Permeability and Porosity Reduction of Fused Deposition Modeling Parts via Internal Epoxy Injection Methods

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

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Abstract

Fused deposition modeling, or FDM, is a rapidly developing technology currently used in prototyping and some manufacturing areas. Available since the 1980s and commercialized by Stratasys in the 1990s, FDM has quickly become a standard in the area of rapid-prototyping or as it is most commonly known, 3D printing. FDM is known as an additive process in which a shape is created by extruding material into layers which are controlled by a computer to form the final shape. Some FDM machines allow the user to control various aspects of the layering process such as layer thickness, air gap between extrusions, process speed, contour angle, and extrusion width. These directly impact the final shape’s mass, density, strength, durability and permeability. This study looks into the various aspects of ensuring FDM permeability for its use in pressure applications utilizing different printable materials. Not only will this study recommend ideal machine settings in order to reduce porosity and design the optimal internal structure for the part, but will also suggest post-processing techniques based on injecting epoxy into the parts that will reduce porosity and decrease permeability. The two FDM machines that are used for testing samples are the Fortus 400mc and the Stratasys Dimension 1200es. The ultimate goal of this study is to understand how to create permeable plastic solutions in order to improve the use of FDM prototyping and manufacturing for high pressure applications, without compromising the part’s original exterior dimensions and surface finishes.
Dedication

This document is dedicated to my family, for all their support throughout my education.
Acknowledgements

I would like to thank my thesis committee members, Dr. Lilly, Dr. Castro, and Dr. Dupaix for all their support and advice.

I would like to thank Dr. Lilly, my adviser, for his incredible support over the last 5 years and whose encouragement and advice throughout those years has led me to where I am today. Thank you!

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Finally, I would like to thank my husband, Marko, for his continued love and support, and the encouragement to always take something to the next level.
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Major Field: Mechanical Engineering
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Chapter 1: Introduction

Fused deposition modeling (FDM) is a technology based on layering strands of semi-molten thermoplastics on top of each other in order to create a 3-dimensional shape. The model is created on a computer and then exported as an STL (stereolithography) file for processing. The computer sections the STL file into layers, which are then used by the FDM machine to create the desired shape. However, because of the inherent layering process that FDM uses to create parts, there are air-gaps left in between the layers which allow for air and/or liquids to permeate through the parts.

Since FDM allows users to conveniently create complex shapes and “print” them easily, it is a technology that has been rapidly growing over the last few years. FDM machines are becoming more affordable due to companies like MakerBot who target their machines to hobbyists. However, other applications for FDM that have proven to be quite successful are in the field of tissue engineering, in which porous structures are desired. As Liu-Tsang explains in her paper, “CAD-based techniques have been adapted to fabricate three-dimensional polymer for tissue engineering applications (Liu–Tsang 2004). Although a positive property for tissue engineering, one of the pitfalls of FDM is that “while FDM allows exceptional control in the xy plane, this method is however limited in the z-direction in that the height of the pores is by the size of the polymer filament extruded through the nozzle (Liu-Tsang, 2004).” Liu-Tsang points out one of the inherent properties of FDM that makes parts non-permeable, which is the porosity.
created by the printing process itself. Another limitation of FDM is the print size which not only applies to not being able to print parts larger than the machine’s pre-determined print envelope, but prints smaller than a certain size are not possible. The size limitations for small parts are based on the material extrusion width as well as the malleability of the material based on the oven’s temperature and material properties. Complex or small features require support material and if the part is too small, support material may not be able to be layered and the small parts would collapse creating deformed features. Another concern is that when the extruding head lifts away from the part surface, it leaves a globule of material that extends the print’s outline and creates a ridge on the part. In complex small features, this can potentially decrease the part’s accuracy. Stratasys’ printing guidelines recommend that parts not be printed smaller than 1 in. x 1 in. x 1 in. or larger than 16 in. x 14 in. x 16 in. (Stratasys, 2). Although FDM does indeed have several limitations, there are ways in which parts can be post-processed in order to become fully functional parts.

**Thesis Structure**

The first part of the study consisted of an initial analysis of samples from both the Fortus 400mc and the Dimension 1200es machines. It was determined that if a part was printed as “solid” as possible using custom machine settings, the parts were nevertheless quite permeable to air, when compared to an aluminum control sample. Parts coated with BJB epoxy performed better than the non-treated samples, for the most part, but were still able to diffuse air. Parts were then printed with a semi-hollow internal structure and were filled with various types of epoxy to seal them from the inside instead of externally as
with BJB epoxy and other currently accepted external sealants. Once parts were tested, it was determined that this method was successful in making parts non-permeable and non-porous when compared to the aluminum control sample. The latter part of the study consisted of creating more complex shapes to assure that the method of injecting epoxy into the parts as a sealing agent was successful. This process was then compared to commercially available software for simulating mold filling in injection molding to determine if users could plan an injection scheme for their models using the simulation, and successfully fill them after fabrication. This new method of post-processing components fabricated by FDM definitely has potential, but further work remains to be done. The final test compared the mechanical properties of composite plastic-epoxy parts to plain plastic parts.

Although various methods currently exist for sealing parts, each of these methods has serious drawbacks. Some of the methods currently used include acetone dips, vapor smoothing, and exterior epoxy coating. With all these methods, the main drawback is that the exterior surface is physically altered. This may be desirable in some cases but not all, as parts could potentially be dimensionally altered to the point at which they would be out of their tolerance range. Acetone and vapor smoothing make the parts smaller, while the BJB epoxy coating and paint add to the overall dimensions. Another drawback in using acetone are the serious health hazards associated with the material. With BJB epoxy, the surface finish is typically not constant throughout the entire part and air bubbles are seen on the outer surface of parts prepared using this method.

The present study analyzes the different types of epoxy used for part sealing, as well as various methods for filling and testing the parts once they have cured. Finally, the
study recommends ideal settings and guidelines for being able to make parts non-permeable and non-porous, without relying on an external post-print process.
Chapter 2: Background and Literature Review

Additive Manufacturing and Fused Deposition Modeling

Additive manufacturing is generally classified into three main categories: liquid, solid, and powder–based technologies. Fused deposition modeling (FDM) is considered to belong to the solid category. FDM is a technology which was developed by S. Scott Crump, co-founder of Stratasys, in the 1980s (Crump, 1992). The basic concept of all additive manufacturing methods is that a three-dimensional CAD (computer aided design) model in an ‘.stl’ format is ‘sliced’ into layers. An ‘.stl’ file is created by converting a three-dimensional CAD object into a ‘shell’ using a series of triangles created by an algorithm based on either an ASCII or Binary code (Burkardt, 2001). Software used by the FDM machines reads the STL shell data and ‘slices’ the model into layers. These layers are then ‘printed’ or extruded one by one on top of each other thus creating the complete shape of the model. The Stratasys website defines FDM as a “process [which] creates parts by extruding molten thermoplastic in fine layers to build the part layer by layer.” Chua explains that the air in the printing chamber is maintained at a slightly lower temperature than the solidification temperature of the material used to print the part, so that it solidifies almost instantly following extrusion (Chua, 2003).

In terms of order of operations, once the CAD model has been converted from an IGES or native format into a stereolithography (.stl) file, it is loaded into the FDM
machine’s software. Before the desired part can be made, the FDM software first needs to create another model of support material which will hold the part on the printer tray and support features which protrude from the main body of the part. This support material is separated from the final part once the process is finished by mechanically separating the two materials or dissolving the support material in a chemical bath. When creating complex geometries, this support geometry is highly necessary to avoid any deformities in the final product, especially when the model itself uses thermoplastics that have a relatively high melting point.

As rapid prototyping technology has advanced, the resolution of individual layers that can be printed has improved, thus creating smoother and higher quality products. As Chua (2003) explains, the primary physical constraints in using FDM are “material column strength, material flexural modulus, material viscosity, positioning accuracy, road widths, depositions speed, volumetric flow rate, tip diameter, envelope temperature and part geometry.” Similarly, Montero, et al. (2001) explain that when printing a model, one must consider the following parameters, some of which are shown in Figure 1.

- **Bead (row) width**: The width of the individual track of model material laid down by the extruding tip. FDM machines typically have a range of bead width, which are a function of the speed at which the model material is laid down, as well as the diameter of the actual extrusion nozzle.
- **Slice Height**: Similar to bead width, but in a vertical rather than horizontal direction.
- **Model Build Temperature**: The extrusion temperature of the material.
- *Air Gap*: The amount of air left in between successive beads or slices. In certain machines, one can set the air gap to be negative, which means that the layers are printed “on top” of each other in attempts to remove air pockets from the model.

- *Raster Orientation*: Direction of the bead relative to the loading of the part (see Figure 2).

![Figure 1 - Programmable Printer Parameters](image)

![Figure 2 - Possible Raster Orientation – Vertical / Horizontal; Angular; Concentric](image)

![Figure 3 - Interrupted Raster vs. Continuous Raster Tool path Setting](image)
Figure 3 represents an interrupted raster vs. a continuous raster. Depending on the settings of the FDM machine, one can set the print setting to a continuous raster to minimize print time as well as reduce the air gap. However, this can potentially reduce the accuracy of the model, based on the speed that the FDM machine extrudes the molten material. One must analyze the part being printed and decide on the most appropriate tool path for the application.

