

# **Investment Casting Using FDM/ABS Rapid Prototype Patterns**

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## **Introduction**

Investment casting (IC) is one of the most economical ways to produce complex shaped parts from metal. In some cases, it is the only method available when parts have undercuts, thin walls or inaccessible configurations. One disadvantage of using IC for small quantities is the long lead time and high cost of tooling to produce the necessary wax patterns. As a substitute for the wax patterns, rapid prototype parts may be used, resulting in substantial time and cost savings.

Six foundries participated in a program that evaluated the use of ABS parts created from Stratasys® FDM Rapid Prototype (RP) systems. The ABS parts were produced as substitutes for the injected wax patterns. Each foundry had experience using different RP parts. Feasibility and expertise were established over nine months, using three test geometries.

## **Purpose**

The purpose of this document is to present the results of the IC evaluation program, as well as process data, to both FDM customers and IC foundries. It is meant to be a guideline that takes into account the different variables in the part build process and the foundry business. For Stratasys FDM users who want to produce ABS patterns for making metal castings, this document outlines guidelines and provides fundamental procedures. For foundries experienced in rapid prototyping, it can serve as a guide for tuning their process for materials other than epoxy, polycarbonate, laminated paper or other RP produced material. Finally, for foundries that have little or no experience, it provides process information to serve as a general guide for using ABS parts or IC patterns.

## **ABS Versus Wax Patterns**

The traditional IC process creates wax patterns utilizing a process similar to plastic injection molding, where wax is injected into an aluminum tool to produce the pattern. Today, this process is well understood and practiced by thousands of IC foundries across the world. The Stratasys FDM process offers an alternative approach to creating a wax pattern from a tool. Patterns may be created directly from either ABS or wax materials. ABS is offered on FDM 1600, FDM 1650, FDM 2000, FDM 8000 and FDM Quantum™ machines. Wax, termed ICW-06, is offered on the FDM 1600, FDM 1650, and FDM 2000 machines.

## **Advantages and Disadvantages**

The advantages and disadvantages of patterns made from FDM ABS, FDM wax, and wax from a tool are shown in Table 1.

**Table 1. Advantages/Disadvantages of Patterns Made from FDM ABS, FDM Wax and Wax from Tooling.**

	<b>FDM ABS</b>	<b>FDM Wax</b>	<b>Wax from Tooling</b>
<b>A D V A N T A G E S</b>	<ul style="list-style-type: none"> <li>• Parts are strong and able to withstand the rigors of transportation</li> <li>• Thin-walled parts can be created</li> <li>• Surface finish is better than RP wax</li> <li>• Parts can be post-finished without fear of breakage</li> <li>• Users are more experienced at building accurate parts in this material</li> </ul>	<ul style="list-style-type: none"> <li>• Foundries prefer to use wax</li> <li>• There is no change in the foundry process when using the wax</li> </ul>	<ul style="list-style-type: none"> <li>• Large quantities can be produced economically</li> <li>• Consistency of dimensions</li> <li>• Good surface finish</li> </ul>
<b>D I S A D V A N T A G E S</b>	<ul style="list-style-type: none"> <li>• Only a few foundries, at this time, have experience using ABS</li> <li>• Foundries that have no experience, need time to become proficient</li> </ul>	<ul style="list-style-type: none"> <li>• Any wax part is fragile, and transportation to a foundry could yield multiple parts</li> <li>• The softening point is 170 °F (77 °C), which can be reached in the hot sun</li> </ul>	<ul style="list-style-type: none"> <li>• High tooling cost that may exceed \$50,000</li> <li>• Long lead times of up to 12 weeks</li> </ul>

## **The Investment Casting Process for Rapid Prototyping**

### **The Conventional IC Process**

In the conventional production of IC parts, each wax pattern has wax gating and vents attached to it by wax welding. One or more of these subassemblies is attached to what is called a tree and shelled with several layers of ceramic, starting with a colloidal silica binder and fine grained fused silica, then finished with courser grains of silica layers. These layers are air-dried between applications. After the shell has dried the tree is placed in an autoclave to melt out the wax. Inside the chamber of the autoclave, high pressure, super-heated steam penetrates the shell and immediately melts the wax, leaving a hollow shell.

### **RP Pattern Process using ABS**

In the case of RP, wax gates and vents are attached to the ABS pattern by the foundry. The part is then coated with layers of ceramic, as described in the normal production of IC. At this point, the process is different. The shell is placed into a flash fire furnace where temperatures reach upwards of 2000 °F (1093 °C), and the pattern combusts, giving off gas and possibly leaving a small amount of ash in the hollow shell mold. The gates and

vents allow gas to escape the mold during burn-out and allow molten metal to be poured into the mold.

An autoclave may not be used because the ABS thermoplastics *does not* melt at those relatively low temperatures.

The shells are removed from the furnace and inspected for cracks and residual ash. If any ash remains it is removed by rinsing or high pressure air. Vents need to be patched and any cracks repaired. From this point on, apart from having to re-heat the molds, there is no difference in the process than if wax were being used.

## Material Properties of ABS

The following tables outline the material properties of ABS. Table 2 is a generic grade of ABS, while Table 3 is product data from Stratasy, Inc.

**Resin** (generic name: *acrylonitrile-butadiene-styrene*)

**Table 2. ABS<sup>1</sup>**

Density	0.038 lbs/in <sup>3</sup>
Specific volume	26.3 in <sup>3</sup> /lb
Flexural strength	10,000 psi
Flexural modulus	320,000 psi
Yield strength	5,700 psi
Tensile modulus	320,000 psi
Compressive strength	7,000 psi
Shrinkage	0.005/in/in
Coefficient of linear thermal expansion	$5.0 \times 10^{-5}$ (0.00005) in/in/°F
Coefficient of thermal expansion	$5.3 \times 10^{-5}$ (0.000053) in/in/°F
Melt temperature	440-510 °F
Heat Deflection Temperature (HDT)	180 °F

**Table 3. FDM ABS<sup>2</sup>**

Specific gravity	1.05 gm/cm <sup>3</sup>
Tensile strength	5,000 psi
Tensile modulus	360,000 psi
Elongation	>10%
Flexural strength	9,500 psi
Flexural modulus	380,000 psi
Notched Impact	2.0 ft-lb./in
Hardness	78 D
Softening point	220 °F (Vicat)
Coefficient of linear thermal expansion	$5.0 \times 10^{-5}$ (0.00005) in/in/°F

## Laboratory Tests

Tests were conducted on FDM ABS samples to determine the characteristics during typical foundry processes. Samples were sent to three laboratories who provided data relevant to the pattern burn-out process. These tests included typical expansion and thermal decomposition and ash content.

### Thermal Expansion

Thermal expansion testing was provided courtesy of Ransom and Randolph<sup>3</sup> who offered their technical expertise and equipment. The tests were conducted to understand the relationship between ABS material expansion and temperature. An Orton dilatometer, was used to measure the changes in length over a temperature range up to 2912 °F (1600 °C). Samples are loaded into a holder where a quartz push-rod applies a small load as the temperature is elevated. The equipment plots the percent linear thermal expansion versus temperature.

ABS samples were built using an FDM 2000. The geometry built was a cylinder .75-in. and .5-in. in diameter by 2-in. in length. Two different build orientations, horizontal and vertical, were also used to simulate the extremes of the pattern's part build style:

- lot #1 — .75-in. diameter, 2-in. length, vertical orientation
- lot #2 — .5-in. diameter, 2-in. length, vertical orientation
- lot #3 — .5-in. diameter, 2-in. length, horizontal orientation

The results of their tests are shown in Table 4.

**Table 4. Percentage of Linear Expansion**

Lot #	Temp °C (F)	Max. % linear expansion	Temp. at expansion decline °C (F)
1A	95 (203)	0.35	180 (356)
1B	95 (203)	0.2	192 (378)
2A	95 (203)	0.28	147 (297)
2B	102 (216)	0.24	178 (352)
3A	97 (207)	0.22	105 (221)
3B	102 (216)	0.22	130 (266)
3C	110 (230)	0.16	140 (284)

Conclusions derived from these tests and from the plots in Appendix A, show that over the range of samples:

- the average percent linear expansion was 0.24% or 0.0024-in./in.
- lot #2 samples provided an average expansion amount of 0.24% (0.0022-in./in.)
- lot #3 samples provided an average of .19% (or .0019-in./in.) at similar temperatures.
- when lots #2 and #3 were compared (the same diameter, but opposite orientations) the results did not differ appreciably.

The plots also suggest that between 221-352 °F (105-178 °C) the ABS samples reached the softening point where there was a decline in expansion. These test results demonstrate the low expansion rates of the ABS material.

### **Comparison with Epoxy**

Solid ABS material expands at a smaller rate than epoxy. These tests showed that the average expansion rate is 0.24%, while the maximum expansion of solid ABS is less than 0.35% (0.003-in./in.). Solid epoxy expands linearly with temperatures, and at 482 °F (250 °C) it reached 3.5% (0.035-in./inch)<sup>4</sup>, which is the reason SL resin parts must be semi-hollow and fully drained before they are investment cast.

### **Thermal Decomposition**

The following tests were conducted by Schenectady Materials and Processes Laboratory, Inc. located in Schenectady, New York. The purpose was to determine the temperature at which the ABS material burned-off and if there was a difference between air and an inert atmosphere.

