays down material while passing over a printing surface. After a printing pass the surface is then lowered a specified distance allowing the device to print the next layer, thus building the model. There are various different subgroups to 3DP based upon the material and manufacturer. One form of 3DP sprays curing agent, from its printing head, onto a powder spread over the printing surface. This agent cures and solidifies the powder in desired areas. After each printing pass a fresh layer of powder is spread across the printing surface for the next pass. Once complete the model is removed from the printing area and cleaned via vacuum to remove loose unbounded powder. The final product is a net shape item which is fairly brittle. Typically, the model is then subjected to a secondary finishing process whereby the model is submerged or coated with a resin. This resin treatment eliminates excess porosity and acts as a matrix to add strength to the system.

This technology excels in fast model production. It’s print speed, compared to other RP technologies is double and even triple the speed. 3DP technology allows for
very large build areas without the need of a secondary support or “scaffolding” material. This makes it ideal for large complex conceptual mock-ups and design studies. One of the largest users of 3DP technologies are the architectural industry. Examples of models created via the 3DP process can be seen below in Figure 86 and Figure 87.

A derivative method of 3DP uses Dot Matrix technology and sprays a UV curable polymer onto the printing surface. As the resin is sprayed into place a UV light, tracing behind the spray head, cures the polymer immediately following its adherence. This method, marketed as PolyJet® by the Objet© company, yields a solid polymer model. Due to the thin mist of polymer extruded during the printing process extremely high
detail, high strength models can be produced. Out of all the current polymer-based RP technologies this process generates the strongest, least porous, and highest detail models. These attributes make it the best starting point for this research.

A.2 INJECTION MOLDING

Injection molding, is defined as a cyclic process for producing identical articles from a mold, and is one of the most widely used polymer processing operation. The main advantage of this process is the capacity for repetitively creating parts having complex geometries at high production rates. (Rong Zheng, 2011) Polymer resins are first melted then forced, or injected, into a mold cavity. Once inside of the mold cavity the polymer cools and solidifies into the shape of the cavity. Once solidified, the mold is then opened and the form is then ejected.

The injection molding cycle is typically between 2 seconds and 2 minutes. The injection molding process consists of five steps to complete one cycle. In operation, plastic granules are fed to the machine through a hopper or feeding system. The resin granules then enter an enclose barrel containing a screw. The screw rotates and moves the granules forward in the screw channels. The granules are forced against the wall of the barrel, and melt due to both the friction heat generated by the rotating screw and the conduction from the heating units along the barrel. (Todd, 1994) The molten material is conveyed to the tip of the screw. When the desired volume of the melted resin is obtained, the screw rotation stops. The volume is controlled via a reservoir at the front of the screw. The distance of the screw from the tip determines the volume of melt which can be stored. This stage of process is also called the plasticizing stage. Then the
injection stage begins. The injection stage is characterized by the following four Phases (Rong Zheng, 2011):

**Clamping**

Typically one half of the mold is mounted to a stationary platen. The remaining mold half is attached to a moving platen. The most common machines actuate the moving platen mechanically or hydraulically. To start the molding cycle the moving platen moves towards the stationary platen closing the mold and clamping it together. The pressure the mold is clamped together under can range from several to thousands of tons. The tonnage required for clamping is related to the pressure of injection and the area of the mold to be filled. Therefore, clamping force will vary based upon resin type, part geometry and other factors.

**Filling**

Once the mold is fully clamped together the screw moves forward as a ram and forces the melted resin into the mold cavity. The resin enters the tool under a great deal of speed filling or "Injecting" the tool and its cavities with plastic. At this point in the process the mold is not fully filled with resin. During filling critical factors such as shot size, injection pressure and injection time play are critical to molding as this factors control the fill rate.

**Packing**

When the mold is nearly filled, the screw is held in the forward position or moves with a small displacement to maintain a holding pressure. Another name for this point in the process is the V/P switch over where V refers to velocity and P refers to pressure.
During this time the pressure causes the resin to fill in the remaining sections of the cavity. As the resin is packed or "held" in position the resin begins to cool and shrink. Resin which remains in the barrel will continue to flow into the mold, as a result of the pressure, until the gate of the mold has solidified. This pressure and additional flow is used to accommodate volumetric shrinkage in the mold due the resin cooling.