On certain machines, such as the Fortus 400mc, one can set different parameters in terms of contour style and contour width to be able to reduce the air gap and porosity in a given part. Most FDM machines will also allow the user to define parameters that will determine how the inside interior structure of the part will be. For example, if one is not concerned with porosity, but is concerned with the weight of the part, speed of production, and cost, one can reduce the amount of material built into the interior sections of the part as “filler.” Alternatively, one can choose to make the part as dense as possible in order to reduce porosity (Stratasys, 2011). The Dimension 1200es FDM machine has three different built-in parameters for part density. These include low-density (sparse), high-density, and solid; the cross-sections of these can be seen in Figure 4. The Fortus 400mc can be programmed to create custom part interiors, or default tool paths can be used. Figure 4 shows various types of layers that can be printed, as well as which of the FDM machines used in this study these correspond to. Standard practice calls for the solid layer to be used for creating the outer surface of the entire part, while the other layer types are used for interior supporting structures.

The Dimension 1200es (using CatalystEX software) allows the user to pick a default solid layer for the exterior and a solid, sparse, or sparse double dense structure for
the interior, without giving the user the option of defining which layers they would like to build using the solid or sparse structures. The Fortus 400mc, which uses the more advanced Insight software, allows the user to customize individual layer types as well as allowing users to have multiple layer types in one printed part. Note that Figure 4 also shows the porosity that is inherent in this process, even when one chooses the ‘solid’ layer setting. Porosity typically occurs when features have tight radii as well as features having transitions from straight to curved sections.
<table>
<thead>
<tr>
<th>Raster Type</th>
<th>Image</th>
<th>Machine Availability</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default Solid</td>
<td><img src="image" alt="Image" /></td>
<td>Dimension 1200es</td>
<td>Fortus 400mc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yes, on edges, corners</td>
<td></td>
</tr>
<tr>
<td>Sparse</td>
<td><img src="image" alt="Image" /></td>
<td>Dimension 1200es</td>
<td>Fortus 400mc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Sparse Double</td>
<td><img src="image" alt="Image" /></td>
<td>Dimension 1200es</td>
<td>Fortus 400mc</td>
</tr>
<tr>
<td>Dense</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Hexagonal</td>
<td><img src="image" alt="Image" /></td>
<td>Fortus 400mc</td>
<td>Yes</td>
</tr>
<tr>
<td>Sawtooth</td>
<td><img src="image" alt="Image" /></td>
<td>Fortus 400mc</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure 4 - Raster Types
Materials Used in this Study

The recent growth of the three-dimensional printing industry has led to companies being able to create parts in many different types of materials, including many different types of thermoplastics. Depending on parameters such as cost, strength, print time, overall finish, and application, users have recently gained the ability to choose a wider range of materials based on its properties. The Additive Manufacturing Lab at Ohio State is currently (2014) capable of fabricating parts using the materials discussed here.

Acrylonitrile-Butadiene-Styrene Terpolymer (ABS)

ABS is a very widely used engineering plastic. The terpolymer is typically composed of “…more than 50% styrene and varying amounts of acrylonitrile and butadiene. The three components are combined by a variety of methods involving polymerization, graft copolymerization, and physical blending (Massey, 2003).” Manufacturing processes that employ ABS include extrusion and injection molding. Various grades of ABS have been tested for water and gas permeability, with results showing that ABS is a permeable plastic. Permeability tests conducted on various grades of ABS have shown the following, according to Massey (2003).
### Table 1 - ABS Permeability Properties

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Gas Permeability (cm(^3) * mil/24 hr * 100 in(^2)* atm)</th>
<th>Vapor Permeability (g * mil/24 hr * 100 in(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE Plastics Cycolac</td>
<td>Oxygen: 39.3</td>
<td>Water Vapor: 5.88</td>
</tr>
<tr>
<td>BASF AG Terluran 997 VE</td>
<td>Oxygen: 81 Nitrogen: 20.3 Carbon Dioxide: 304</td>
<td>Water Vapor: 2.7</td>
</tr>
<tr>
<td>BASF AG Terluran 967 K</td>
<td>Oxygen: 50.7 Nitrogen: 10.1 Carbon Dioxide: 203</td>
<td>Water Vapor: 2.7</td>
</tr>
<tr>
<td>BASF AG Terluran 877 M</td>
<td>Oxygen: 45.6 Nitrogen: 10 Carbon Dioxide: 203</td>
<td>Water Vapor: 3.1</td>
</tr>
</tbody>
</table>

**Acrylonitrile-Butadiene-Styrene - M30i (ABS-M30i)**

ABS-M30i is a “biocompatible 3D printing material” that can be used for food and medical applications (Stratasys, 2011). This is a proprietary formulation of ABS that is used only by the Stratasys company in their FDM machines. We assume that this particular formulation includes flow enhancing additives to aid in the extrusion process.

**Polycarbonate (PC)**

According to Massey (2003), polycarbonate is “…one of the strongest, toughest, and most rigid thermoplastics, [although] not generally considered [a] good barrier material.” Polycarbonate is generally used as a structural plastic while other materials are used as gas barriers. Polycarbonate, which is also known by the trade name Lexan, is widely used in injection molding, extrusion, blow molding, and rotational molding to produce a very
large number of consumer products. Polycarbonate formulations from various manufacturers were found to have the following permeability properties:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Gas Permeability (cm³ * mm/m² * day * atm)</th>
<th>Vapor Permeability (g * mm/m² * day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOW Chemical Calibre</td>
<td></td>
<td></td>
</tr>
<tr>
<td>For Grade 300-4</td>
<td>Nitrogen: 12.2</td>
<td>Oxygen: 102</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide: 768</td>
<td></td>
</tr>
<tr>
<td>For Grade 300-15</td>
<td>Nitrogen: 10.6</td>
<td>Oxygen: 90.6</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide: 677</td>
<td></td>
</tr>
<tr>
<td>For Grade 800-6</td>
<td>Nitrogen: 22.4</td>
<td>Oxygen: 124</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide: 827</td>
<td></td>
</tr>
<tr>
<td>Type: PC Film</td>
<td>Carbon Dioxide: 307</td>
<td>Oxygen: 102</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water Vapor: 3.82-4.33</td>
</tr>
<tr>
<td>Bayer Makrolon: Film</td>
<td>Oxygen: 67.9</td>
<td>Nitrogen: 11.2</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide: 436</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water Vapor: 1.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Polycarbonate Permeability Properties

**Polycarbonate - Acrylonitrile-Butadiene-Styrene (PC-ABS)**

The PC-ABS material used in this study is a proprietary blend of polycarbonate and acrylonitrile-butadiene-styrene specifically formulated for the FDM process. Stratasys states that PC-ABS has “…superior mechanical properties and heat resistance of PC, excellent feature definition and surface appeal of ABS, and has the highest impact strength.”

**Ultem**

Ultem is a type of polyetherimide (PEI) produced by SABIC (formerly GE Plastics Division). In general, polyetherimides have “…good chemical, creep, and heat resistance, and dielectric properties (Massey, 2003).” This plastic is well known for its high strength at relatively high temperatures (for a thermoplastic resin). Stratasys claims that this material will retain its structural integrity at temperatures close to 400° F (Stratasys,
Parts made using PEI are typically manufactured by extrusion, thermoforming, compression, injection, and blow molding processes.

FDM Machines

The two FDM machines used for this study are the Fortus 400mc and the Dimension 1200es, both manufactured by Stratasys, Ltd. of Eden Prairie, Minnesota. The Dimension 1200es is an older, smaller machine which uses a single model material, ABSplus. The Dimension 1200es printing software, CatalystEX, allows the user to import the stereolithography file, place it on the printer’s build surface, choose the type of internal structure desired, and commence the printing process. CatalystEX allows users to print multiple files at once as long as they don’t exceed the machine’s print envelope. The Fortus 400mc is a newer and larger machine, capable of printing with four different materials. This machine uses the Insight software, which is much more flexible for fabricating custom components. Insight allows users to create custom tool paths and change part densities to allow for more part customization. This section provides detailed information on both machines so one can compare and contrast, using information provided by Stratasys, 2011.

FORTUS 400mc Specifications

The FORTUS 400mc has the following print specifications.

- Build envelope: 16 x 14 x 16 inches
- Accuracy: +/- 0.005 inch or +/- 0.0015 inch per printed inch
Operating environment: Max room temperature: 85°F

Software: Insight™ and Control Center™

**DIMENSION 1200es Specifications**

The DIMENSION 1200es has the following specifications.