Thermogravimetric analysis (TGA) was used to measure the weight loss of samples as the temperature was increased. TGA measures the change of mass in a sample as it is heated. The significance of measuring the mass for this particular application is that it represents the decomposition temperature after being subjected to varying temperatures, as well as the amount of residual ash. In this experiment, the temperature range was from 32 to 1832 °F (0 to 1000 °C). The TGA results, shown as plots in Appendix B, indicated the following:

- there was greater decomposition and less ash produced by burning ABS in air, when it is in the presence of oxygen, than without air using an argon atmosphere
- complete decomposition occurred at lower temperatures in air than in argon
- the amount of ash was only slightly different between the two atmospheres at higher than 1832 °F (1000 °C)

Table 5 summarizes the TGA results. Note that in oxygen, 95% of the sample had burned-off between 572 and 752 °F (300 and 400 °C). The remaining material was burned-off at 1067 °F (575 °C). The argon atmosphere yielded a result of 87% at 842 °F (450 °C) and 2% at 1067 °F (575 °C). At 1832 °F (1000 °C) in the argon atmosphere, while there was no ash visible, the instrument did show 1%. The sample size was .4 oz., which is small and most likely contributed to the zero (0.0%) reading.



**Table 5. Ash Content at Different Temperatures**

Temperature °F (°C)	% Ash in Argon	% Ash in Oxygen
842 (450)	13	5
1067 (575)	2	0
1000 (1832)	1	0

## **Residual Ash**

An additional test was conducted to characterize the amount of residual ash produced during the burn-out cycle. Howmet Research Company provided the following results:

- A standard sample size of 4 oz. of ABS was burned at a temperature of 1472 °F (800 °C) for a period of one hour. Residual ash was measured to be 0.021%, which is below the 0.05% specification for this type of material<sup>5</sup>.

## **Emissions**

There are two decomposition materials that are classified as hazardous materials—acrylonitrile and hydrogen cyanide<sup>6</sup>. The combustion temperatures required for 99.99% destruction efficiencies are 1344 °F (729°C) at one second residence and 1328 °F (720 °C) at five seconds residence, respectively<sup>7</sup>.

From the recommended burn-out temperatures (see page 17, “Table 6. Burn-out Sequences from some Foundries”), the decomposition temperatures are exceeded by more than 250 °F (121 °C) at the suggested load temperatures and by more than 450 °F (232 °C) at the burn-out temperature.

Because each location has different regulations, each foundry is responsible for compliance to local standards. This data is provided as information to assist in the compliance process.

## **Ash Morphology**

An ash morphology test was also conducted by Schenectady Materials and Processes Laboratory, Incorporated. Morphology is the study of form and structure. A sample of 40 grams (1.4 oz.) was burnt in a porcelain crucible overnight at 1022 °F (550 °C) to produce ash. Portions of this ash adhered to the sides of the crucible but could be dislodged easily by tapping. Examination under a stereo microscope revealed the ash had a finely divided structure composed of fine particles of a light tan color with darker spots of reddish-brown color. The resulting photograph is shown in Appendix C.

## Foundry Project

This project involved a small number of key foundries, located around the USA, who participated in establishing the use of ABS patterns for RP castings.

### Participants

The following foundries participated in the initial project and donated valuable resources to ensure it was successful. Any one of these foundries has the capability of furnishing quality castings consistent with the supplied pattern. For detailed information about each of these foundries, refer to Appendix D.

Aurora Casting and Engineering, California  
High Tech Castings, Inc., Ohio  
Shellcast Foundries, Inc., Quebec, Canada

BarronCast, Inc., Michigan  
Nu-Cast, Inc., New Hampshire  
Solidiform, Inc., Texas

### Foundry Plan

The foundry project included two phases.

#### *Phase I*

The purpose of Phase I was to reach an agreement with a select group of IC foundries to participate in the test project. Selection was based on: (a) their prior expertise in RP, (b) whether they were willing to invest in R&D, and (c) their diverse locations. Two groups of foundries were selected—ferrous and non-ferrous. An industry defacto standard part design was used since it could be benchmarked against other RP materials. This phase concluded by having the following questions answered:

- Does it work?
- Is an acceptable part produced?
- What needs to be changed?

Since most of the selected foundries had prior experience getting started in RP, and all had used a similar part known as the *Boeing door bracket*, it was determined that the bracket should be used as a starting point. The features of this geometry make it a safe part—there are no thin sections and it is not subject to warpage. Each foundry was supplied with five patterns. Actual experiments by the participating foundries yielded 27 parts. All the shelled parts produced a metal cast part (see Photo 1).



**Photo 1. Test Part 1 Results**

*bottom row, left to right:*

Solidiform–aluminum, High Tech Castings–aluminum, High Tech Castings–brass,  
Aurora Cast–stainless steel,

*top row, left to right:*

Nu-Cast–aluminum, ABS Pattern, BarronCast–carbon steel

### *Phase II*

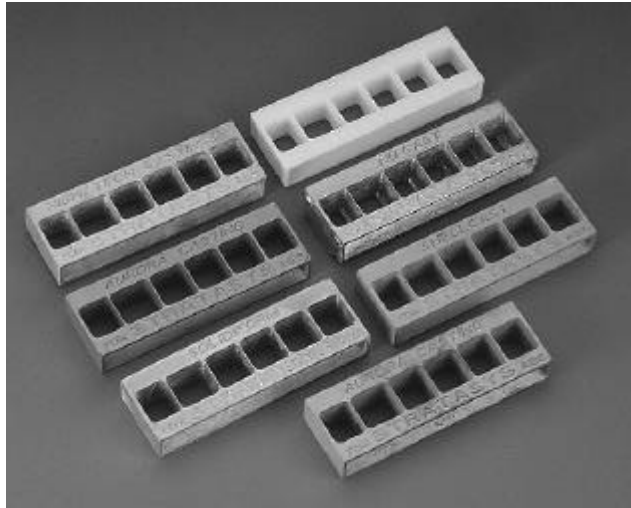
The purpose of Phase II was to design two test parts that best characterized users needs and have the foundries use them to obtain casting data and tune their process.

### **Thinwall Test Part**

The first part was also a derivative of an industry standard test case called the *Thinwall* part. This design tested FDM’s capability to build consistent wall thicknesses, plus test the ability of foundries to cast thin sections. This part was designed with thin wall features of 0.025-in., 0.035in., 0.04-in., 0.05-in., 0.07-in. and 0.1-in. Because ABS parts do not need to be hollow, there is no restriction on wall thickness for drainage. Each set of parts was embossed with the individual foundry name so it could be used as a show piece.

A total of nineteen parts were produced from five foundries. In this phase, one of the foundries decided not to cast any more experiments, citing the desire and capability to work directly with customer parts.

Photo 2 shows the results from the foundry tests. These parts demonstrate the capability of casting the thin wall features. While these parts were designed to test specific capabilities, it should be noted that the industry standard wall thickness is typically .060-in.



**Photo 2. Thin Wall Test Part Results**

*from top to bottom, left to right:*  
 High Tech Castings—aluminum, ABS part  
 Aurora Cast—stainless steel, Nu-Cast—aluminum  
 Solidiform—aluminum, Shellcast Foundries —aluminum  
 Aurora Cast—beryllium copper

### **Wedge Test Part**

The design for the second part was derived from a sketch supplied by a participating foundry. Features included a spline, holes to test shrink rates and a sharp tapered edge. This part was also measured to assess shrinkage rates of the different foundry processes (Photo 3).



**Photo 3. Wedge Test Part Results**

*from top to bottom, left to right:*  
 ABS Pattern  
 Shellcast Foundries—aluminum, Solidiform—aluminum  
 Aurora Cast—stainless steel, High Tech Castings—aluminum

One finding in the tapered edge feature, showed that shell break-down was experienced by several of the foundries. All other part features were cast successfully. The tapered knife-edge is one of the most challenging types of geometries to cast, regardless of pattern material, and is not a good design practice. It should be avoided when producing IC designs(Photo 4).



**Photo 4. Wedge Test Part Results (close-up)**

In addition to the feature capability test, these parts were measured to characterize the shrink rates. The average shrinkage for similar parts from each foundry varied from 1.10%, 0.63%, 0.76%, and 0.71%. This was to be expected since there was dissimilarity between shell systems, burn-out cycle and gating. Foundries using RP patterns determine the shrinkage to apply for specific configurations. The tables shown in Appendix E document the specific dimensional shrinkage calculations.

## Foundry Comments

The following paragraphs are quotes from a questionnaire that asked for comments from Solidiform, Inc., after working with ABS patterns.

“ABS is one of the cleaner materials to process through a burn-out cycle. The material does not leave any residue ash attached to the shell surfaces. The ash produced by the material can be easily blown clear of the mold cavity.”

“ABS build style material has several advantages over the other current RP systems in use at this time, from the foundry point of view. These advantages include:

- Dimensional stability in different moisture environments
- Maintenance of stiff wall integrity under different moisture environments
- There is no requirement for pressure testing each part before processing
- The ABS material reduction process during the burn-out cycle produced a better shell cavity—by not leaving the ash residue attached to cavity surfaces that is experienced with some other RP systems

Although, ABS build style material does have one major disadvantage. The surface layer and build style definition produces a very rough surface condition.”

## Customer Results

The following two companies have successfully produced IC from ABS patterns.