**Cooling**

The packing stage concludes once the gate has frozen shut. At this point the part, which was molded, is still too warm to be withdrawn without distortion. Therefore, the pressure is released or greatly reduced to prevent wear on the machine. The part is left in the mold to cool for a prescribed amount of time. The length of time the part remains in the mold depends on the cooling characteristics of the mold, the part being molded and other environmental factors.

**Ejection (Demolding)**

Once the part has been cooled to a point where it will no longer be deformed during extraction the mold is then opened. Final part is then removed from the molding machine. The final part can be extracted by a manual operation, robotic manipulator, or using an injection system incorporated within the tooling.

After the injection molding cycle, some post-processing is typically required. During cooling, the material in the channels of the mold will solidify attached to the part. This excess material, along with any flash that has occurred, must be trimmed from the part, typically by using cutters. For some types of material, such as thermoplastics, the scrap material that results from this trimming can be recycled by being placed into a
plastic grinder, also called regrind machines or granulators, which regrinds the scrap material into pellets. Due to some degradation of the material properties, the regrind must be mixed with raw material in the proper regrind ratio to be reused in the injection molding process. (Rostato, 2000)
APPENDIX B: EQUIPMENT

Figure 88: Fluke 971 environment monitor

Figure 89: Motan resin dryer system
Figure 90: Roboshot injection mold press
APPENDIX C: TECHNICAL ENGINEERING DRAWINGS

C.1 MUD BASE COMPONENTS

Figure 91: A-Side clamp plate
Figure 92: A-Plate (sheet 1 of 2)
Figure 93: A-Plate (sheet 2 of 2)
Figure 94: B-Side clamp plate
Figure 95: B-Side (sheet 1 of 2)
Figure 96: B-Side (sheet 2 of 2)
Figure 97: A-Side support pillar
Figure 98: B-Side support pillar
Figure 99: Support pillar plug
C.2 MOLD INSERTS

Figure 100: Mud insert (blank)
Figure 101: Mud insert (Phase I adapter)
Figure 102: Phase I insert (blank)
Figure 103: Phase I Mold 1 (part inspection)
Figure 104: Phase I Mold 1 (mold insert)
Figure 105: Phase I Mold 2 (part inspection)
Figure 106: Phase I Mold 2 (insert design)
Figure 107: Phase I Mold 3 (part inspection)
Figure 108: Phase I Mold 3 (insert design)
Figure 109: Phase II Lens (part inspection)
Figure 110: Phase II Housing (part inspection)
Table 25: LEXAN 940 material properties

### Processing

#### INJECTION MOULDING-USA

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<td>h</td>
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### Properties

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<td>psi</td>
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<td>psi</td>
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<td>%</td>
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</tr>
<tr>
<td>Tensile Elongation, break, Type I 0.125*</td>
<td>9.0%</td>
<td>%</td>
<td>ASTM D 638</td>
</tr>
<tr>
<td>Flexural Strength, yield, 0.125*</td>
<td>13200</td>
<td>psi</td>
<td>ASTM D 790</td>
</tr>
<tr>
<td>Flexural Modulus, 0.125*</td>
<td>325000</td>
<td>psi</td>
<td>ASTM D 790</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>12500</td>
<td>psi</td>
<td>ASTM D 695</td>
</tr>
<tr>
<td>Compressive Modulus</td>
<td>325000</td>
<td>psi</td>
<td>ASTM D 695</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>10000</td>
<td>psi</td>
<td>ASTM D 732</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>114000</td>
<td>psi</td>
<td>ASTM D 4065</td>
</tr>
<tr>
<td>Hardness, Rockwell M</td>
<td>70</td>
<td>-</td>
<td>ASTM D 785</td>
</tr>
<tr>
<td>Hardness, Rockwell R</td>
<td>118</td>
<td>-</td>
<td>ASTM D 785</td>
</tr>
<tr>
<td>Taber Abrasion, CS-17, 1 kg</td>
<td>10</td>
<td>mg/1000cy</td>
<td>ASTM D 1044</td>
</tr>
<tr>
<td>Fatigue Limit, 2.5 MM cycles</td>
<td>1000</td>
<td>psi</td>
<td>ASTM D 671</td>
</tr>
</tbody>
</table>

### IMPACT

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical Data</th>
<th>Unit</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Izod Impact, unnotched, 73F</td>
<td>60.0</td>
<td>ft-lb/in</td>
<td>ASTM D 4812</td>
</tr>
<tr>
<td>Izod Impact, notched, 73F</td>
<td>12.0</td>
<td>ft-lb/in</td>
<td>ASTM D 256</td>
</tr>
</tbody>
</table>
Table 26: LEXAN 940 material properties cont.