- Build envelope: 10 x 10 x 12 inches
- Accuracy: 0.010 inches
- Materials: ABSplus
- Layer thickness: 0.010 and 0.013 inches
- Software: CatalystEX
Sealing Methods

Stratasys (2011) recommends the following procedures for sealing parts in their *Comparison of Sealing Methods for FDM Materials* guidelines. Some of these methods are clearly intended for improving aesthetics, while others are intended for permeability purposes. The methods recommended in their technical guide include paint and filler, solvent, finishing tough smoothing station, adhesive Hysol E-20HP (epoxy), and adhesive BJB TC-1614 (epoxy). Considerations include cost, processing time, cure time, additional equipment, skill level, geometry of the part, part size, viscosity, accuracy retention, pressure applied to part, chemical resistance, and temperature sensitivity.

Stratasys (2011) has put together the table, shown in Table 3, outlining the various properties of the various sealing methods.

<table>
<thead>
<tr>
<th></th>
<th>Paint &amp; Filler</th>
<th>Solvent</th>
<th>Finishing Touch Smoothing Station</th>
<th>Hysol E-20 Epoxy</th>
<th>BJB TC-1614 Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>Processing Time</td>
<td>2 hr</td>
<td>5 min</td>
<td>5 min</td>
<td>10 min</td>
<td>10 min</td>
</tr>
<tr>
<td>Cure Time</td>
<td>24 hr</td>
<td>18 hr</td>
<td>18 hr</td>
<td>24 hr</td>
<td>2 hr</td>
</tr>
<tr>
<td>Additional Equipment</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Skill Level</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Geometry Dependent</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Maximum Part Size</td>
<td>NA</td>
<td>NA</td>
<td>14 x 20 x 18 (35 x 51 x 46)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Low</td>
<td>Low</td>
<td>NA</td>
<td>Med.</td>
<td>Low</td>
</tr>
<tr>
<td>Accuracy Retention</td>
<td>Great</td>
<td>Good</td>
<td>Great</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Maximum Air Pressure</td>
<td>N/A</td>
<td>Atmospheric</td>
<td>Atmospheric</td>
<td>65 psi+</td>
<td>65 psi+</td>
</tr>
<tr>
<td>Chemically Resistant</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>Varies</td>
<td>176 (80)</td>
<td>176 (80)</td>
<td>212 (100)</td>
<td>347+ (175+)</td>
</tr>
</tbody>
</table>

*Table 3 - Stratasys Table of Sealant Properties*
A popular method for sealing FDM parts is with the use of acetone, as McCullough (2013) stated in his research for the use of FDM in biomedical applications. His research involved “…a method to fabricate water-tight microfluidic devices using a method of chemical dissolution via acetone is shown to render a porous FDM ABS device impervious to water flow between layers, while preserving the structural fidelity of printed microstructures down to 250 μm (McCullough, 948).” There are several drawbacks to the use of acetone, one being that “undiluted acetone very quickly dissolves ABS and can erode the features of the printed devices (McCullough, 949).” Another drawback of using acetone is that it can cause damage to the user’s body, including kidney and liver damage as well as fertility issues (New Jersey D.O.H., 2011).

**Previous FDM Permeability and Porosity Studies**

This section summarizes previously conducted studies that have looked into the areas of FDM permeability and porosity. Currently, most of the studies in this area deal with medical applications of FDM, some of which regard porosity as a positive aspect of FDM. Other studies look into methods of reducing permeability and porosity. The two studies described in this section dealt with the currently accepted methods of sealing FDM parts with varying levels of success.

*Mireles, et al. (2013)*

Jorge Mireles et al. at the University of Texas El Paso, working closely with Stratasys has conducted an analysis of various different types of sealants that could be applied to the exterior of FDM parts. The sealants used are the following:
DEFT Clear Brushing Lacquer
- IPS Weld-On 3 Cement
- Minwax Sanding Sealer
- Minwax Oil Base Polyurethane
- Thompson’s Multi-Surface Waterproofer
- BJB TC-1614 A/B, Hysol E-30CL
- Styca W19 + Catalyst 9
- West Marine Penetrating Epoxy + West System 105 Resin + 209 Hardener

The sealant methods employed in this study included vacuum infiltration and brushing. The most successful of their sealants was BJB TC-1614 epoxy which was able to withstand pressures of 276 kPa (40 psi) and 138 kPa (20 psi) for 5 minutes using the brushing and vacuum infiltration processes respectively. However, one of the main drawbacks stated in this study is the potential for dimensional changes which are hard to control using either of their sealing methods. Their results yielded many sealant accumulations around tight corners of their test parts. Their pressures were also added gradually as opposed to instant, which could yield different results during pressure application.

The testing apparatus they used included a custom-made shape that was modeled to include complex features and abrupt shape changes to more accurately measure the success of their sealants. This ABS-M30i part was mounted onto a plate with O-ring seals in between the part and the plate in order to ensure a tight seal. The plate had a hole drilled at the bottom of it where a pressure line would deliver air into the part. The part
was then submerged in water. In order to visually check for leaks, the researchers observed air bubbles forming on the part, which would show an indication of an air leak. It was noted that the majority of air bubbles formed at the locations where there were abrupt changes in the shape.

Overall results for this study concluded that the best external sealant is BJB Epoxy TC-1614 applied as two coats using a brushing method. This was the only method able to withstand a pressure of 207-276 kPa. Other sealants that were applied with 2 brushed coats and able to withstand pressures between 138-207 kPa include Minwax Sanding Sealer, Minwax Oil Based Polyurethane, PRO Finisher Water-Base Polyurethane, Styecast W19 + Catalyst 9, and West System’s 105 Resin + 209 Hardener Epoxy. The only vacuum infiltration process that was able to withstand 138-207 kPa of pressure was the BJB Epoxy TC-1614, with all other processes yielding lower pressure results or no pressure retention.

*McCullough (2013)*

Eric McCullough et al. conducted a study to seal FDM parts using acetone. Their study focused on biocompatible applications, and focused on specific properties such as roughness, charge, modulus, and hydrophilicity. Their solution to treating the FDM part surfaces was to soak parts in acetone (Smith-Aldrich and deionized water 18.2 MΩcm) for various amounts of time. Their samples were then placed in high-humidity environments and colored dye was injected into printed channels to visually check for fluid seepage.
Their samples were printed on a Dimension 1200es machine using ABSplus. Samples were composed of thin rectangles that had a series of channels on the top surface. Prior to the acetone bath, researchers were able to physically observe and measure individual strands of ABSplus that made up the part. After the acetone bath, the strands of ABSplus were smoother and fused together, making it difficult to measure strands individually. Researchers also observed that un-treated samples were permeable to liquids, and post-processed samples were able to retain liquids. The liquids were placed in the channels that were on the top surface of the part and parts were observed for permeability.

Although their treatment was successful for sealing samples, it was noted that there were surface changes that occurred from the acetone chemically interacting with the ABS. One other drawback from their study was that with surface modifications their CAD models would have to be updated and removal of material using acetone had to be accounted for so the specifications for desired contact angle between specimens would remain. Another drawback stated by the researchers was that some applications relied on surface roughness for flow in microfluidic devices, and roughness was one characteristic that changed due to the addition of acetone. The one interesting observation pointed out by the researchers was that the amount of time the acetone was left of the part was not proportional to the amount of roughness measured, concluding that surface roughness was due to the concentration of acetone in the solution, rather than the amount of time the samples were left in the acetone bath. Overall, their results were successful in showing that acetone can indeed be used as an FDM part sealer, with certain characteristics to be kept in mind if one is interested in maintaining the part’s original dimensional quality.
Chapter 3: Methodology

The testing that was completed for this thesis evolved over the course of the project. Because so little was known about the porosity of parts produced by the fused deposition modeling process, and because prior work in this area is so limited, the testing protocols employed here were revised according to the results obtained in prior tests.

The overall sequence of events reported on here was as follows:

- The first test was to print disks using the Dimension 1200es machine and analyze the internal structure in order to understand the inherent porosity due to print structure in FDM applications.
- Concluding that the Dimension 1200es “solid” disks still had a large amount of porosity, the next step was to print disks using the Fortus 400mc machine and try to reduce the porosity by printing parts with customized raster patterns.
- Multiple disk samples were then tested against a ‘control’ disk machined from an aluminum blank, using a simple piston-cylinder system in order to gauge air permeability rates. These disks were printed on the Dimension 1200es and the Fortus 400mc, using various print parameters as well as various materials. Figure 6 shows a sample of the disks tested: from left to right, aluminum, Fortus 400mc Ultem Custom, Fortus 400mc ABS-M30i Custom, Fortus 400mc ABS-M30i default, and Dimension 1200es ABS-plus. Samples were tested under a Low...
Pressure (LP) condition of 4.35 psi or a High Pressure (HP) condition of 38.16 psi based on an initial assessment of pressure that the parts could hold over a long enough time to be able to accurately measure a displacement.