### **Biomet Inc.**

Biomet is a medical company located in Warsaw, Indiana. Biomet designs and manufactures joint replacement devices including knees, hips, etc. They have utilized ABS patterns to generate IC since the second quarter of 1997. To date they produce over 50 castings a month of cobalt chrome or 17-4 stainless steel materials in a company-owned foundry. Cycle times have resulted in a reduction to two weeks to produce these preproduction castings, at an annualized cost savings of \$120,000. Photos 5 and 6, shown on the following page, demonstrate several of their parts.



**Photo 5. ABS IC pattern for an elbow (with gating) and two knees (Biomet).**



**Photo 6. Example of two cobalt chrome knee implant investment castings (Biomet).**

## Hydro Quebec

Hydro Quebec is the principle electrical power company in Quebec, Canada. They have been producing IC since the third quarter of 1997. The following examples, (Photo 7 and 8), show a set of six ABS parts that were cast at Shellcast in Montreal, Canada.



Photo 7. ABS Patterns (Hydro Quebec)



Photo 8. Aluminum Investment Castings from ABS Patterns (Quebec Hydro)

## Foundry Guidelines

This section generalizes the actual foundry processes. In reality, each foundry uses a different process because of their equipment, capabilities, experience, requirements and personnel.

### Pattern Preparation

Wiping the ABS pattern with 90% grade or higher isopropyl alcohol (IPA) may be used to remove residue oils. Hydrocarbon solvents that might be used by foundries for wax patterns might soften an ABS pattern and should not be used.



## Gating and Venting

Gating and venting considerations are very important to the success of the IC casting. Although ABS is a thermoplastic and can be re-melted it must be burned out to rid the shell of all traces of plastic by combustion. For proper combustion to occur, air must get inside the investment through properly placed gates and vents. The gates and vents are also necessary to provide passages for the ash removal.

## Shelling

Thermal expansion experiments have shown that ABS expands up to a maximum of 0.35% at approximately 212 °F (100 °C), at which point it levels off. After 257 °F (125 °C), melting starts to occur. Therefore, the shell must withstand these conditions.

## Burn-out

The burn-out procedure varies with different foundries. In general, the furnace is preheated to about 1600°F (871 °C) then loaded with the shells. The temperature is ramped up to 1950–2050 °F (1066–1120 °C) and held between 50 minutes to 2 hours, depending on the foundry.

Table 6 shows burn-out sequences that have been used by three foundries.

**Table 6. Burn-out Sequences from Some Foundries.**

Foundry	Pre-heat & load	Ramp to:	Hold	Cooling
A	1600 °F (871 °C)	1950 °F (1066°C)	1.5 - 2 hr.	Natural over night
B	1600 °F (871 °C) for 10 minutes	2050 °F (1120 °C)	50 mins.	1600 °F (871°C) remove to cool
C	Ambient	1800 °F (982 °C)	3 hr.	Natural over night
D	1900 °F (1038 °C)	1900 °F (1038 °C)	2 hr.	–

## ABS Part Build Preparation

The following information is for the individual who produces ABS patterns.

### Model Techniques

This report demonstrates the capability of using solid ABS parts or patterns in the IC process. Hollow parts may also be used. Hollow parts offer the advantage of building faster with a smaller mass to burn-out.

### Part Design

All parts that are to be cast require good design techniques for manufacturing. This includes working with the foundry to establish part sizes, wall thicknesses, minimum feature size, the addition of fillet radii and the elimination of sharp corners and knife-edges.

## Shrinkage

All ABS patterns must be supplied in a larger size to compensate for the metal shrinkage. Consult with the foundry regarding the specific required shrinkage factor. This factor will vary for each foundry, due to process and equipment differences.

## Finishing Techniques

Castings produced to date indicate there is exact surface reproduction, which is good for its feature replication ability, but likewise a detriment because it captures layer formation and any defects due to the building process. Usually defects are negative—there are imperfections protruding into the part and are captured by the first shell coat applied, and is therefore replicated in the casting.

It is obvious that any RP surface will never be as good as a wax pattern from a mold. Manual intervention is absolutely necessary to provide an acceptable part. The surfaces can be smoothed by filling (patching) and or by removal of marks (sanding). To help, Stratasys has produced a publication called *Model Finishing Techniques*. You can use practically any filler, including wax and spray epoxy. You should not use any oil based materials since it is detrimental to the shelling process.

The following photograph is an example of improved part surface finishes that may be obtained through different methods. These methods include sanding, wax filling and sandblasting.



**Photo 9. Surface Finish Improvements**

*left to right: Aurora Cast—stainless steel, Solidiform—aluminum*

## Additional Considerations When Obtaining a Casting

This section is provided for users of FDM new to IC and offers guidelines for working with a foundry.

The first step is to select a foundry and consult with them about your plan. The foundry will ask for part details. If they have STL file viewing and editing software like SolidView<sup>®</sup>, Magics<sup>™</sup> or Imageware<sup>®</sup>, you can transmit an STL file of the part design

over the network. Otherwise, fax a dimensioned drawing that includes sections through the part, volume, accuracy, and finish desired.

Without input from a foundry, not all parts can be cast successfully. Normally, designs are filtered by the time they are cast. Foundries make quotes and moldmakers design and build the wax mold tooling. These measures ensure castability. The RP process has the potential of short cutting this process, which is good for the time and cost aspect, but problematic to the foundry. Part designers normally do not know IC requirements. Concurrent engineering principles with the foundry tend to solve this problem.

Currently only the foundries listed in this report (Appendix D) have proven their capability but many others are probably just as capable. Base your selection criteria on metal to be cast, geographic location, and your relationship with the foundry staff.

Once you have reached an agreement, the foundry will supply you with the part shrinkage they require. The ABS part must be built to include the part shrinkage. Another consideration to discuss includes small holes for hole size. The foundry will indicate what is the minimum size that can be cast. Options are to fill the hole or just leave a dimple as a witness mark for drilling.

Additional ABS patterns will need to be supplied to the foundry. The foundry will use these as test cases to ensure proper shrink rates and establish gating and venting techniques.

Finally, the cost of a casting from an RP pattern is typically more than casting from a wax tool. The foundry needs to account for hard work and special processing requirements for their parts.

## **Conclusions**

ABS is a suitable material for RP investment casting patterns. Each of the foundries that participated demonstrated capabilities to produce acceptable investment castings from the ABS patterns.

Patterns built from ABS offer a number of quality advantages over patterns made by other RP processes: Clean burn-out, robustness, the ability to be handled without damage, dimensional stability and ease of pattern preparation. Surface finish preparation of the pattern is important to achieve the best results. Materials that have been cast include 17-4 stainless steel, aluminum, cobalt chrome, brass and beryllium copper.

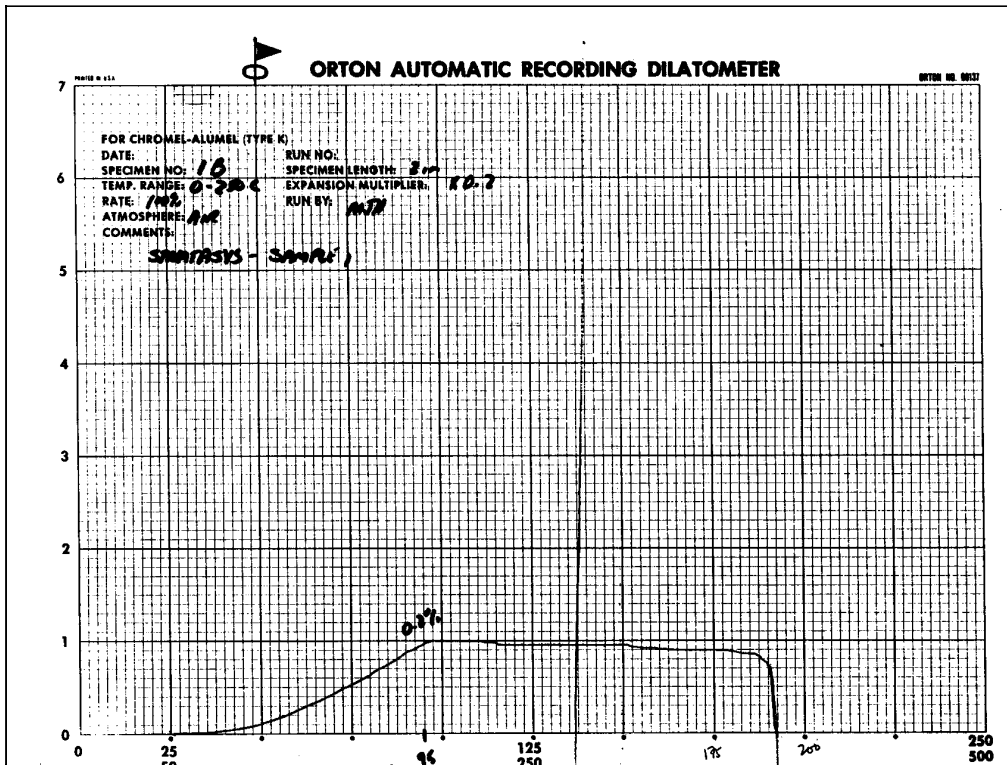
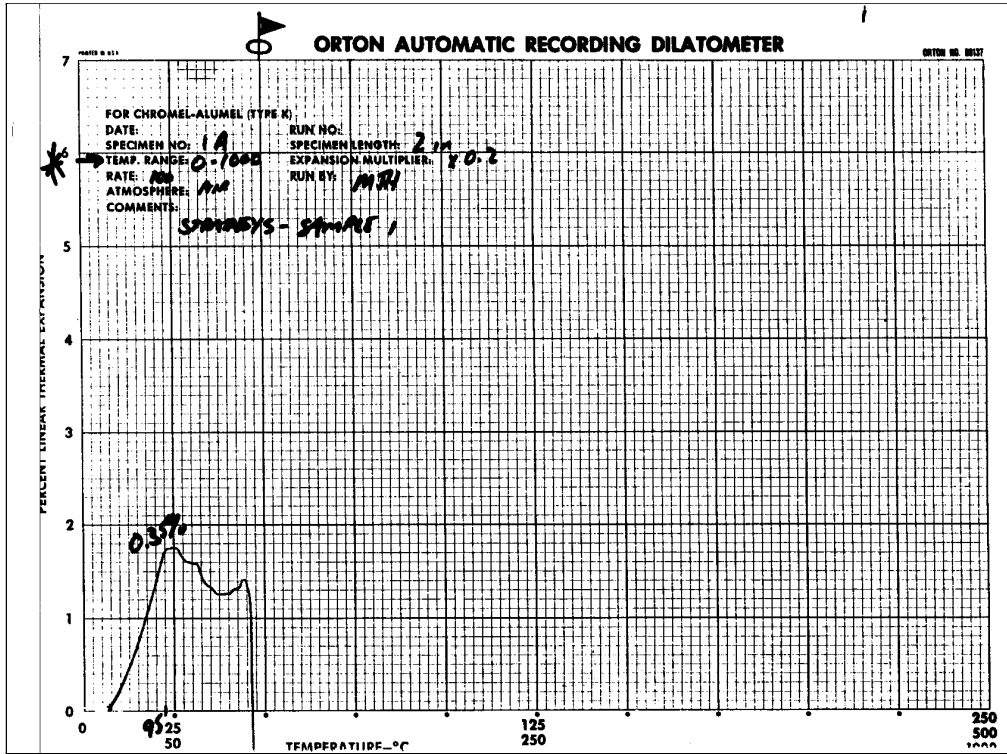
*Stratasys, Inc. wishes to thank all of the foundry participants for their cooperation, test results, and photographs that were an essential part of this report.*