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical Data</th>
<th>Unit</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Impact, Type “S”</td>
<td>250 ft-lb/in²</td>
<td></td>
<td>ASTM D 1822</td>
</tr>
<tr>
<td>Falling Dart Impact (D 3029), 73F</td>
<td>125 ft-lbs</td>
<td></td>
<td>ASTM D 3029</td>
</tr>
<tr>
<td><strong>THERMAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vicat Softening Temp, Rate B</td>
<td>305 deg F</td>
<td></td>
<td>ASTM D 1525</td>
</tr>
<tr>
<td>HDT, 66 psi, 0.250&quot;, unannealed</td>
<td>280 deg F</td>
<td></td>
<td>ASTM D 648</td>
</tr>
<tr>
<td>HDT, 264 psi, 0.250&quot;, unannealed</td>
<td>270 deg F</td>
<td></td>
<td>ASTM D 648</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.19 W/m-C</td>
<td></td>
<td>ASTM C 177</td>
</tr>
<tr>
<td>CTE, flow, -40F to 200F</td>
<td>3 E-5 in/in-F</td>
<td></td>
<td>ASTM E 831</td>
</tr>
<tr>
<td>Thermal Index, Elec Prop</td>
<td>130 deg C</td>
<td></td>
<td>UL 746B</td>
</tr>
<tr>
<td>Thermal Index, Mech Prop with impact</td>
<td>120 deg C</td>
<td></td>
<td>UL 746B</td>
</tr>
<tr>
<td>Thermal Index, Mech prop without impact</td>
<td>130 deg C</td>
<td></td>
<td>UL 746B</td>
</tr>
<tr>
<td><strong>PHYSICAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Gravity, solid</td>
<td>1.21</td>
<td>-</td>
<td>ASTM D 792</td>
</tr>
<tr>
<td>Specific Volume</td>
<td>23.10 in³/lb</td>
<td></td>
<td>ASTM D 792</td>
</tr>
<tr>
<td>Density</td>
<td>0.044 lb/in³</td>
<td></td>
<td>ASTM D 792</td>
</tr>
<tr>
<td>Water Absorption, 24 hours @ 73F</td>
<td>0.150 %</td>
<td></td>
<td>ASTM D 570</td>
</tr>
<tr>
<td>Water Absorption, equilibrium, 73F</td>
<td>0.35 %</td>
<td></td>
<td>ASTM D 570</td>
</tr>
<tr>
<td>Water Absorption, equilibrium, 212F</td>
<td>0.58 %</td>
<td></td>
<td>ASTM D 570</td>
</tr>
<tr>
<td>Mold Shrinkage, flow, 0.125*</td>
<td>5-7 in/in E-3</td>
<td></td>
<td>ASTM D 955</td>
</tr>
<tr>
<td>Melt Flow Rate, norm, 300C/1.2 kgf (O)</td>
<td>10.0 g/10 min</td>
<td></td>
<td>ASTM D 1238</td>
</tr>
<tr>
<td><strong>ELECTRICAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume Resistivity</td>
<td>&gt;1E17 ohm·cm</td>
<td></td>
<td>ASTM D 257</td>
</tr>
<tr>
<td>Dielectric Strength, in air, 125 mils</td>
<td>425 V/mil</td>
<td></td>
<td>ASTM D 149</td>
</tr>
<tr>
<td>Dielectric Constant, 60 Hz</td>
<td>3.01</td>
<td>-</td>
<td>ASTM D 150</td>
</tr>
<tr>
<td>Dielectric Constant, 1 MHz</td>
<td>2.96</td>
<td>-</td>
<td>ASTM D 150</td>
</tr>
<tr>
<td>Dissipation Factor, 60 Hz</td>
<td>0.0009</td>
<td>-</td>
<td>ASTM D 150</td>
</tr>
<tr>
<td>Dissipation Factor, 1 MHz</td>
<td>0.0100</td>
<td>-</td>
<td>ASTM D 150</td>
</tr>
<tr>
<td><strong>FLAME CHARACTERISTICS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UL File Number, USA</td>
<td>E121562</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V-0 Rated (tested thickness)</td>
<td>0.044 inch</td>
<td></td>
<td>UL 94</td>
</tr>
<tr>
<td>CSA (See File for complete listing)</td>
<td>LS88480 File No.</td>
<td></td>
<td>CSA LISTED</td>
</tr>
<tr>
<td>Oxygen Index (LOI)</td>
<td>35.0%</td>
<td></td>
<td>ASTM D 2863</td>
</tr>
</tbody>
</table>