![Figure 6 - Sample of Disks Tested](image)

- The next step was to coat some of the FDM samples in BJB Epoxy and test these relative to the non-coated parts and the aluminum disk.
- Subsequently, the disks were printed using a sparse internal structure and filled with epoxy (poured onto open-section samples). These parts were tested in the piston-cylinder system and compared to the previous parts (non-coated and coated) as well as the aluminum control disk.
- The next step was to determine a way to fill the samples with minimum external modifications as well as filling them using a closed-section sample.
- Following the successful test of the closed-section epoxy-filled samples, it was determined that more complex shapes were to be printed and filled using an injection method.
- Following the successful filling of these parts, they were tested under pressure to compare the rate at which pressure dropped once the part was pressurized.
• The next test was to determine the minimum thickness a part could have that would permit filling using the epoxy-injection method. These samples were fabricated in both the Dimension 1200es and Fortus 400mc machines.

• The last test was to print and fill with epoxy five tensile samples (creating a composite) and compare their mechanical behavior to non-treated tensile samples.

Initial Testing Apparatus

A custom piston and cylinder testing apparatus was designed and built in-house in order to test the permeability of the samples. The cylinder and linkage support systems were built from aluminum, with a piston machined from polyoxymethylene, also known as Delrin, from DuPont. A rubber gasket was used to seal the cylinder to minimize air leakage between the piston and cylinder wall. In order to minimize friction and binding, a Peaucellier-Lipkin linkage was used to support the piston arm. This allows rotary motion to be transformed into pure straight-line motion, with the linkage proportions the same as shown in Figure 7. A weight was suspended from the far end of the linkage to provide a constant pressure to the piston inside the cylinder. A model of the test apparatus can be seen in Figure 8, and detailed drawings can be found in Appendix A.
A dial indicator was mounted to the top of the cylinder in order to accurately measure the displacement caused by the weight on the piston-cylinder assembly. The ‘control disk’ which completely sealed the bottom of the cylinder, and to which the FDM
printed disks were compared, was machined from aluminum, as previously noted. The disk was mounted at the bottom of the cylinder (shown in red in Figure 8) and fixed in place with eight socket–head screws. The FDM disks were originally 1.8 inches in diameter and 0.5 inches in thickness. These were later changed to 1.8 inches in diameter and 0.125 inches in thickness. The change in thickness was made to reduce the material quantity, as it was noted that the change in thickness did not affect the degree of permeability. Three different types of ABS disks were tested using different print parameters, from each of the FDM machines. Disks made from Ultem were also printed and compared to the other samples. Rubber gaskets were placed on the top and bottom surfaces of the disks, as shown in Figure 9, in order to ensure minimum air leakage due to the part geometry. The bottom of each disk was open to the atmosphere.
The test cylinder itself can be considered a thick-walled cylinder. The outer diameter is 2 inches, the inner diameter is 1.629 inches, giving an overall wall thickness of 0.1855 inches.
Eliminating Noise

As Phadke notes, there are various noise factors in the deposition process. The “nonuniform thickness and the surface defects of the [material] layer are caused by variations in the parameters involved in the chemical reactions associated with the deposition process (Phadke, 1989).” Sample dimensions were measured with precision calipers to assure that all specimens were similar to each other, thus eliminating the possibility of “print-noise” as a factor in pressure differences amongst data points. Similarly, samples were picked at random and examined under a microscope to analyze uniformity and print accuracy.

Epoxy Samples

After comparison of the initial piston-cylinder testing apparatus, samples were filled with epoxy as an internal sealing method. These disk samples were then compared to the aluminum samples to assure the reduction of permeability and porosity. Once it was concluded that the epoxy injection method was successful at sealing the samples, it was determined that an integral nozzle, built into each specimen, would be used to fill the parts with epoxy using a syringe or a vacuum pump. These parts were tested for pressure purposes using a vacuum pump. Epoxy-filled tensile samples were also created to compare plain plastic samples to epoxy-plastic composites.
Chapter 4: Results

Initial Disk Porosity Testing

A summary of the printed samples can be seen in Table 4. The original data can be found in Appendix B: Test Data. These values were used to calculate the average percentage of air, or porosity in the samples using the following steps used for one of the sample calculations.

*Disk Volume Calculations:*

\[ Volume = \pi r^2 \times \text{height} \]

For the 0.5 inch height disk with a diameter of 1.80 inches:

\[ Volume = \pi (0.9in)^2 \times (0.5in) = 1.272in^3 \]

For the 0.150 inch height disk with a diameter of 1.80 inches:

\[ Volume = \pi (0.9in)^2 \times (0.150in) = 0.3817in^3 \]

*Conversion from inches to centimeters:*

For the 0.5 inch height disk with a diameter of 1.80 inches:

\[ 1.272 \text{in}^3 \times \frac{16.387cm^3}{1in} = 20.844 \text{cm}^3 \]

For the 0.150 inch height disk with a diameter of 1.80 inches:

\[ 0.3817 \text{in}^3 \times \frac{16.387cm^3}{1in} = 6.255 \text{cm}^3 \]
Theoretical Mass Calculations:

Using a density (ρ) of 1.04 grams per cubed centimeter for ABS,

For the 0.5 inch height disk with a diameter of 1.80 inches:

\[
\text{Theoretical Mass} = 20.844 \text{ cm}^3 \times \frac{1.04g}{\text{cm}^3} = 21.677g
\]

For the 0.150 inch height disk with a diameter of 1.80 inches:

\[
\text{Theoretical Mass} = 6.255 \text{ cm}^3 \times \frac{1.04g}{\text{cm}^3} = 6.5052g
\]

Percentage of Air:

\[
\text{Percentage of Air} = 1 - \left( \frac{\text{Actual Mass}}{\text{Theoretical Mass}} \right) \times 100
\]

For the 0.5 inch height disk with a diameter of 1.80 inches:

\[
\text{Percentage of Air} = 1 - \left( \frac{20.135}{21.677} \right) \times 100 = 7.1\% \text{ air}
\]

For the 0.150 inch height disk with a diameter of 1.80 inches:

\[
\text{Percentage of Air} = 1 - \left( \frac{6.1417}{6.5052} \right) \times 100 = 5.6\% \text{ air}
\]

For batch number 1, six samples were printed from each of the printers using the following parameters:

- The Dimension 1200es samples were printed using the “Solid” default parameter which attempts to print samples without any air gaps. Results from cutting these samples can be seen in Figure 14. These part volumes were made up of approximately 7.12% air.
The Fortus 400mc Default Solid samples were printed using the machine’s pre programmed setting to reduce the amount of air pockets in the samples. It was determined that these samples contained an average of 4.15% air. Figure 10 shows the difference between the default and custom samples that were printed on the Fortus.

The most solid samples of the first batch were the Fortus 400mc custom, circular-linked specimens, where contours were linked (see Figure 3- continuous tool path settings) in order to reduce the air gaps and make the part as solid as possible. It was determined that the amount of air that made up the total volume was approximately 5.34%.

![Figure 10 - Fortus 400mc Custom Circular and Default Samples in ABS-M30i](image)

<table>
<thead>
<tr>
<th>Batch Number</th>
<th>Material</th>
<th>FDM Machine</th>
<th>Print Characteristics</th>
<th>Average Measured Mass (g)</th>
<th>Average Diameter (in)</th>
<th>Density of Material (g/cm³)</th>
<th>Theoretical Mass of Part (g)</th>
<th>Average % of Air in Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ABSplus 1200es</td>
<td>Solid</td>
<td></td>
<td>20.1352</td>
<td>1.797</td>
<td>1.04</td>
<td>21.678</td>
<td>7.117</td>
</tr>
<tr>
<td>1</td>
<td>ABS M30i Fortus 400mc Circular linked contours</td>
<td>20.7784</td>
<td>1.799</td>
<td>1.04</td>
<td>21.678</td>
<td>4.150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>ABS M30i Fortus 400mc Default Solid</td>
<td>20.5208</td>
<td>1.799</td>
<td>1.04</td>
<td>21.678</td>
<td>5.338</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 - Batch 1 Printed Part Characteristics
After initial analysis, these parts were subjected to a pressure of 4.35 psi using weights added to the testing apparatus. The pressure had to be reduced from that initially used with the aluminum control disk (38.16 psi) as this pressure was far too high for the parts to sustain. At the higher pressure level, the cylinder was evacuated essentially instantaneously. Figure 11 shows the preliminary test results which show the Fortus Custom Circular pattern being on average better at holding pressure than the Dimension Default and Fortus Default Samples. The Dimension Default sample on the third test had a higher displacement than the rest of the samples. This could have been due to changes in the internal and external structures that sometime occur during the printing process, which produce slight differences in printed parts.

![Batch 1 Pressure Testing](image)

**Figure 11 - Batch 1 Pressure Testing Results (4.35 psi)**
The second batch to be tested used thinner disks (thickness of 0.150 inches), which were printed using the parameters listed in Table 5. Some of these were then sent to Stratasys for BJB Epoxy coating using the vacuum infiltration method (see Chapter 2 for more information). Although the rate of diffusion decreased for most of the samples, they still were not comparable to the aluminum control sample in terms of holding air pressure.