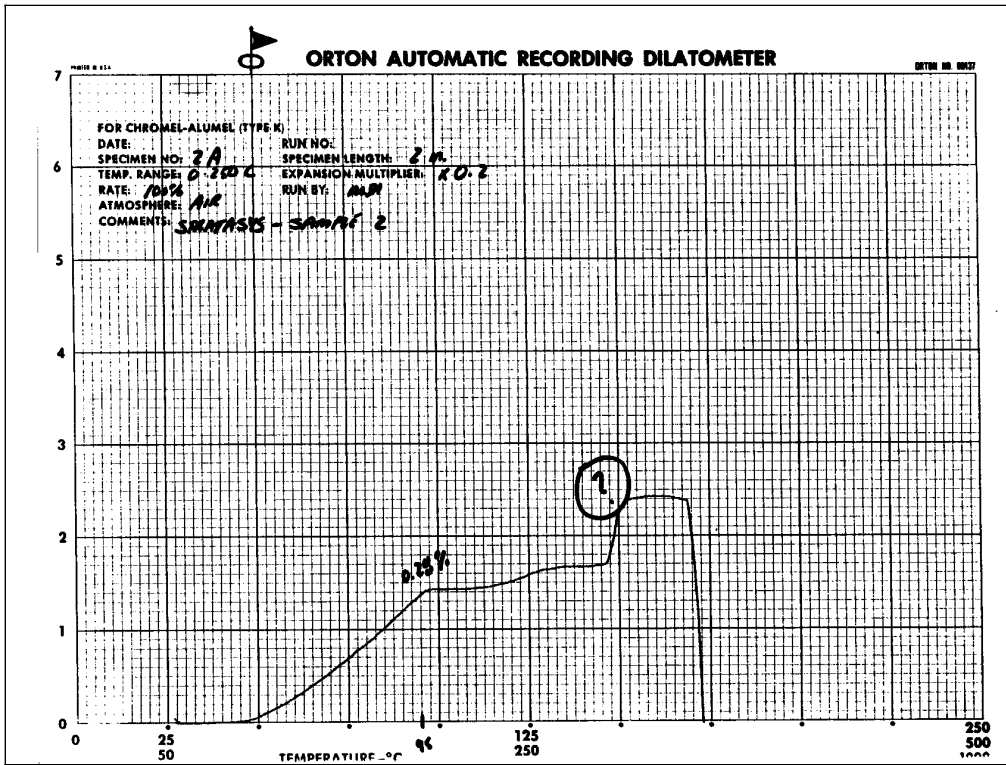
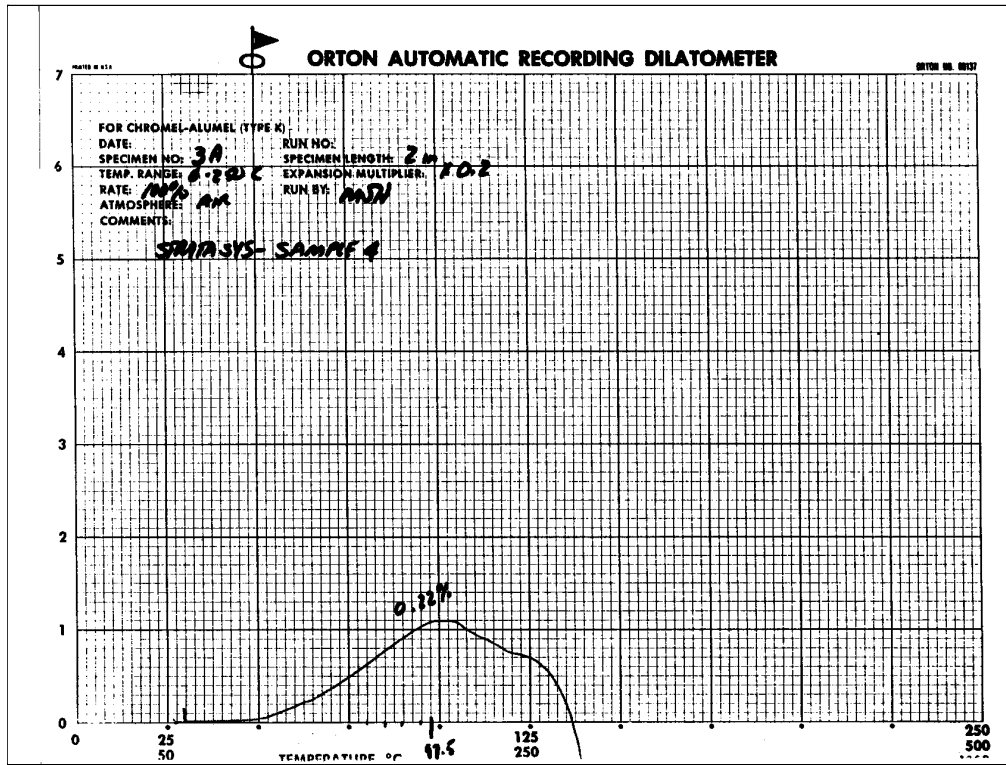
# Appendices