**Disclaimer**

The values shown on the attached pages are typical values that have been obtained using test bars from typical lots and are not intended for specification purposes. These values are for natural colors only. Addition of pigments may alter some values. Inasmuch as the General Electric Company has no control over the use to which others may put the material, it does not guarantee that the same results as those described herein will be obtained. Each user of the material should make his own test to determine the material’s suitability for his own particular use. Statements
Table 27: RGD5160 material properties

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM</th>
<th>Units</th>
<th>Metric</th>
<th>Units</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>D-638-03</td>
<td>MPa</td>
<td>55-60</td>
<td>psi</td>
<td>8000-8700</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>D-638-05</td>
<td>%</td>
<td>25-40</td>
<td>%</td>
<td>25-40</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>D-638-04</td>
<td>MPa</td>
<td>2600-3000</td>
<td>psi</td>
<td>375,000-435,000</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>D-790-03</td>
<td>MPa</td>
<td>66-75</td>
<td>psi</td>
<td>9,500-11,000</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>D-790-04</td>
<td>MPa</td>
<td>1700-2200</td>
<td>psi</td>
<td>245,000-320,000</td>
</tr>
<tr>
<td>HDT, °C @ 0.45MPa</td>
<td>D-648-06</td>
<td>°C</td>
<td>58.68</td>
<td>°F</td>
<td>136.154</td>
</tr>
<tr>
<td>HDT, °C @ 0.45MPa after thermal post treatment procedure A</td>
<td>D-648-06</td>
<td>°C</td>
<td>82.90</td>
<td>°F</td>
<td>180.194</td>
</tr>
<tr>
<td>HDT, °C @ 0.45MPa after thermal post treatment procedure B</td>
<td>D-648-06</td>
<td>°C</td>
<td>92.95</td>
<td>°F</td>
<td>198.203</td>
</tr>
<tr>
<td>HDT, °C @ 1.82MPa</td>
<td>D-648-07</td>
<td>°C</td>
<td>51.55</td>
<td>°F</td>
<td>124.131</td>
</tr>
<tr>
<td>Izod Notched Impact</td>
<td>D-256-06</td>
<td>J/m</td>
<td>65.80</td>
<td>ft lb/inch</td>
<td>1.22-1.50</td>
</tr>
<tr>
<td>Tg</td>
<td>DMA, E+</td>
<td>°C</td>
<td>47.53</td>
<td>°F</td>
<td>117.127</td>
</tr>
<tr>
<td>Shore Hardness (D)</td>
<td>Scale D</td>
<td>Scale D</td>
<td>85-87</td>
<td>Scale D</td>
<td>85-87</td>
</tr>
<tr>
<td>Rockwell Hardness</td>
<td>Scale M</td>
<td>Scale M</td>
<td>67-69</td>
<td>Scale M</td>
<td>67-69</td>
</tr>
<tr>
<td>Polymerized density</td>
<td>ASTM D792</td>
<td>g/m3</td>
<td>1.17-1.18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## APPENDIX E: PROCESSING PARAMETERS

Table 28: PIM1 processing parameters

<table>
<thead>
<tr>
<th></th>
<th>AL</th>
<th>PRT 1</th>
<th>PRT 2</th>
<th>PRT 3</th>
<th>PRT 4</th>
<th>Mold Flow</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Pressure (Max)</td>
<td>12,182</td>
<td>12,328</td>
<td>12,686</td>
<td>12,431</td>
<td>12,221</td>
<td>12,500</td>
<td>psi</td>
</tr>
<tr>
<td>Pressure at V/P Switchover</td>
<td>12,109</td>
<td>12,091</td>
<td>12,426</td>
<td>12,031</td>
<td>12,324</td>
<td>12,353</td>
<td>psi</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>10,763</td>
<td>10,930</td>
<td>11,116</td>
<td>10,738</td>
<td>10,670</td>
<td>10,984</td>
<td>psi</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.57</td>
<td>0.33</td>
<td>1.15</td>
<td>0.56</td>
<td>1.54</td>
<td>1.04</td>
<td>s</td>
</tr>
<tr>
<td>Time to reach Ejection</td>
<td>19.82</td>
<td>19.72</td>
<td>15.82</td>
<td>18.12</td>
<td>22.02</td>
<td>18.42</td>
<td>s</td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>23.73</td>
<td>29.93</td>
<td>36.73</td>
<td>30.03</td>
<td>37.23</td>
<td>31.03</td>
<td>s</td>
</tr>
</tbody>
</table>