One of the drawbacks of the custom circular parts is the decreased dimensional accuracy and aesthetics of the part, especially when looking at the central feature. This can be seen in Figure 12, which shows one of the samples that was printed on the Fortus 400mc in Ultem. The central feature was approximately 0.02 inches thicker than the rest of the part.

Figure 12 - Close-up of Fortus 400mc Ultem Custom Circular Sample
<table>
<thead>
<tr>
<th>Batch Number</th>
<th>Material</th>
<th>FDM Machine</th>
<th>Print Characteristics</th>
<th>Average Measured Mass (g)</th>
<th>Average Diameter (in)</th>
<th>Density of Material g/cm^3</th>
<th>Theoretical Mass of Part (g)</th>
<th>Average % of Air in Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>ABSplus</td>
<td>Dimension 1200es</td>
<td>Solid</td>
<td>6.1417</td>
<td>1.798</td>
<td>1.04</td>
<td>6.5052</td>
<td>5.588</td>
</tr>
<tr>
<td>2</td>
<td>ABS M30i</td>
<td>Fortus 400mc</td>
<td>Circular linked contours</td>
<td>6.2443</td>
<td>1.799</td>
<td>1.04</td>
<td>6.5052</td>
<td>4.011</td>
</tr>
<tr>
<td>2</td>
<td>ABS M30i</td>
<td>Fortus 400mc</td>
<td>Default Solid</td>
<td>6.2101</td>
<td>1.797</td>
<td>1.04</td>
<td>6.5052</td>
<td>4.536</td>
</tr>
<tr>
<td>2</td>
<td>Ultem</td>
<td>Fortus 400mc</td>
<td>Circular linked contours</td>
<td>7.6633</td>
<td>1.798</td>
<td>1.34</td>
<td>8.3817</td>
<td>8.571</td>
</tr>
</tbody>
</table>

Table 5 - Batch 2 Printed Part Characteristics

After the BJB Epoxy coating, the samples were weighed once again to determine the amount of epoxy added to each. The new weight for each sample is shown below, along with the difference between the coated and non-coated samples:

- Dimension Solid: 6.209 g (an addition of 0.0673 g of BJB Epoxy)
- Fortus Circular linked cont. (ABS M30i): 6.364 g (an addition of 0.1198 g of BJB Epoxy)
- Fortus Default Solid: 6.2757 g (an addition of 0.0656 g of BJB Epoxy)
- Fortus Circular linked cont. (Ultem): 7.6891 g (an addition of 0.0258 g of BJB Epoxy)

The differences in the average amount of epoxy added to the samples can be seen in Figure 13. These differences could be due to the epoxy infiltrating into the exterior part pores, or possibly be the excess BJB epoxy left at the surfaces. Some of the parts have uneven surfaces due to the addition of this extra layer.
After testing the BJB Epoxy samples the results were compared to the average displacement of the un-treated samples and the aluminum control disk, which can be seen in Figures 14 – 16. There is a LP (Low Pressure: 4.35 psi) or HP (High Pressure: 38.16 psi) note denoting which pressure they were tested under. The BJB Epoxy samples were all tested under a High Pressure scenario, except for the Dimension Default samples which were not able to be tested under High Pressure conditions. The BJB Epoxy samples were not able to be tested under the Low Pressure setting as the piston kept popping out of the cylinder due to lower permeability of the samples.
Figure 14 - Low Rate of Displacement Samples Tested under High Pressure

Figure 15 - Fortus Default BJB Samples Tested under High Pressure
Three different types of samples were printed on the Dimension 1200es machine to compare the varying amount of porosity in “default” machine settings. Figure 17 contains images of interiors of the parts after they were sectioned. The first one is the Low-Density default option that focuses more on the outer shape while keeping the interior sparse. This allows the machine to use less material and print the part faster. The High-Density profile allows higher density in the part than sparse, an attribute most likely needed if the part is used for a low-load structure. The Solid print profile takes the longest time to complete and obviously uses the most material. This is the parameter one would choose for higher-load structures. As observed in the figure below, even the “solid” print profile has air gaps in between the layers.
A Low-Density (sparse) profile was used for the epoxy filled samples. For this test, parts were printed on the Dimension 1200es and the print process was stopped before the part could completely finish, leaving the internal structure of the part completely exposed at the top. This provided the opportunity to fill the gaps seen in Figure 18 with epoxy for sealing purposes.

Two different epoxies were used for this test. One was a two-part casting epoxy used for arts and crafts (Easy Cast); this specific material has a viscosity of approximately 600 cP. Information on this epoxy can be found on the TAP Plastics website (EX-74, 2014). This epoxy easily flowed through the structure in order to fill in...
any gaps; however, it still shrank slightly upon curing. The other epoxy is a traditional two-part epoxy specifically used for ABS bonding (Loctite Epoxy Plastic Bonder). The viscosity for this epoxy is approximately 110,000 cP, and as seen in Figure 19, this epoxy was not ideal for this application as it did not evenly fill internal gaps in the structure. The un-filled portions are circled on the right image. This epoxy mixture also contained considerably more air bubbles than the casting epoxy, which were trapped in the viscous material and thus not removed through outgassing during the curing process.

![Figure 19 - Epoxy-filled Samples: Casting Epoxy vs. ABS Epoxy](image)

These samples were then tested against the aluminum control disk and compared to the Dimension Default Solid BJB Samples. They were found to be comparable to the aluminum disk for holding air pressure. Results for this test can be found in Figure 20.
After these initial tests, a third Epoxy was used to test a vacuum method of filling the samples. The epoxy used was Epikote Resin MGS RIMR 135, along with Epikure Curing Agent MGS RIMH 137. The viscosity for this epoxy is between 700-1,100 cP, depending on mixture ratios. The sample geometry was a completely enclosed version of the samples seen in Figure 19. They disks were drilled on the sides in order to be able to attach the vacuum pump hoses, as seen in Figure 22.
The sample was attached to the vacuum pump using the setup seen in Figures 22 and 23. The vacuum pump was set to 30 psi.

Figure 22 - Sample setup on the work table

Figure 23 - Complete view of sample setup
Although this test was not successful at completely filling the samples with the epoxy, it was useful as a learning tool to brainstorm a different method of filling the samples. One of the features that led to the test failing was that the inlet and outlet hoses that went from the epoxy to the printed part, and then from the part to the vacuum pump were not physically attached to the part. They were simply placed next to the part and held in place by double-stick tape and the vacuum bag itself. This allowed for some of the epoxy to spill out of the part once it was left to cure. Subsequent epoxy trials used integral nozzles printed directly into the parts in order to inject the epoxy straight into the part.

After due consideration of the previous attempt, the research team brainstormed methods of “injecting” epoxy into the samples. One of the methods proposed was to use gravity as a means to guarantee that the epoxy reached all of the voids in the parts. The epoxy was injected into a hose with a syringe that was attached to a nozzle printed directly onto the bottom of the part, until the epoxy flowed through the entire part. It was determined that the epoxy completely filled the internal cavities of the part when the epoxy began to fill the hose that was attached to the outlet at the top of the part. The initial trial part can be seen in Figure 24.
Figure 24 - Initial Epoxy Injection Sample

Figure 25 shows the syringe used to fill the sample with epoxy, and Figure 26 shows the part being left to cure. Note that the sample was oriented vertically during filling, in order that the syringe would inject the epoxy upward into the part; this method ensured that gravity would aid in the diffusion of the epoxy across the cross-section of the part as it filled.
Figure 25 - Part being filled with a syringe full of epoxy

Figure 26 - Part filled with epoxy during curing stage

For the most part, the parts were able to be successfully filled using this method, but there were still a few air bubbles left in the samples as can be seen in Figure 27. The internal structure of the sample was exposed by milling off the outermost layers of the sample. The sample shown in Figure 27 has been prepared by this method.
These results indicated that the process of injecting epoxy into the samples was successful, but needed some refinement in order to reduce the number of air bubbles left by the initial filling process with the syringe. The inherent porosity of FDM was revealed when epoxy started leaking out one of the outer surfaces, as can be seen in Figure 28. Even though the outer walls of the part were approximately 1/8 of an inch thick (or in this case, 4 solid layers thick), there were still enough gaps between the layers to allow the epoxy to permeate through.
The next step after this test was to create more complex shapes to make sure the specific epoxy used would be able to flow properly through a part and fill any porosity gaps. The part that was created for this test can be seen in Figure 29. Initially, the part was created without the 45 degree sections between the flange and the cone, also seen in Figure 29, but this proved to be inadequate for filling because the software used for creating print maps was not able to create one single hollow shape, and instead would separate it into a shape with two separate hollow compartments. This would mean that the shape would not have been able to be filled just with one nozzle. A detailed drawing of the part can be found in Appendix A.
Figure 29 - Complex shape without and with 45 degree side sections

Figure 30 contains the section view of the CAD model showing the intended semi-hollow space inside of the part, which when printed, would have an internal structure similar to the Low-Density print profile in Figure 18. This would allow for the use of only one of the bottom nozzles to be used for filling purposes.