# Appendix A

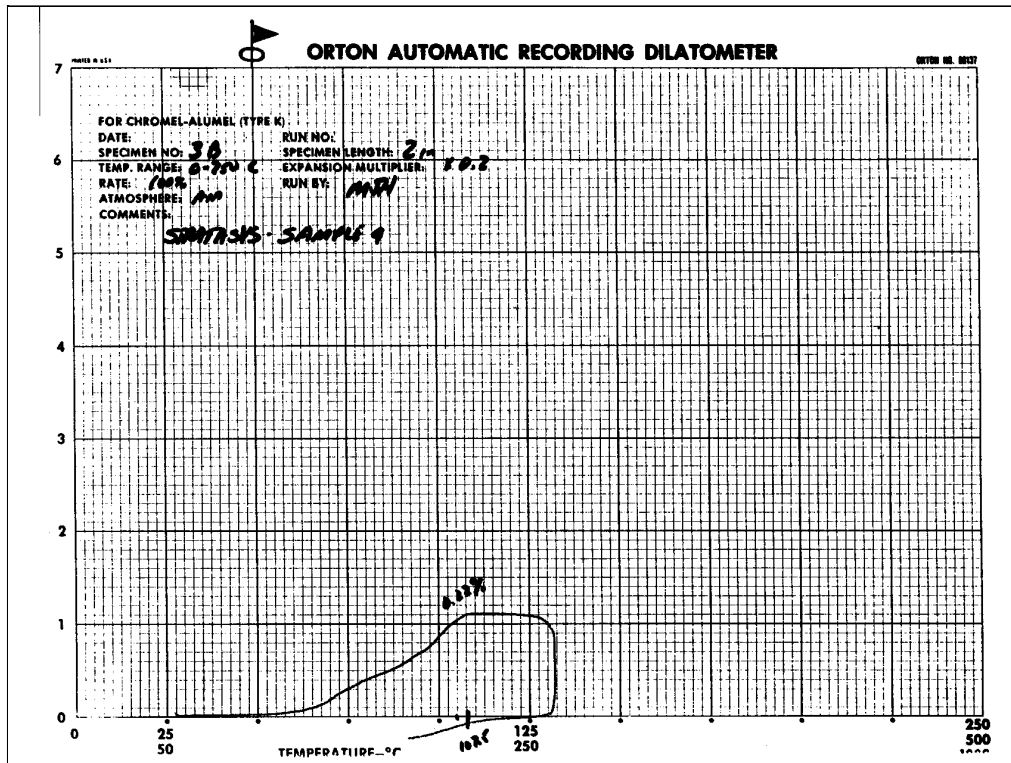
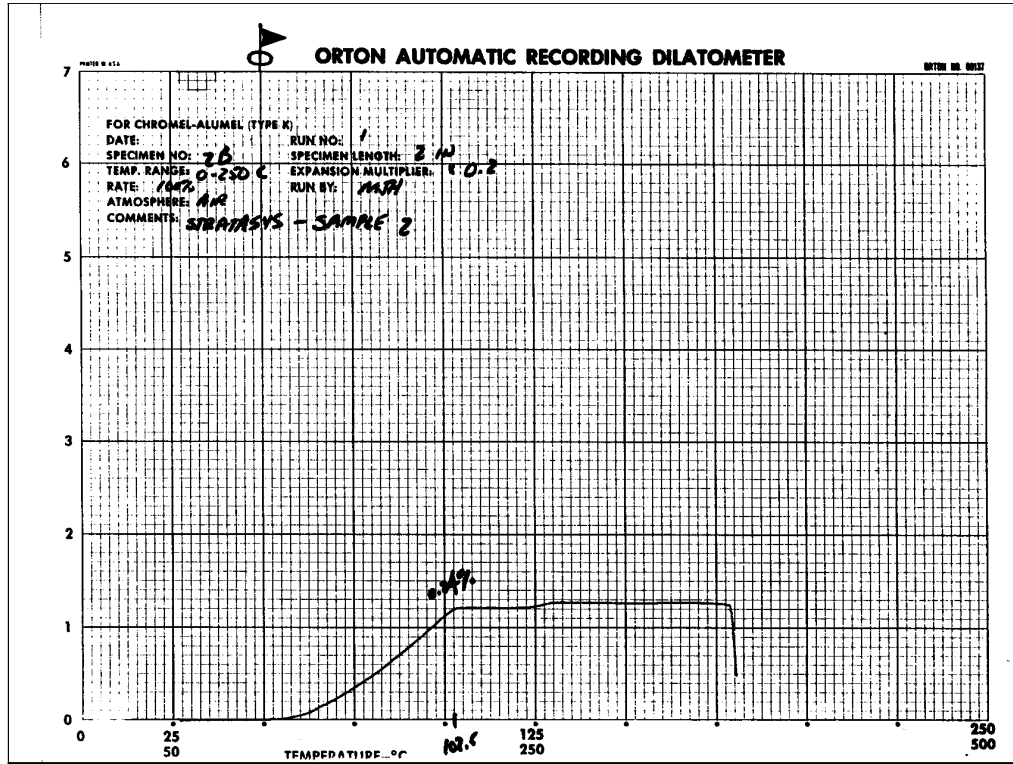


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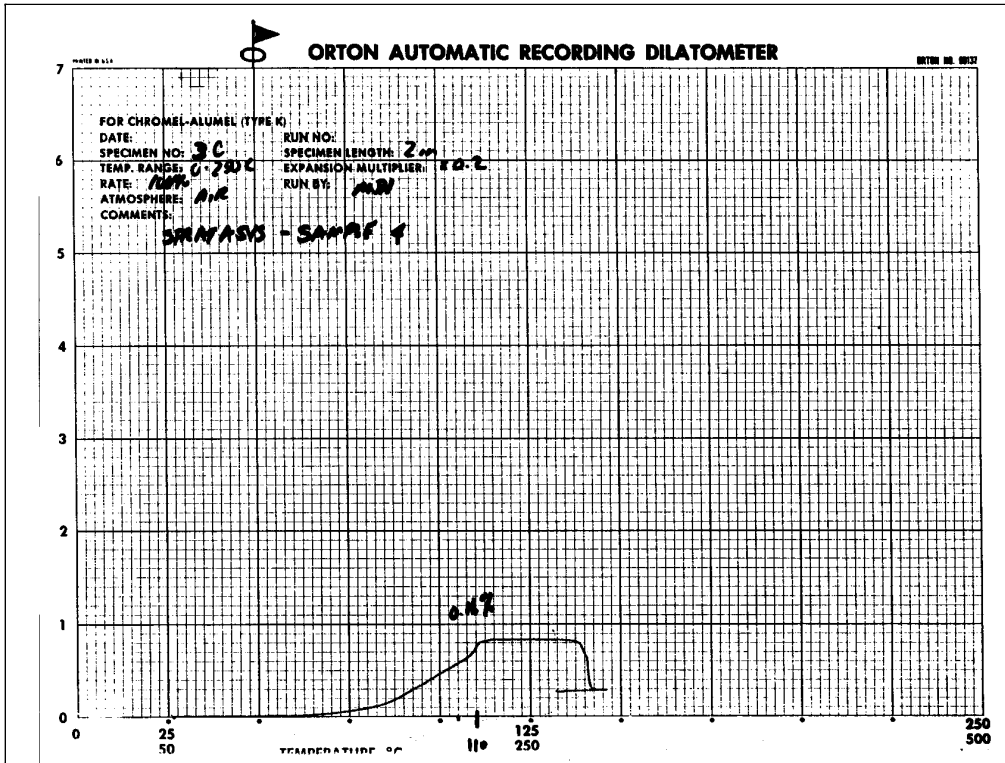




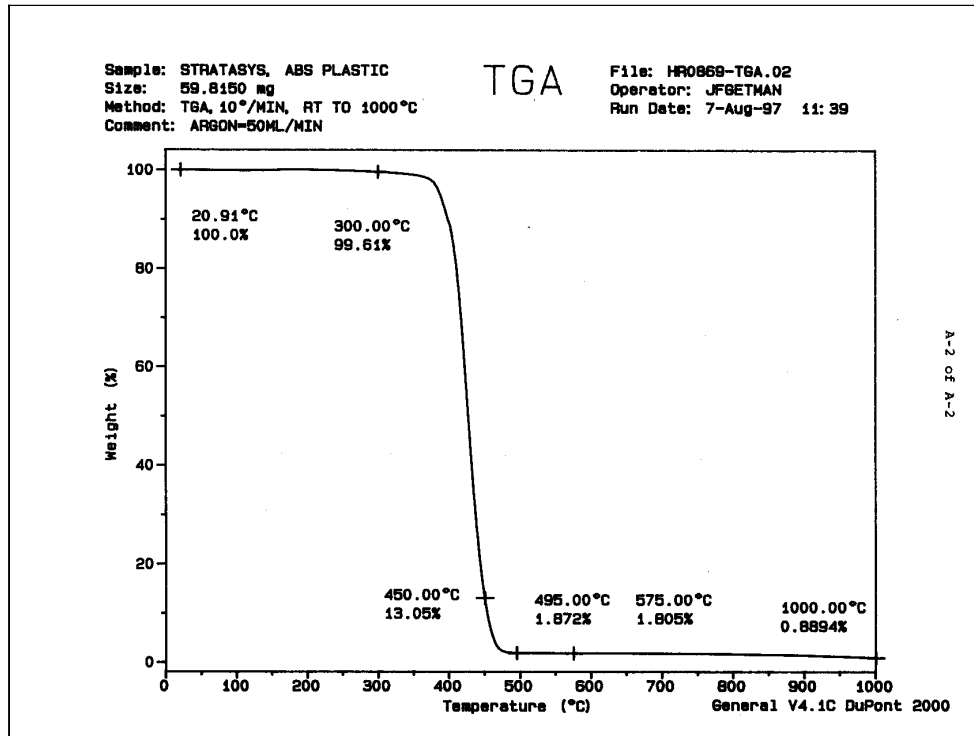
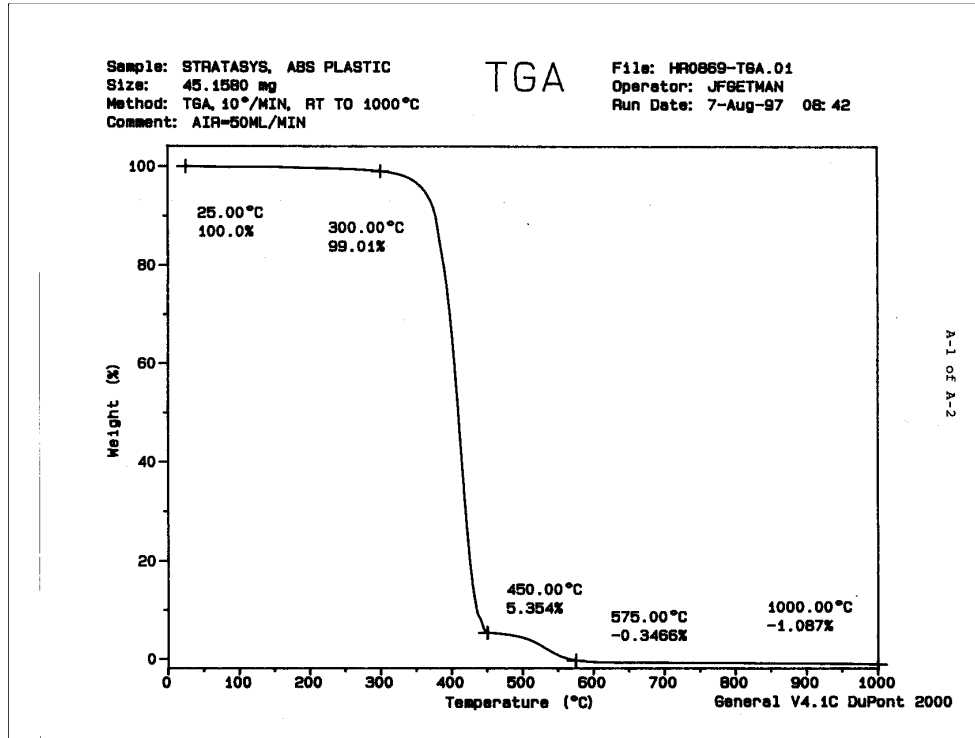
Appendix A (continued)