Table 29: PIM2 processing parameters

<table>
<thead>
<tr>
<th></th>
<th>AL</th>
<th>PRT 1</th>
<th>PRT 2</th>
<th>PRT 3</th>
<th>PRT 4</th>
<th>Mold Flow</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Pressure (Max)</td>
<td>25,423</td>
<td>25,826</td>
<td>25,826</td>
<td>25,698</td>
<td>25,879</td>
<td>23,750</td>
<td>psi</td>
</tr>
<tr>
<td>Pressure at V/P Switchover</td>
<td>24,269</td>
<td>24,205</td>
<td>24,205</td>
<td>24,146</td>
<td>24,173</td>
<td>22,152</td>
<td>psi</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>17,520</td>
<td>17,520</td>
<td>17,520</td>
<td>17,520</td>
<td>17,520</td>
<td>17,704</td>
<td>psi</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.34</td>
<td>1.32</td>
<td>1.32</td>
<td>1.28</td>
<td>1.30</td>
<td>1.11</td>
<td>s</td>
</tr>
<tr>
<td>Time to reach Ejection</td>
<td>21.00</td>
<td>21.00</td>
<td>21.00</td>
<td>20.00</td>
<td>19.00</td>
<td>21.47</td>
<td>s</td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>28.76</td>
<td>31.28</td>
<td>31.28</td>
<td>30.29</td>
<td>40.50</td>
<td>31.03</td>
<td>s</td>
</tr>
</tbody>
</table>

Table 30: PIM3 processing parameters

<table>
<thead>
<tr>
<th></th>
<th>AL</th>
<th>PRT 1</th>
<th>PRT 2</th>
<th>PRT 3</th>
<th>PRT 4</th>
<th>Mold Flow</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Pressure (Max)</td>
<td>7,437</td>
<td>7,650</td>
<td>7,778</td>
<td>7,493</td>
<td>7,914</td>
<td>7,750</td>
<td>psi</td>
</tr>
<tr>
<td>Pressure at V/P Switchover</td>
<td>7,933</td>
<td>7,825</td>
<td>7,949</td>
<td>7,476</td>
<td>7,437</td>
<td>7,668</td>
<td>psi</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7,008</td>
<td>7,335</td>
<td>7,116</td>
<td>6,925</td>
<td>7,008</td>
<td>7,067</td>
<td>psi</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.29</td>
<td>1.30</td>
<td>1.52</td>
<td>1.38</td>
<td>1.30</td>
<td>1.34</td>
<td>s</td>
</tr>
<tr>
<td>Time to reach Ejection</td>
<td>9.79</td>
<td>17.29</td>
<td>15.89</td>
<td>16.69</td>
<td>14.09</td>
<td>15.69</td>
<td>s</td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>34.34</td>
<td>36.54</td>
<td>37.14</td>
<td>32.34</td>
<td>32.44</td>
<td>31.34</td>
<td>s</td>
</tr>
</tbody>
</table>
### Table 31: PIIM1 processing parameters

<table>
<thead>
<tr>
<th></th>
<th>AL</th>
<th>PRT 1</th>
<th>PRT 2</th>
<th>PRT 3</th>
<th>PRT 4</th>
<th>Mold Flow</th>
<th>[Unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Pressure (Max)</td>
<td>12,418</td>
<td>11,921</td>
<td>11,870</td>
<td>12,000</td>
<td>11,871</td>
<td>12,137</td>
<td>[psi]</td>
</tr>
<tr>
<td>Pressure at V/P Switchover</td>
<td>11,948</td>
<td>11,931</td>
<td>11,905</td>
<td>11,902</td>
<td>12,279</td>
<td>12,137</td>
<td>[psi]</td>
</tr>
<tr>
<td>Fill Time</td>
<td>2.51</td>
<td>1.29</td>
<td>1.94</td>
<td>1.14</td>
<td>2.22</td>
<td>1.90</td>
<td>[s]</td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>30.80</td>
<td>40.40</td>
<td>38.90</td>
<td>31.70</td>
<td>39.90</td>
<td>36.00</td>
<td>[s]</td>
</tr>
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</table>