Figure 30 - Section view of the intended internal structure
After the part was converted to a stereolithography and imported into Insight (the software used to convert stereolithography models to printable models) it was discovered that the model would be printed with two separate compartments. The first compartment would include all of the base of the part and the second compartment would include all of the cone part of the shape. Figure 31 shows a section view of what the printed part would look like if it were printed without any shape modifications.

![Figure 31 - Section view of part with two hollow compartments](image)

Initially two nozzles were printed onto the parts in case the computer simulations showed that it was better to fill the part from two sides. The nozzles at the top are used as outlets that would let the air out of the part as it is being filled with epoxy. All of the nozzles are initially printed solid and can be drilled individually if they need to be open.

Concurrent to the printing of the model, a simulation was run using the injection molding software Moldex 3D to analyze the flow of the epoxy via selected inlet nozzles. The simulation shown in Figure 32 shows a top view sequence of the flow from an inlet
placed at the bottom left-hand corner of the part. The simulation shows that it would be ideal to open one of the nozzles at the top of the part, on the opposite side of where the epoxy is being injected.

![Injection Molding Simulation](image)

**Figure 32 - Injection Molding Simulation**

This simulation was then used to compare how the internal structure of the printed part behaved when compared to a theoretical, hollow injection-molded part of identical shape and size. Results from this study showed that the simulation was accurate in showing the flow of the epoxy, as it was noted that the epoxy reached the top of the part first on the right side and then the left, in accordance to the orientation shown in Figure 32. The last section of the part to be filled was the location of the outlet nozzle, as shown in Figure 34.

Moldex 3D also predicted the location of the weld lines of the injection molded part, which of course is not an issue for this case. In this specific model, the software predicted the weld lines in the areas shown in Figure 33, which corresponded with the actual flow pattern observed.
A thermal–imaging camera was used to capture the various stages of the filling process, and then compared to the simulation. It was determined that the use of Moldex 3D as a simulation tool to place the nozzles was successful, and the actual flow of the epoxy matched the simulation closely. A comparison of both the simulation and the experimental tests can be seen in Figure 34. The epoxy mixture was warmed before being injected into the test part in order to be able to more easily see the contrast on the thermal camera. The warming of the epoxy caused it to become runnier than the usual room-temperature mixture. Because the viscosity of the epoxy is quite sensitive to temperature, this led to some of the epoxy leaking through the existing pores on the outside of the part during filling. This served as further confirmation that the viscosity of the epoxy shouldn’t be so low that it easily seeps through the part, yet not so high that it becomes difficult to inject it into the part, as was seen during the initial hollow-disk filling test. The EasyCast epoxy with a viscosity of 600 cP used at room temperature was ideal for injection purposes.
After the first part was printed using ABS M30i on the Fortus 400mc, it was determined that having a single layer of printed material on the outer surface (the contour of the part) was not thick enough, as cavities formed during the printing process as seen in Figure 35. Although these were sealed with electrical PVC tape and clear packing tape in order to prevent any of the epoxy from leaking, subsequent prints would have at least two or four contour layers to prevent these cavities. Similarly, cavities appeared on the part surface between the bolt-hole and the filleted edge. These cavities show that since the layering process is not perfect, parts that could be expected to be solid may actually have defects on them, thus making them porous. It was noted that even after printing the parts with either two or four layers, there was still some porosity. These were sealed, once again with tape, before the epoxy injection process.
The FDM part can be seen in Figure 36. The figure also shows the inlet and outlet used for the epoxy injection. Since the nozzles are originally printed as solids, the two that were used for the test were drilled before testing. The nozzles were printed in such a way because small features, such as these holes, tend to collapse and not be geometrically perfect if they aren’t large enough for support material.
Results from the epoxy fill concluded that it is not ideal to have such large cavities on the outer surface of the part, as it resulted in complications during the filling process even when the part was sealed using a strong adhesive tape. However, results did show that the base of the part was successfully filled up to the point of the large cavity.

For the second test part, the sawtooth raster interior was used. The sawtooth is particularly good at creating a honey-comb-like structure on parts that are more geometrically complex than prism-like parts. Figure 37 shows the sawtooth raster transitioning from layer X to X+1 and X+2 (starting from the base of the part), creating shifts in the internal structure that make it a good option for filling.
The new part was also created using 2 contour (outer) layers in order to prevent the large cavities on the outside. Although this did improve the final finish of the part, there were still cavities formed. For testing purposes, these cavities were sealed using a semi-molten strand of ABS and a soldering gun. Once cool, the epoxy was injected into the part using the same nozzle locations as shown in Figure 36. There were some smaller cavities, or pores, where the epoxy did leak out, but for the most part this test was successful. Epoxy flowed all through the part and out the upper outlet nozzle. The final part can be seen in Figure 38, including the areas where ABS was added to the part to prevent leaks. The epoxy also leaked through the porous areas at the top of the part. This not only served to show that the epoxy flowed through the part, but it also sealed any pores that could contribute to air leaks. It was noted that any of the epoxy that dripped onto the outside of the part was able to be peeled off; therefore leaving the surface in its original state. The extra ABS that was added to the outside of the part to prevent leaks was also easy to remove without any damage being done to the original shape. A suggestion for the future was to create a linked-contour upper layer to prevent, or reduce leaks.
This part was used for pressure testing to see what the rate of pressure loss was after the parts were subjected to pressure. The parts were sealed at the bottom by adhering a gasket to the part and mounting the part onto an aluminum plate. The final part, once the nozzles were cut-off and sanded, can be seen in Figure 39. Two parts were used for pressure testing; the part seen in Figure 39, which was the one injected with epoxy, and an un-treated part for comparison. The parts were mounted onto a bell jar pressure apparatus, as seen in Figures 40 and 41.
Figure 39 - Post-processed part ready for pressure testing

Figure 40 - Bell Jar Pressure Testing Apparatus
Results for this test concluded that the untreated part was not able to hold any pressure at all. When the part was placed on the bell jar apparatus and a vacuum was pulled, the part was not able to hold any measurable pressure. Meanwhile, the treated part was able to hold a pressure of 250 mmHg, with a slight drop of 10 mmHg in 4:19:96 minutes. Possible leaks could have occurred due an uneven surface-to-surface contact between the test part and the gasket in between the bell jar base and the part.

Another test was used to determine if a thin, printed part would be able to be injected with epoxy. The part used for the initial test was a 3 in. x 1 in. by 0.1 in. flat piece, similar to those used for stress-strain testing. This test was used to determine if injecting a stress-strain piece with epoxy would be viable for creating composite parts
and thus potentially increasing the strength of the part depending on the material injected, as well as suggesting minimum thicknesses that can be used for epoxy injection. The part is shown in Figure 42.

![Flat sample used for epoxy testing](image)

**Figure 42 - Flat sample used for epoxy testing**

Results from this test concluded that thin parts, such as this 0.1 inch thick sample, are not ideal to print on the Fortus 400mc using double-dense or saw-tooth rasters because the raster pattern used for layering the interior was compressed during the printing process, creating individual air pockets that were sealed from the rest of the part. Even after a new part was created with an even sparser raster pattern (saw-tooth), the epoxy was not able to flow through. The upper image in Figure 43 shows the ideal raster spacing where epoxy could flow through one compartment to the next through the horizontal slots, as opposed to the lower image, which shows the way the printer fused the rasters together, thus creating sealed compartments that do now allow the epoxy to permeate through.
Figure 43 - Theoretical vs. Experimental raster patterns in the flat samples

Table 6 shows the results of the flat-sample tests that were conducted, which lead to the creation of a guideline specifying the minimum thickness of a part in order to be filled with epoxy using the injection method.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Material</th>
<th>Part Thickness (in)</th>
<th>Total Layers</th>
<th>Total Contour Layers</th>
<th>Total Interior Layers</th>
<th>Interior Raster Pattern</th>
<th>Able to be filled?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fortus 400mc</td>
<td>ABS M30i</td>
<td>0.10</td>
<td>9</td>
<td>4</td>
<td>5</td>
<td>Double-dense</td>
<td>No</td>
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<tr>
<td>Fortus 400mc</td>
<td>ABS M30i</td>
<td>0.10</td>
<td>9</td>
<td>4</td>
<td>5</td>
<td>Saw-tooth</td>
<td>No</td>
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<td>Fortus 400mc</td>
<td>PC-ABS</td>
<td>0.13</td>
<td>12</td>
<td>4</td>
<td>8</td>
<td>Saw-tooth</td>
<td>No – exterior too porous (PC-ABS)</td>
</tr>
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<td>PC-ABS</td>
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<td>8</td>
<td>2</td>
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<td>ABSplus</td>
<td>0.13</td>
<td>12</td>
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</table>

Table 6 - Flat Sample Thickness Tests

Results from these tests showed that on the Dimension 1200es, samples can be printed using the default sparse (low density) setting with at least 2 sparse layers in the middle. On the Fortus 400mc, results showed that samples can be printed as thin as 0.11 inches in order to be filled with epoxy, but the internal rasters also have to be printed using the sparse setting. If they are printed using the saw-tooth or double-dense setting, they will
not be able to be filled. On the Fortus 400mc, it is also recommended that when printing with PC-ABS, at least 4 contour layers be used since this material contains a lot more porosity than the others.