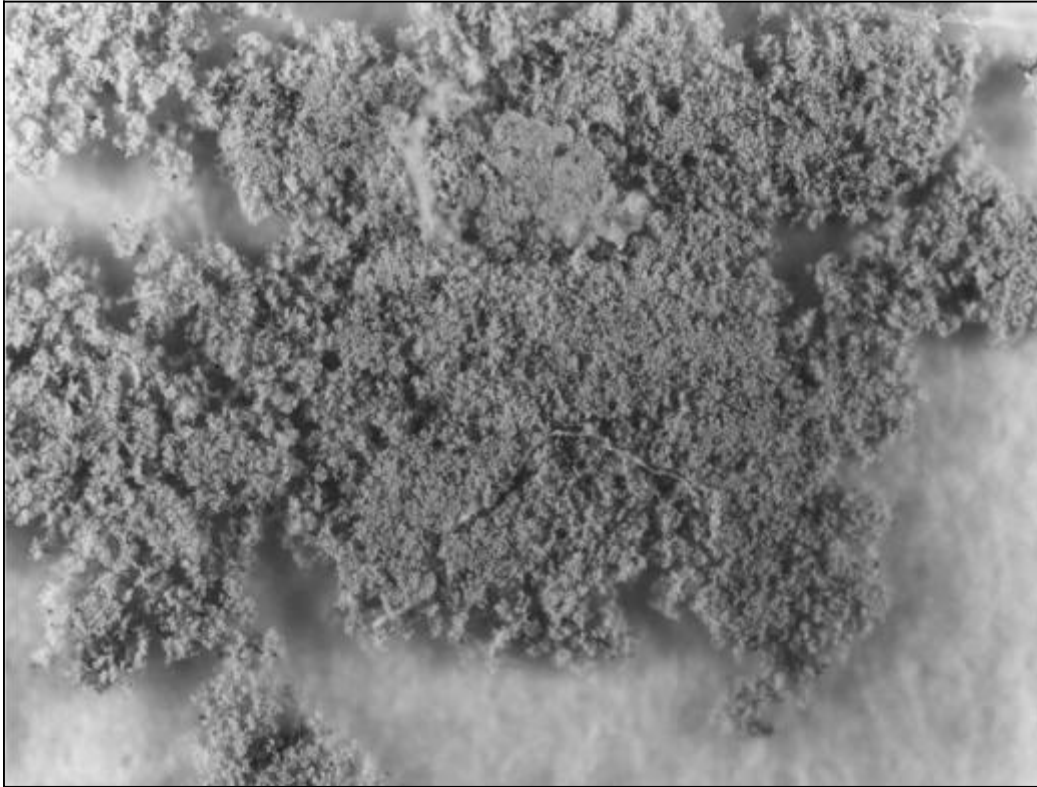
# Appendix A (continued)



# Appendix B



## Appendix C – ABS Ash



## Appendix D - Foundry Project Participants

<p><b>Aurora Casting and Engineering</b>  <b>Frank Penrose</b> – <i>President</i>  <b>Steve Fichter</b> – <i>General Manager</i>            1451 East Main St.            Santa Paula, CA 93060            Tel: (805) 933-2761            Fax: (805) 525-5816            E-mail: <a href="mailto:RunWizard@aol.com">RunWizard@aol.com</a>            Max. part size: 12" x 12" x 12" with gating            Metal cast: Aluminum and steel/copper              base            Years in RP business: 2            Type of CAD software: None            Type of STL viewer: SolidView            Delivery schedule: 3–4 weeks            Foundry equipment: Conventional            No. of RP parts cast: 200+ RP, 50 production parts</p>	<p><b>BarronCast, Inc.</b>  <b>Paul Barron</b> - <i>President</i>            411 North Oxford Road            P.O. Box 138            Oxford, MI 48371            Tel: (517) 628-4300            Fax: (517) 628-3810            E-mail: <a href="mailto:sales@barroncast.com">sales@barroncast.com</a>            Metal cast : Ferrous &amp; non ferrous</p>
<p><b>High Tech Castings, Inc.</b>  <b>Bill Storey</b> - <i>President</i> , <b>Dan Gaier</b> - <i>Engineer</i>            12170 Milton-Carlisle Rd.            P. O. Box 10            New Carlisle, OH 45344            Tel: (937) 845-1204            Fax: (937) 845-1016            E-mail: <a href="mailto:douggaier@htc-inc.com">douggaier@htc-inc.com</a>            Max. part size: 12' x 18" x 12"            Metal cast: Aluminum, investment &amp; plaster              Years in RP business: 12            Type of CAD software: Autocad, Rel. 14            Type of STL viewer: SolidView            Delivery schedule: Advise with quote            Foundry equipment: Pacific Kiln flash fire de-wax furnace              Other: Patterns sealed with paste wax</p>	<p><b>Nu-Cast, Inc.</b>  <b>Don McKitterick</b> - <i>President</i>, <b>John Bowkett</b> - <i>Sales</i>            29 Grenier Field Rd.            Londonderry, NH 03053            Tel: (603) 432-1600            Fax: (603) 432-0724            E-mail: <a href="mailto:nci@grolen.com">nci@grolen.com</a>            www.nu-cast.com            Max. part size: Up to 50" x 50" x 50"            Metal cast: A354,5,6,7 Aluminum Beryllium Aluminum              Years in RP business: 3            Type of CAD software: Pro-E, CadKey            Type of STL viewer: SolidView            Delivery schedule: 1-2 weeks            Foundry equipment: Conventional            No. of RP parts cast: 2,000</p>
<p><b>Shellcast Foundries, Inc.</b>  <b>Bob Pearson</b>- <i>Sales Manager</i>  <b>Peter Budkewitsch</b> - <i>Plant Manager</i>            10645 Lamoureux Ave.            Montreal- North, Quebec            CANADA H1G 5L4            Tel: (514) 322-3760            Fax: (514) 322-7226            E-mail:<a href="mailto:eng@shellcast.com">eng@shellcast.com</a>, <a href="mailto:paula@shellcast.com">paula@shellcast.com</a> (sales)            Max. part size: Up to 24" x 24" x 24"            Metal cast: Aluminum            Years in RP business: 9            Type of CAD software: Autocad R13            Type of STL viewer: SolidView            Delivery schedule: 3-4 prototype, 10-12 production            Foundry equipment: Conventional            No. of RP parts cast: 5,000 plus            Other: Solid mold also available</p>	<p><b>Solidiform, Inc.</b>  <b>Larry André</b> – <i>Vice President &amp; General Manager</i>            P.O. Box 7656            3928 Lawnwood            Fort Worth, TX 76111            Tel: (817) 831-2626            Fax: (817) 831-8258            E-mail: <a href="mailto:sales@solidiform.com">sales@solidiform.com</a>            E-mail: <a href="mailto:landre@solidiform.com">landre@solidiform.com</a>            Max. part size: 8" x 8" x 14" and 8" x 12" x 24            Metal cast: A356 &amp; A357 Aluminum            Years in RP business: 6            Type of CAD software: (2) Pro-E, -Casting, Mold Rel. 18, (1) Catia 4.1.8, Solidworks 98, AutoCAD R14, SolidView/RP Master 2.1, Imageware Surfacer 7.0              Type of STL viewer: SolidView            Delivery schedule: Sand-3 days, IC-5 days            Foundry equipment: Pacific Kiln flash fire de-wax furnace              No. of RP parts cast: Sand-8000, IC-5,000            Other: Precision sand casting available</p>