### Table 32: PIIM2 processing parameters

<table>
<thead>
<tr>
<th></th>
<th>AL</th>
<th>PRT 1</th>
<th>PRT 2</th>
<th>PRT 3</th>
<th>PRT 4</th>
<th>Mold Flow</th>
<th>[Unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Pressure (Max)</td>
<td>14,564</td>
<td>14,942</td>
<td>14,691</td>
<td>15,210</td>
<td>14,954</td>
<td>14,911</td>
<td>[psi]</td>
</tr>
<tr>
<td>Pressure at V/P Switchover</td>
<td>14,050</td>
<td>14,186</td>
<td>14,319</td>
<td>14,148</td>
<td>14,414</td>
<td>14,206</td>
<td>[psi]</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>5,111</td>
<td>5,342</td>
<td>5,082</td>
<td>5,137</td>
<td>5,279</td>
<td>5,104</td>
<td>[psi]</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.63</td>
<td>1.59</td>
<td>1.55</td>
<td>1.59</td>
<td>1.63</td>
<td>1.53</td>
<td>[s]</td>
</tr>
<tr>
<td>Time to reach Ejection</td>
<td>15.60</td>
<td>16.25</td>
<td>16.50</td>
<td>16.40</td>
<td>16.30</td>
<td>12.90</td>
<td>[s]</td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>26.65</td>
<td>38.75</td>
<td>36.75</td>
<td>27.35</td>
<td>34.75</td>
<td>33.15</td>
<td>[s]</td>
</tr>
</tbody>
</table>
Figure 111: PIM1 - AL mold Dia. 1 run chart

Figure 112: PIM1 – PRT mold 1 Dia. 1 run chart

Figure 113: PIM1 – PRT mold 2 Dia. 1 run chart
Figure 114: PIM1 – PRT mold 3 Dia. 1 run chart

Figure 115: PIM1 – PRT mold 4 Dia. 1 run chart

Figure 116: PIM1 - AL mold Dia.2 run chart
Figure 117: PIM1 – PRT mold 1 Dia. 2 run chart

Figure 118: PIM1 – PRT mold 2 Dia. 2 run chart

Figure 119: PIM1 – PRT mold 3 Dia. 2 run chart
Figure 120: PIM1 – PRT mold 4 Dia. 2 run chart

Figure 121: PIM1 – Al mold thickness 1 run chart

Figure 122: PIM1 – PRT mold 1 thickness 1 run chart
Figure 123: PIM1 – PRT mold 2 thickness 1 run chart

Figure 124: PIM1 – PRT mold 3 thickness 1 run chart

Figure 125: PIM1 – PRT mold 4 thickness 1 run chart
Figure 126: PIM1 – AL mold thickness 2 run chart

Figure 127: PIM1 – PRT mold 1 thickness 2 run chart

Figure 128: PIM1 – PRT mold 2 thickness 2 run chart
Figure 129: PIM1 – PRT mold 3 thickness 2 run chart

Figure 130: PIM1 – PRT mold 4 thickness 2 run chart
F.2: PHASE I MOLD 2: RUN CHARTS

Figure 131: PIM2 –Al mold plate 1 thickness

Figure 132: PIM2 –PRT mold 1 plate 1 thickness

Figure 133: PIM2 –PRT mold 2 plate 1 thickness
Figure 134: PIM2 –PRT mold 3 plate 1 thickness

Figure 135: PIM2 –PRT mold 4 plate 1 thickness

Figure 136: PIM2 –Al mold plate 2 thickness
Figure 137: PIM2 – PRT mold 1 plate 2 thickness

Figure 138: PIM2 – PRT mold 2 plate 2 thickness

Figure 139: PIM2 – PRT mold 3 plate 2 thickness
Figure 140: PIM2 –PRT mold 4 plate 2 thickness

Figure 141: PIM2 –Al mold plate 3 thickness

Figure 142: PIM2 –PRT mold 1 plate 3 thickness
Figure 143: PIM2 –PRT mold 2 plate 3 thickness

Figure 144: PIM2 –PRT mold 3 plate 3 thickness

Figure 145: PIM2 –PRT mold 4 plate 3 thickness
Figure 146: PIM2 – Al mold plate average length