Figure 44 shows the Dimension 1200es 0.130 inch thick sample which was the first flat sample that was successfully filled with epoxy. The first image shows the epoxy about one-quarter of the way up the part; the second image shows the epoxy about one-half of the way up the part, and the last image shows the epoxy all the way to the top of the part.
Results from these successful fill tests were used for the last test, which was to epoxy-fill sparse tensile test specimens and compare the results to non-epoxy, solid tensile samples. The samples were printed using the following properties:

- **Material**: PC-ABS, printed on the Fortus 400mc
- **Dimensions**: 1 inch wide; 0.25 inch thick and 10 inches long.
- **Structure**: 4 default (45 degree) contour layers each at the bottom and top of the part and a sparse interior.
- **Total material used**: 1.553 cubic inches.

A total of five samples were printed, although only four were able to be filled with epoxy. This was due to the high amount of porosity in the PC-ABS samples, which allowed a large amount of epoxy to leak through the sample on the first fill attempt. The fill process was later modified for the remaining samples, which were tighter with a larger amount of packing tape used to seal the exteriors of the parts to prevent excessive leakage. The final 4 samples can be seen in Figure 45.

![Figure 45 - Epoxy-filled PC-ABS Tensile Samples](image-url)
The samples were tested using an Instron tensile testing machine, with an extensometer attached to the samples, as seen in Figure 46.

![Sample Tensile Test on Instron](image)

Figure 46 - Sample Tensile Test on Instron

Results for this test can be seen in Table 7 and Figure 47 which shows the stress-strain curves of the samples, as compared to solid PC-ABS samples that were tested by Ryan Kay (2014). These samples were printed and tested on the same machines. Results indicate that the samples had a significantly lower maximum stress value, but had
approximately 3% higher strain values. Figure 48 shows the samples after the tensile tests, and Figure 49 shows the interior of the parts showing a successful epoxy fill.

<table>
<thead>
<tr>
<th></th>
<th>Thickness (mm)</th>
<th>Width (mm)</th>
<th>Maximum Load (N)</th>
<th>Tensile stress at Maximum Load (MPa)</th>
<th>Maximum Modulus (Secant, Cursor) (MPa)</th>
<th>Tensile Stress at Yield (Zero Slope) (MPa)</th>
<th>Tensile Stress at Yield (Offset 0.2 %) (MPa)</th>
<th>Tensile strain at Yield (Zero Slope) (%)</th>
<th>Tensile strain at Yield (Offset 0.2 %) (%)</th>
<th>Tensile Stress at Break (Standard) (MPa)</th>
<th>Tensile strain at Break (Standard) (%)</th>
<th>Modulus Young (MPa)</th>
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<td>1.805</td>
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</table>

Table 7 - Tensile Test Results for Epoxy-Filled Parts
Figure 47 - PC-ABS Stress-Strain Curve Comparison

Figure 48 - Epoxy-Filled Samples after Tensile Tests
It is suspected that the reasons the samples behaved the way they did were due to the following:

- The samples broke on 45 degree angles due to the raster patterns inside and outside of the part. Considering the bonds between strands are weaker than the strands themselves (Kay, 2014), it can be assumed that the orientation of the rasters limited the part’s strength.

- Due to the internal structure of the part being compartmentalized, there were few areas in which either the epoxy or the PC-ABS formed continuous strands.

Figure 49 - Internal Structure of Epoxy-Filled Tensile Sample
From these results, it can be determined that parts created using 45 degree internal and external raster patterns and filled with EasyCast casting epoxy were not stronger than solid parts, but were more flexible.

**Final Recommendations and Guidelines**

This section is intended as a set of recommendations and guidelines that one should use when trying to seal FDM parts internally using the epoxy injection method. Although refinements will no doubt continue to be made to the process in the future, these guidelines will yield a successfully sealed FDM part.

**Dimension 1200es**

The Dimension 1200es machine only prints in ABS, and has three pre-determined print parameters for part density (low-density, high-density, and solid). Tests showed that the minimum part thickness one can print on the Dimension 1200es while still being able to fill the part using the injection method was 0.11 inches thick, using the pre-determined low-density setting. This setting created four solid layers at the top and bottom of the part, and 2 sparse layers in between.

Due to the lack of flexibility of the printer’s parameters, the Dimension 1200es is better for creating parts that are not too complex if they are to be filled using the epoxy injection method. This is due to the lack of ability to create custom layers, thus not allowing users to manipulate the internal structures needed for the epoxy to flow through.

The overall quality of the parts created on the Dimension 1200es were fairly good. The surfaces were smooth and consistent, but the edges of the parts were the
surfaces met the part contours were still relatively porous. These pores allowed for some of the epoxy to leak through the part during the injection process; however, the epoxy was able to be removed easily after curing.

Fortus 400mc

The Fortus 400mc machine is highly customizable and is able to build parts using multiple materials. For the epoxy injection method, materials used were ABS-M30i, PC-ABS, and PC. All of these were printed at a resolution of 0.010 inches, but can be printed with a resolution of 0.005 inches if necessary.

The minimum thickness for creating a part on the Fortus 400mc to fill with epoxy is 0.11 inches as well, but with a sparse-only interior as opposed to using either the saw-tooth raster or double-dense raster.

Of the three materials used for epoxy-injection, the ABS-M30i was found to be the least porous. ABS seemed to adhere better to adjacent layers, as opposed to PC, or PC-ABS, where gaps between strands were clearly visible. More contour (outer) layers are needed for PC and PC-ABS to prevent excessive leaks than for the ABS parts.

As for the layer types used for the Fortus parts, the following were found to be the best combinations for filling specific types of parts:

- A flat, simple, thin part (0.11 inches thick) was printed with default solid layers for the outsides (at least 3 layers, especially when using PC or PC-ABS) and a sparse internal raster.
- A thicker part, e.g., 0.25 inches or more, was able to be easily filled with epoxy with minor external leaks when there were 4 contour-outside layers and an
interior structure such as sparse-double-dense or saw-tooth. The PC-ABS parts still had more exterior leaks than the ABS even when 4 outer layers were created. It is recommended that more than 4 contour layers be used when using PC and PC-ABS if the part geometry allows.

- A more complex part may require the use of custom tool path settings. For example, the part should have a base of at least 4 solid layers; an internal structure made up of a saw-tooth or sparse structure, and an upper layer created of solid, linked contours. Circular features should be created with concentric circles as opposed to a hatching-like pattern that doesn’t follow the shape’s contour. This will reduce the number of pores created on the boundaries between the surfaces and the contours.

Nozzle Design

The nozzle used for filling the parts was designed from a standard part made to fit tubing with an inner diameter of 3/8 of an inch. The nozzle was small enough that it wouldn’t drastically change the exterior surface of the part when removed for finishing purposes, but large enough that it would allow epoxy to easily flow through it. The nozzle itself was printed as solid and was later drilled. This was to prevent any collapse of the structure during fabrication, as well as improve the overall appearance. Figure 50 shows a detailed drawing of the nozzle. The drill bit used for drilling the interior had an 11/64 inch diameter. A fillet of radius 0.05 inches was used to add strength to the edge between the nozzle and the part.
Nozzle Location

It is recommended that the nozzle placement be simulated using a plastic injection simulation software, such as Moldex 3D, prior to printing the final part. This was helpful in simulating the path the epoxy would take, even though the actual filling process would occur at a much slower rate than traditional injection molding.

Epoxy

The epoxy that yielded the best results for epoxy injection was the two-part EasyCast casting epoxy using a 50-50 mixture of resin to hardener. This epoxy has a viscosity of 600 cP. It was noted that the epoxy performed the best when it was used at room temperature, as opposed to being warmed up. The process worked best when the rate of flow was slow enough that the epoxy wouldn’t seep through the small pores on the outer layers of the parts. After mixing the epoxy, it was best to leave it in the mixing cup for about 10 minutes before use, in order to allow most of the air bubbles to escape. This specific epoxy takes approximately 24 hours to cure, so it was best to leave the part, un-
touched and on a cardboard surface for about a day before handling. The amount of epoxy needed for the part can be calculated using the CAD drawings of the part.

**Part Preparation**

Before the part can be injected with epoxy, it had to be prepared. This included making sure the part was completely dry before the process. Water and/or the chemical solution used to dissolve the support material always seeps into the part’s pores so one must make sure that the part is dry before completing the next steps. This can be done using an oven at low heat.