## Appendix E - Measurements of Castings from ABS parts

PART Test-2													
DATE 12/21/97													
DESCRIPTION Measurements of castings from ABS parts													
				Part 1		Part 2		Part 3		Part 4		Average	Average
Dwg. location	Dwg. type	Reference	Nom dimen	ABS	Cast alu.	ABS	Cast alu.	ABS	Cast alu.	ABS	Cast alu.	of castings	of ABS
L/H top	Y dim	1	4	3.997	3.985	4.002	3.970	4.000	3.985	4.003	3.969	3.972	4.001
	X dim	2	1.13	1.120	1.110	1.123	1.111	1.121	1.110	1.123	1.112	1.111	1.122
	Dia	3	0.75	0.730	0.746	0.730	0.740	0.728	0.750	0.730	0.750	0.747	0.730
	Dia	4	1.25	1.235	1.223	1.230	1.220	1.233	1.220	1.230	1.222	1.221	1.232
Top center	Y dim	5	2.75	2.745	2.723	2.748	2.723	2.742	2.722	2.750	2.723	2.723	2.746
	Y dim	6	1.75	1.747	1.725	1.746	1.728	1.749	1.728	1.751	1.627	1.702	1.748
	Y dim	7	1	0.998	0.984	0.998	0.988	0.995	0.983	0.999	0.985	0.985	0.998
	X dim	8	1	0.996	0.985	0.994	0.984	0.996	0.984	0.997	0.985	0.985	0.996
	Dia	9	0.75	0.744	0.742	0.743	0.740	0.744	0.745	0.745	0.742	0.742	0.744
	Dia	10	0.375	0.370	0.369	0.372	0.370	0.370	0.367	0.370	0.370	0.369	0.371
	L/H, X dim	11	0.25	0.248	0.247	0.250	0.245	0.250	0.250	0.250	0.250	0.248	0.250
	R/H, X dim	12	0.25	0.247	0.245	0.245	0.242	0.247	0.245	0.248	0.242	0.244	0.247
Detail 'A'	Dia	13	0.75	0.745	0.742	0.748	0.744	0.745	0.745	0.746	0.740	0.743	0.746
	Dia	14	0.68	0.678	0.670	0.680	0.676	0.678	0.677	0.678	0.675	0.675	0.679
	Spline width	15	0.115	0.115	0.106	0.110	0.105	0.115	0.104	0.115	0.104	0.105	0.114
Lower	X dim	16	2.5	2.448	2.485	2.500	2.494	2.500	2.480	2.500	2.490	2.487	2.487
	Y dim	17	0.5	0.507	0.505	0.508	0.505	0.510	0.505	0.512	0.505	0.505	0.509
	Dia	18	1	0.995	0.988	0.997	0.990	0.995	0.985	0.996	0.988	0.988	0.996

Note: Where a dimension had an upper and lower number, the lower (minimum) was chosen  
 Some measurements were taken where gating was attached producing results derived from hand finishing.

### Casting Data for Test-2 part

Dimension ID	Drawing dimension	Average RP dimension (ABS)	Average casting dimension (alu)	Deviation	% shrink
1	4	4.001	3.972	0.028	0.71
2	1.13	1.122	1.111	0.011	0.98
3	0.75	0.730	0.747	-0.017	-2.33
4	1.25	1.232	1.221	0.011	0.87
5	2.75	2.746	2.723	0.023	0.86
6	1.75	1.748	1.702	0.046	2.65
7	1	0.998	0.985	0.013	1.25
8	1	0.996	0.985	0.011	1.13
9	0.75	0.744	0.742	0.002	0.24
10	0.375	0.371	0.369	0.002	0.40
11	0.25	0.250	0.248	0.002	0.60
12	0.25	0.247	0.244	0.003	1.32
13	0.75	0.746	0.743	0.003	0.44
14	0.68	0.679	0.675	0.004	0.59
15	0.115	0.114	0.105	0.009	7.91
16	2.5	2.487	2.487	-0.000	-0.01
17	0.5	0.509	0.505	0.004	0.83
18	1	0.996	0.988	0.008	0.80
Average				0.009	1.10

## Appendix E - Measurements of Castings from ABS parts (continued)

PART		Test-2											
DATE		11/04/97											
DESCRIPTION		Measurements of castings from ABS parts											
				Part 1A		Part 2A		Part 3A		Part 4A		Average	Average
Dwg. location	Dwg. type	Reference	Nom dimen	ABS	Cast alu.	ABS	Cast alu.	ABS	Cast alu.	ABS	Cast alu.	of castings	of ABS
L/H top	Y dim	1	4	4.000	3.973	3.998	3.964	4.002	3.954	4.000	3.958	3.962	4.000
	X dim	2	1.13	1.125	1.126	1.121	1.113	1.124	1.109	1.125	1.108	1.114	1.124
	Dia	3	0.75	0.750	0.750	0.750	0.747	0.753	0.752	0.750	0.747	0.749	0.751
	Dia	4	1.25	1.245	1.235	1.243	1.234	1.243	1.240	1.243	1.243	1.238	1.244
Top center	Y dim	5	2.75	2.743	2.725	2.751	2.731	2.748	2.719	2.747	2.720	2.724	2.747
	Y dim	6	1.75	1.750	1.737	1.748	1.732	1.745	1.722	1.748	1.729	1.730	1.748
	Y dim	7	1	0.998	0.992	1.001	0.990	0.998	0.987	0.999	0.988	0.989	0.999
	X dim	8	1	0.994	0.992	0.996	0.994	0.996	0.979	0.995	0.986	0.988	0.995
	Dia	9	0.75	0.740	0.740	0.745	0.747	0.746	0.739	0.745	0.740	0.742	0.744
	Dia	10	0.375	0.370	0.365	0.372	0.370	0.372	0.370	0.372	0.367	0.368	0.372
	L/H, X dim	11	0.25	0.250	0.247	0.250	0.250	0.250	0.250	0.250	0.250	0.249	0.250
	R/H, X dim	12	0.25	0.248	0.247	0.250	0.245	0.248	0.245	0.247	0.246	0.246	0.248
Detail 'A'	Dia	13	0.75	0.745	0.742	0.745	0.740	0.748	0.740	0.746	0.740	0.741	0.746
	Dia	14	0.68	0.676	0.675	0.676	0.670	0.679	0.674	0.680	0.675	0.674	0.678
	Spline width	15	0.115	0.116	0.106	0.118	0.106	0.116	0.106	0.115	0.107	0.106	0.116
Lower	X dim	16	2.5	2.500	2.480	2.500	2.480	2.500	2.500	2.500	2.495	2.489	2.500
	Y dim	17	0.5	0.510	0.510	0.510	0.507	0.508	0.522	0.507	0.525	0.516	0.509
	Dia	18	1	0.995	0.988	0.995	0.985	0.997	0.990	0.993	0.999	0.991	0.995

### Casting Data for Test-2 part

Dimension ID	Drawing dimension	Average RP dimension (ABS)	Average casting dimension (alu)	Deviation	% shrink
1	4	4.000	3.962	0.038	0.94
2	1.13	1.124	1.114	0.010	0.87
3	0.75	0.751	0.749	0.002	0.23
4	1.25	1.244	1.238	0.006	0.44
5	2.75	2.747	2.724	0.024	0.86
6	1.75	1.748	1.730	0.018	1.02
7	1	0.999	0.989	0.010	0.98
8	1	0.995	0.988	0.007	0.75
9	0.75	0.744	0.742	0.002	0.34
10	0.375	0.372	0.368	0.004	0.94
11	0.25	0.250	0.249	0.000	0.30
12	0.25	0.248	0.246	0.003	1.01
13	0.75	0.746	0.741	0.005	0.74
14	0.68	0.678	0.674	0.004	0.63
15	0.115	0.116	0.106	0.000	0.00
16	2.5	2.500	2.489	0.011	0.45
17	0.5	0.509	0.516	0.000	0.00
18	1	0.995	0.991	0.004	0.45
Average				0.008	0.63

#### NOTES:

- 1) Deviation is from ABS part dimension
- 2) Dim #15 is the spline width. dev=.01, shrink=8.6. Quite large.
- 3) Dim #17 is the thickness of the base. No explanation for the -ve growth. dev=-.0 shrink=-1.43%
- 4) The above, 15 & 17 have been omitted when calculating averages.

## Appendix E - Measurements of Castings from ABS parts (continued)

PART		Test-2													
DATE		11/25/97													
DESCRIPTION		Measurements of castings from ABS parts													
				Part 1B		Part 2B		Part 3B		Part 4		Average of castings	Average of ABS		
Dwg. location	Dwg. type	Reference	Norm dimen	ABS	Cast alu.	ABS	Cast alu.	ABS	Cast alu.	ABS	Cast alu.				
L/H top	Y dim	1	4	4.001	3.987	4.002	3.991	3.993	3.984	4.001	3.999	3.990	3.999		
	X dim	2	1.13	1.120	1.100	1.122	1.100	1.124	1.097	1.125	1.115	1.103	1.123		
	Dia	3	0.75	0.734	0.730	0.732	0.738	0.728	0.730	0.730	0.773	0.743	0.731		
	Dia	4	1.25	1.243	1.221	1.243	1.230	1.240	1.230	1.240	1.230	1.228	1.242		
Top center	Y dim	5	2.75	2.746	2.734	2.750	2.740	2.743	2.737	2.748	2.743	2.739	2.747		
	Y dim	6	1.75	1.748	1.742	1.749	1.739	1.746	1.743	1.750	1.745	1.742	1.748		
	Y dim	7	1	1.000	0.987	1.000	0.990	0.998	0.995	1.000	0.998	0.993	1.000		
	X dim	8	1	0.997	1.008	0.998	1.015	0.996	1.016	0.995	1.015	1.014	0.997		
	Dia	9	0.75	0.745	0.740	0.745	0.745	0.745	0.740	0.746	0.741	0.742	0.745		
	Dia	10	0.375	0.374	0.370	0.372	0.370	0.373	0.367	0.370	0.369	0.369	0.372		
	L/H, X dim	11	0.25	0.250	0.236	0.246	0.240	0.250	0.242	0.250	0.244	0.241	0.249		
	R/H, X dim	12	0.25	0.247	0.230	0.246	0.240	0.246	0.239	0.250	0.247	0.239	0.247		
Detail 'A'	Dia	13	0.75	0.746	0.738	0.746	0.740	0.745	0.738	0.746	0.730	0.737	0.746		
	Dia	14	0.68	0.676	0.676	0.678	0.675	0.678	0.673	0.680	0.673	0.674	0.678		
	Spline width	15	0.115	0.114	0.113	0.115	0.113	0.114	0.113	0.114	0.113	0.113	0.114		
Lower	X dim	16	2.5	2.497	2.450	2.497	2.478	2.497	2.471	2.500	2.480	2.470	2.498		
	Y dim	17	0.5	0.505	0.500	0.508	0.500	0.510	0.506	0.515	0.513	0.505	0.510		
	Dia	18	1	0.995	0.989	0.995	0.995	0.992	0.985	0.995	0.996	0.991	0.994		