Figure 147: PIM2 – PRT mold 1 plate average length

Figure 148: PIM2 – PRT mold 2 plate average length
Figure 149: PIM2 – PRT mold 3 plate average length

Figure 150: PIM2 – PRT mold 4 plate average length

Figure 151: PIM2 - Al length measurement run chart
Figure 152: PIM2 - PRT 1 length measurement run chart

Figure 153: PIM2 - PRT 2 length measurement run chart

Figure 154: PIM2 - PRT 3 length measurement run chart
Figure 155: PIM2 - PRT 4 length measurement run chart

Figure 156: PIM2 - Al average width run chart

Figure 157: PIM2 - PRT 1 average width run chart
Figure 158: PIM2 – PRT 2 average width run chart

Figure 159: PIM2 – PRT 3 average width run chart

Figure 160: PIM2 - PRT 4 average width run chart
Figure 161: PIM2 - Al width measurements

Figure 162: PIM2 - PRT 1 width measurements

Figure 163: PIM2 - PRT 2 width measurements
Figure 164: PIM2 - PRT 3 width measurements

Figure 165: PIM2 - PRT 4 width measurements
F.3: PHASE I MOLD 3: RUN CHARTS

Figure 166: P1M3 – Al mold diameter run chart

Figure 167: P1M3 – PRT mold 1 diameter run chart

Figure 168: P1M3 – PRT mold 2 diameter run chart
Figure 169: P1M3 – PRT mold 3 diameter run chart

Figure 170: P1M3 – PRT mold 4 diameter run chart

Figure 171: P1M3 – Al mold thickness run chart
Figure 172: P1M3 – PRT mold 1 thickness run chart

Figure 173: P1M3 – PRT mold 2 thickness run chart

Figure 174: P1M3 – PRT mold 3 thickness run chart
Figure 175: P1M3 – PRT mold 4 thickness run chart

Figure 176: P1M3 – Al mold length run chart

Figure 177: P1M3 – PRT mold 1 length run chart
Figure 178: P1M3 – PRT mold 2 length run chart

Figure 179: P1M3 – PRT mold 3 length run chart

Figure 180: P1M3 – PRT mold 4 length run chart
Figure 181: P1M3 – Al mold width run chart

Figure 182: P1M3 – PRT mold 1 width run chart

Figure 183: P1M3 – PRT mold 2 width run chart
Figure 184: P1M3 – PRT mold 3 width run chart

Figure 185: P1M3 – PRT mold 4 width run chart
F.4: Phase II Lens: Run Charts

Figure 186: PIIM1 – Al mold thickness 1 run chart

Figure 187: PIIM1 – PRT mold thickness 1 run chart

Figure 188: PIIM1 – PRT vs. AL mold thickness 1 comparison run chart
Figure 189: PIIM1 – Al mold thickness 2 run chart

Figure 190: PIIM1 – PRT mold thickness 2 run chart

Figure 191: PIIM1 - PRT vs. AL mold thickness 2 comparison run chart
Figure 192: PIIM1 – Al mold thickness 3 run chart

Figure 193: PIIM1 – PRT mold thickness 3 run chart

Figure 194: PIIM1 - PRT vs. AL mold thickness 3 comparison run chart
Figure 195: PIIM1 – Al mold length run chart

Figure 196: PIIM1 – PRT mold length run chart

Figure 197: PIIM1 - PRT vs. AL mold length comparison run chart
Figure 198: PIIM1 – Al mold width run chart

Figure 199: PIIM1 – PRT mold width run chart

Figure 200: PIIM1 - PRT vs. AL mold width comparison run chart
F.4: PHASE II HOUSING: RUN CHARTS

Figure 201: PIIM2 - AL mold thickness 1 run chart

Figure 202: PIIM2 - PRT mold thickness 1 run chart

Figure 203: PIIM2 - PRT vs. AL mold thickness 1 comparison run chart
Figure 204: PIIM2 - AL mold thickness 2 run chart

Figure 205: PIIM2 - AL mold thickness 2 run chart

Figure 206: PIIM2 - PRT vs. AL mold thickness 2 comparison run chart
Figure 207: PIIM2 - AL mold thickness 3 run chart

Figure 208: PIIM2 - PRT mold thickness 3 run chart

Figure 209: PIIM2 - PRT vs. AL mold thickness 3 comparison run chart
Figure 210: PIIM2 - AL mold length run chart