The next part is to drill the holes through the nozzles using an 11/64 inch drill bit. It is a good idea to blow air through the part to make sure any plastic pieces are out of the part. The next step is to use electrical tape to wrap the nozzles a few times, just to guarantee a good seal between the nozzles and the tubing. After that, one can place the tubing on top of the nozzles and secure them using small zip ties. If any small pores are present on the outer layers of the parts, one can use either electrical tape or clear packing tape to seal them. If larger holes are present, one can use a soldering gun to melt strands of the material used to print the part onto the part itself, always being careful to not damage the part. These pieces of molten material can be easily peeled-off once the epoxy has been cured. Now one can start filling the part with epoxy using a syringe. If the syringe is too small for the tubing used, electrical tape can be wrapped at the end of the syringe to create a good seal with the tubing. It is important that the correct amount of epoxy to fill the whole part be in the syringe in order to avoid injecting bubbles into the parts. Once the part is fully filled, one can clamp the ends of the inlet and outlet tubing to
prevent any of the epoxy from leaking back out of the part. The part can then be left to cure for at least 24 hours.

Once the part has cured, one can remove the tubing and cut off the nozzles using a small saw. The part can then be sanded down to the exterior surface to create a smooth finish. There will only be a small circle of diameter 11/64 inches of epoxy left on the outer surface of the part, which is where the epoxy inlets and outlets were located.
Chapter 5: Conclusion

Additive manufacturing, especially the area of fused deposition modeling, has progressed substantially in the past few decades. Not only are FDM machines now available at a low cost for hobbyists, but food and aerospace industries, among others, are finding creative ways to use this technology to advance their sectors. However, due to the nature of the FDM process there are limitations as to what can be printed successfully. This specific study looked at the inherent porosity of FDM parts, a characteristic that is inherent to this process. Due to this porosity, industries that attempt to use FDM parts for purposes of holding high pressure or vacuum, or to create permeable parts, have no choice but to substantially modify their parts using a chemical agent which causes external part modifications, or abandon the use of this technology altogether. Currently, the only available methods of sealing parts involve modifications to the exterior of the part through the addition of adhesives, sealants or paint, or by chemically altering the surface using substances such as acetone. These methods all physically change look of the part, and in most cases, also change the dimensions of the part. This study looked at a method of internally sealing FDM parts using a method of epoxy injection that would leave the exterior of the parts virtually un-changed and able to hold pressure.
Research Outcomes

Initial Test Samples

From the initial samples that were printed, it was determined that no matter how “solid” one makes the part, it will still be porous. Materials printed with a custom raster pattern were able to hold pressure better than parts created by default settings, but not as well as the aluminum ‘control’ disk. Samples coated with BJB Epoxy were able to hold more pressure than the un-coated samples, but not as well as the aluminum control disk. The only samples that were able to perform as well as the aluminum control disk were the epoxy-filled samples. This led to the second part of the study, which focused on creating a process that could be used to successfully fill parts in order to reduce porosity and permeability.

Epoxy Samples

From the three different types of epoxy used, the one that had the best viscosity for filling the samples was the 2-part EasyCast casting epoxy. With a viscosity of 600 cP, it was able to fill the parts easily, without being so fluid that the epoxy seeped through the surface pores. It was also determined that it was best to use the epoxy at room temperature as opposed to elevated temperatures. Printed part recommendations for filling with epoxy are listed in the Final Recommendations section of the Results chapter.
Simulation

It was determined that the use of the injection molding software, Moldex 3D, was beneficial for the placement of the inlet and outlet nozzles. Similarly, the path of the epoxy was accurately mapped in the simulation and physically verified through the use of a thermal imaging camera.

Tensile Samples

Tests showed that if one is interested in creating samples that have a higher strain (in the case of PC-ABS) than just regular, solid samples, one can fill them with epoxy in order to achieve about 3% higher strain. Samples had an overall lower maximum stress point before breaking. This was most likely due to the internal and external raster patterns and the compartmentalization of the part, but needs further tests to verify this theory.

Future Recommendations

The epoxy injection method has the potential to change the way FDM technology is viewed in industry. Not only does it provide a new and unique method of sealing parts that has not been attempted before, but shows potential for making the technology more usable in manufacturing settings. Due to the infancy of the process, much more can be done to improve efficiency and the method itself. Below are some future recommendations that could take this process to new levels.
Ideal Pressure Settings for Epoxy Fill

For the test samples creating in this study, the epoxy was filled using a store-bought syringe. Epoxy was injected into the parts by simply pressing on the plunger at a slow rate, keeping in mind that a higher rate could potentially cause errors. These errors include not filling the entire part with epoxy, as well as having a rate too high that a significant amount of epoxy is pushed through the surface’s pores. A future study could look into ideal rate settings based on the internal structures of the parts, the overall shapes, and the viscosity of the epoxy.

Temporarily Sealing the Parts for Epoxy-Fill Preparation

One of the drawbacks of printing with materials such as PC-ABS, is that the material doesn’t adhere to itself as well as ABS. This creates quite a bit of external surface porosity and makes filling parts with epoxy somewhat messy. Although electrical and packing tape were used to temporarily seal the parts so epoxy doesn’t seep through, it was not the ideal method for complex shapes. One future recommendation for this issue is to investigate different methods of sealing these parts externally before the epoxy-injection process. One method could be to use the vacuum bag method that was used to initially fill the samples with epoxy. Custom bags could be made to seal the parts externally, which could be removed once the epoxy has cured.

An example of this was during the tensile part filling process, with parts that were long and slender, and made from PC-ABS. These were particularly difficult to inject with epoxy due to the high levels of external porosity. Although wrapping the samples in packing tape helped to seal some of the pores and prevent excessive epoxy leakage, it would be a good idea to find a method that is less messy.
**Filling Extra-large Samples with Epoxy**

One of the drawbacks of using the syringe method of filling the parts is that one is limited by the size of the syringe. It is not recommended that the syringe be removed from the tubing in the middle of the filling process because this can lead to the injection of bubbles into the part. Therefore, the recommendation is to look into methods of filling large parts, possibly using a low-pressure vacuum pump that will slowly fill the parts with epoxy. The one used for the initial epoxy filling trial was set to 30 psi, had a large diameter tube attached to it, and the epoxy had a low viscosity. These settings were not ideal for this particular scenario, as it was seen that the part was not fully filled with epoxy. Another recommendation would be to possibly add multiple nozzles on the part (using the help of the injection molding simulation software Moldex 3D) to aid in the filling of large parts.

**Filling Parts with Different Materials**

From the literature review it was determined that multiple industries would benefit from the addition of different materials into parts created by the FDM process. One of these includes the addition of antibiotics and other medicines to FDM parts to aid in custom implant and tissue creation. Other materials that could be mixed into the epoxy include magnetic fragments, metal fragments, and other small parts that could be mixed into the epoxy and injected into parts for various applications. This could allow users to create magnetic components with a magnetic core, instead of the addition of an external magnet.
Print Orientation Comparison

The initial test disks were all tested under the worst-case scenario conditions, where most of the porosity was in the direction of airflow. Another test could look into printing parts where the airflow is perpendicular to the surface of maximum porosity, which in some cases is purely related to the material being used to print the parts. It was observed that un-coated PC-ABS parts were fairly porous all around, and Ultem, ABS, and PC were more porous on the surface in the Z-direction of the print. Figure 51 shows the current method that was used to print the test disks which led to a significant amount of porosity on the layers facing the direction of the airflow. Figure 52 shows a proposed method of printing parts that would reduce the porosity on the surface that faces the airflow by rotating the part 90 degrees on the print table. One of the drawbacks is that circular features, such as the disk shown, would become extremely faceted and the overall part would lose dimensional accuracy.

Figure 51 - Porosity on the Top Layer of a Test Disk
Another future study could look into modeling the internal structure of the parts in CAD in order to more accurately simulate the epoxy flow. This could aid in nozzle placement for more complex parts seeing as epoxy dispersion is a factor due to the internal structure.

*Internal Structure Simulation*

Figure 52 - Disk Printed on the Side with Raster Directions Highlighted in Yellow
References


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Appendix A – CAD Drawings

Peaucellieur-Lipkin Linkage Testing Apparatus
Plate

(thickness 0.25"

Miriam Cater

A

REV

SCALE: 1:4

WEIGHT: SHEET 1 OF 1

81
Updated Lower Cylinder

SECTION A-A

8 X Ø 0.15

8 X Ø 0.3125 ± 0.20

Miriam Cater

cater.16

A
Updated Top Cylinder

SECTION A-A
SCALE 1:1

8 x Ø10-24 NC Ø.50

83
Piston

![Diagram of a Piston]

**Dimensions:**
- Diameter: 1.629
- Height: 1.00
- Width: 0.747

**Materials:**
- Brass or Bronze

**Drawing Information:**
- Designer: Miriam Cater
- Scale: 1:1

**Remarks:**
- This drawing is for the piston component used in engine applications.
- DO NOT SCALE DRAWING.
Connecting Vertical Rod
New Base

NewBase

Miriama Cater

A

Scale: 1:2  Weight:  Sheet 1 of 1
Long Links
Mid Links
Short Links
Appendix B – Test Data

The following acronyms correspond to the pressure the parts were subjected to.

**LP**: Low Pressure = 4.35 psi

**HP**: High Pressure = 38.16 psi

### Phase 1 Data

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<th>Diameter (Inches)</th>
<th>Displacement (in/hr) under LP</th>
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Phase 3 Data: Open Epoxy Disks

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