### Casting Data for Test-2 part

Dimension ID	Drawing dimension	Average RP dimension (ABS)	Average casting dimension (alu)	Deviation	% shrink
1	4	3.999	3.990	0.009	0.23
2	1.13	1.123	1.103	0.020	1.76
3	0.75	0.731	0.743	-0.012	-1.62
4	1.25	1.242	1.228	0.014	1.11
5	2.75	2.747	2.739	0.008	0.30
6	1.75	1.748	1.742	0.006	0.34
7	1	1.000	0.993	0.007	0.70
8	1	0.997	1.014	-0.017	-1.71
9	0.75	0.745	0.742	0.004	0.50
10	0.375	0.372	0.369	0.003	0.87
11	0.25	0.249	0.241	0.009	3.41
12	0.25	0.247	0.239	0.008	3.34
13	0.75	0.746	0.737	0.009	1.24
14	0.68	0.678	0.674	0.004	0.55
15	0.115	0.114	0.113	0.001	1.09
16	2.5	2.498	2.470	0.028	1.12
17	0.5	0.510	0.505	0.005	0.93
18	1	0.994	0.991	0.003	0.30
Average				0.005	0.76

**NOTES:**

1) Deviation is from ABS part dimension



## Appendix E - Measurements of Castings from ABS parts (continued)

PART		Test-2												
DATE		04/25/98												
DESCRIPTION		Measurements of castings from ABS parts												
				Part 1E		Part 2E		Part 3E		Part 4E		Average	Average	
Dwg. locatio	Dwg. type	Reference	Nom dimer	ABS	Cast alu.	ABS	Cast alu.	ABS	Cast alu.	ABS	Cast alu.	of castings	of ABS	
L/H top	Y dim	1	4	3.998	3.964	3.993	3.959	3.997	3.963	4.001	3.966	3.963	3.997	
	X dim	2	1.13	1.122	1.112	1.119	1.105	1.120	1.105	1.119	1.104	1.107	1.120	
	Dia	3	0.75	0.750	0.775	0.750	0.748	0.748	0.748	0.747	0.750	0.755	0.749	
	Dia	4	1.25	1.241	1.233	1.245	1.237	1.242	1.233	1.244	1.232	1.234	1.243	
Top center	Y dim	5	2.75	2.743	2.719	2.744	2.714	2.746	2.718	2.751	2.722	2.718	2.746	
	Y dim	6	1.75	1.745	1.723	1.747	1.720	1.745	1.724	1.744	1.721	1.722	1.745	
	Y dim	7	1	0.999	0.984	0.998	0.979	0.998	0.980	0.999	0.982	0.981	0.999	
	X dim	8	1	0.997	0.992	0.996	0.984	0.995	0.989	0.998	0.982	0.987	0.997	
	Dia	9	0.75	0.745	0.742	0.746	0.744	0.746	0.744	0.745	0.744	0.744	0.746	
	Dia	10	0.375	0.372	0.368	0.373	0.368	0.372	0.370	0.370	0.370	0.370	0.372	
	L/H, X dim	11	0.25	0.248	0.244	0.246	0.244	0.250	0.244	0.248	0.240	0.240	0.243	0.248
	R/H, X dim	12	0.25	0.248	0.245	0.247	0.246	0.247	0.248	0.247	0.242	0.245	0.247	
Detail 'A'	Dia	13	0.75	0.745	0.745	0.744	0.744	0.746	0.744	0.748	0.744	0.744	0.746	
	Dia	14	0.68	0.678	0.676	0.678	0.672	0.678	0.676	0.679	0.677	0.675	0.678	
	Spline width	15	0.115	0.115	0.117	0.115	0.114	0.115	0.118	0.115	0.115	0.116	0.115	
Lower	X dim	16	2.5	2.498	2.490	2.497	2.487	2.499	2.484	2.500	2.490	2.488	2.499	
	Y dim	17	0.5	0.507	0.505	0.504	0.503	0.505	0.500	0.507	0.500	0.502	0.506	
	Dia	18	1	0.995	0.990	0.992	0.985	0.995	0.990	0.995	0.986	0.988	0.994	

Note: Where a linear dimension had an upper and lower number, the lower (minimum) was chosen  
The upper limit for holes was chosen.

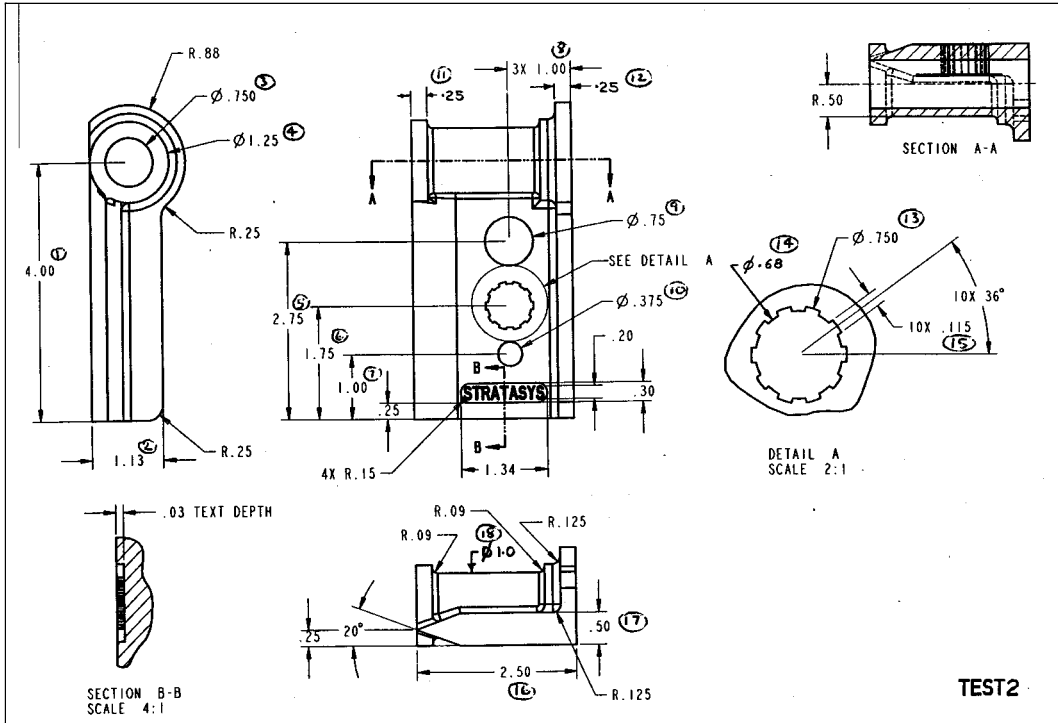
### Casting Data for Test-2 part

Dimension ID	Drawing dimension	Average RP dimension (ABS)	Average casting dimension (alu)	Deviation	% shrink
1	4	3.997	3.963	0.034	0.86
2	1.13	1.120	1.107	0.014	1.21
3	0.75	0.749	0.755	-0.006	-0.86
4	1.25	1.243	1.234	0.009	0.74
5	2.75	2.746	2.718	0.028	1.01
6	1.75	1.745	1.722	0.023	1.33
7	1	0.999	0.981	0.017	1.73
8	1	0.997	0.987	0.010	0.98
9	0.75	0.746	0.744	0.002	0.27
10	0.375	0.372	0.370	0.002	0.61
11	0.25	0.248	0.243	0.005	2.02
12	0.25	0.247	0.245	0.002	0.81
13	0.75	0.746	0.744	0.002	0.20
14	0.68	0.678	0.675	0.003	0.44
15	0.115	0.115	0.116	0.000	0.00
16	2.5	2.499	2.488	0.011	0.43
17	0.5	0.506	0.502	0.000	0.00
18	1	0.994	0.988	0.006	0.65
Average				0.008	0.71

#### NOTES:

1) Deviation is from ABS part dimension

# Appendix F - Wedge Part Dimensions



TEST2

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## References

<sup>1</sup> *Designing with Thermoplastics*, Dow Chemical, 1992.

<sup>2</sup> Stratasys material properties..

<sup>3</sup> Ransom and Randolph – supplier of shell systems and other products to the IC industry.

<sup>4</sup> Loose, K., *Investigation of Optimum Process Parameters for Burnout of SLA Parts*, Institute of Industrial Science, University of Tokyo.

<sup>5</sup> Howmet Research Corporation, communication to Stratasys, INC.-June 1998.

<sup>6</sup> ABS-P400 MSDS Sheet, November 4, 1994.

<sup>7</sup> EPA Handbook, *Control Technologies for Hazardous Air Pollutants*, June 1991.

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