Figure 211: PIIM2 - PRT mold length run chart

Figure 212: PIIM2 - PRT vs. AL mold length comparison run chart
Figure 213: PIIM2 - AL mold width run chart

Figure 214: PIIM2 - PRT mold width run chart

Figure 215: PIIM2 - PRT vs. AL mold width comparison run chart
Figure 216: PIIM2 - AL mold diameter run chart

Figure 217: PIIM2 - PRT mold diameter run chart

Figure 218: PIIM2 - PRT vs. AL mold diameter comparison run chart
APPENDIX G: EXPERIMENTATION PICTURES

G.1: MUD UNIT AND INSERTS

Figure 219: MUD Unit Installed in Molding Press (with Housing Insert)

Figure 220: MUD Unit with Adapter and PRT Insert

Figure 221: MUD Unit with AL Insert

Figure 222: MUD Uninstalled (with AL Housing Insert)

Figure 223: A-Side MUD Unit with AL and PRT Inserts

Figure 224: Aluminum Mold Insert
Figure 225: Aluminum Adapter Insert for Phase I

Figure 226: Phase I Adapter With and Without Insert

Figure 227: Phase I Insert Adapter with Aluminum PIM1 Insert

Figure 228: Phase I Insert Adapter with Aluminum Blank Insert

Figure 229: Phase I Insert Adapter with PRT PIM1 Insert

Figure 230: Phase I Insert Adapter with PRT Blank Insert
G.2: PIM1 “CYLINDER”

Figure 231: PIM1 Aluminum Insert

Figure 232: PIM1 PRT Insert

Figure 233: PIM1 PRT Inserts for Comparison

Figure 234: PIM1 Sample Part 50 from Aluminum Control

Figure 235: PIM1 Sample Part 15 from PRT Mold 1

Figure 236: PIM1 Sample Part 21 from PRT Mold 1
Figure 237: PIM1 Sample Parts 5, 10, & 25 from PRT Mold 2

Figure 238: PIM1 Sample Parts 5, 10, 15, & 34 from PRT Mold 3

Figure 239: PIM1 PRT Mold Loaded into MUD

Figure 240: PIM1 PRT Mold Loaded in MUD (After Failure)
G.3: PIM2 “Rectangles”

Figure 241: PIM2 Aluminum Insert

Figure 242: PIM2 Aluminum Insert Close-Up

Figure 243: PIM2 PRT Insert

Figure 244: PIM2 Inserts for Comparison

Figure 245: PIM2 Sample 50 from AL Control Mold

Figure 246: PIM2 Sample 28 from PRT Mold 2
G.4: PIM3 “ANGULAR”

Figure 252: PIM3 Aluminum Insert

Figure 253: PIM3 PRT Insert

Figure 254: PIM3 Inserts for Comparison

Figure 255: PIM3 Sample 2 from Aluminum Control Insert

Figure 256: PIM3 Sample 25 from Aluminum Control Insert

Figure 257: PIM3 Sample 13 from PRT Mold 1
Figure 258: PIM3 Samples 5, 10, &15 from PRT Mold 2

Figure 259: PIM3 Sample 5, 10, 15, 20, 25 from PRT Mold 3

Figure 260: PIM3 Sample 15 from PRT Mold 4

Figure 261: PIM3 PRT Mold Loaded in MUD (After Failure)

Figure 262: PIM3 PRT Mold Loaded in MUD
G.5: PIIM1 “LENS”

Figure 263: Phase II AL Mold A-Side

Figure 264: Phase II AL Mold B-Side

Figure 265: Phase II AL Mold A & B side Comparison

Figure 266: Phase II Mold Insert (Combined)

Figure 267: Phase II Lens Mold Snap Feature

Figure 268: Phase II Sample Produced from AL Mold (Showing Snap Feature)
Figure 269: Phase II Lens Sample from PRT (Showing Rear Snap Feature)

Figure 270: Phase II Lens Sample Parts from PRT
G.6: P1IM2 “TAIL-LIGHT HOUSING”

Figure 271: Phase II Housing PRT and AL Insert Comparison

Figure 272: Phase II Housing AL & PRT A-Side Comparison

Figure 273: Phase II Housing AL & PRT B-side Comparison

Figure 274: Phase II Component As Molded From AL Insert

Figure 275: Phase II Sample from PRT

Figure 276: Phase II Sample Parts from PRT Mold
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