Thermoforming Rohacell for the MVD's Radio Frequency Enclosure

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Abstract

In order to block out unwanted radiation from the MVD's sensitive electronics and to isolate the MVD's environment, a radio frequency shield will be installed around the MVD. The structural component that provides support for the thin foil shielding is made of Rohacell. The Rohacell sheets must be formed into the correct shape in order to be attached to the MVD endplates and not interfere with the beam pipe. The forming process requires the Rohacell to be heated to the point that the molecular bonds in the material weaken, and the sheets can be "molded" into the correct shape. Two adverse side effects of the forming process are Rohacell's tendency to "springback" towards its original shape, and its growth in size at the elevated temperature.

Tests were performed to determine the relationships between the variables involved in forming the Rohacell and the amount of springback and size growth incurred. The results of the tests showed that a major factor contributing to the amount of springback is the rate at which the test specimen cooled down. The faster the cool down rate, the more the springback. The results also suggested that a major factor contributing to the size growth is the method that the specimen is allowed to cool down. If high pressure was put on the fixture used to mold the specimen, then the Rohacell's size growth would be low.

Because the graphs used to draw the conclusions stated above have relatively few data points, it is recommended that more tests be performed at a larger range of variation to ensure reproducibility of the results.

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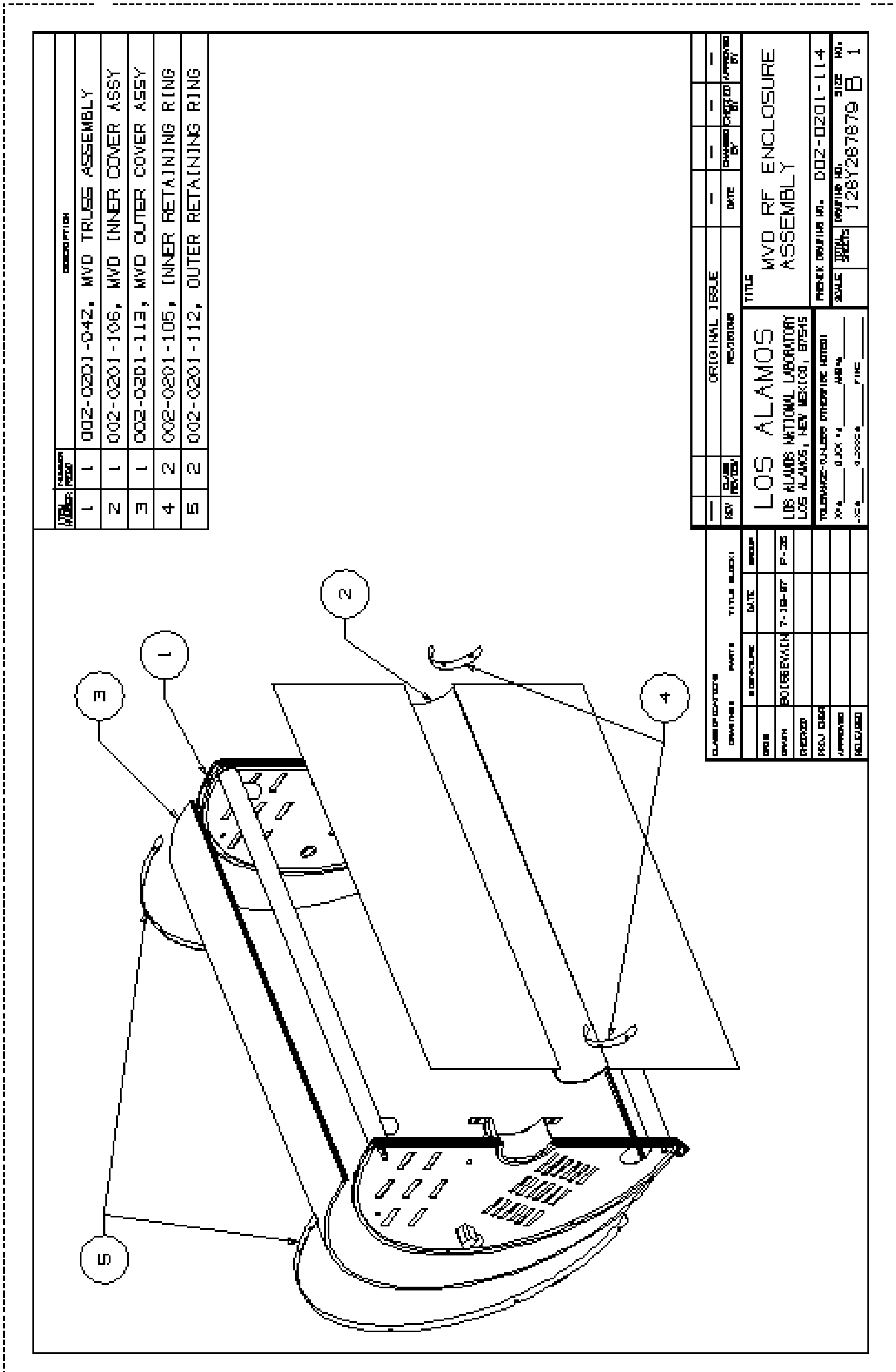


Figure 1: Exploded isometric view of the assembled Radio Freqeuency Enclosure

Introduction

The purpose of this document is to provide general information about the Multiplicity Vertex Detector's (MVD's) inner and outer enclosures, information on the materials used in constructing the enclosures, graphs of the experimental data obtained, and the conclusions drawn from the analysis of the data, which help to determine the optimal procedures for making the enclosures.

The outer and inner enclosures of the MVD must each serve two purposes:

1) They serve as radio frequency (RF) shields to isolate the MVD from outside sources of radio wave radiation. Unwanted radiation waves are constantly entering PHENIX Hall, which houses the MVD. This can cause interference with the MVD's detection of the multiplicity and vertex of the heavy ion collisions. In order to minimize the effects of these waves on the silicon inside the MVD, the radio frequency shields enclose the MVD and block out as many of the radio waves as possible while still allowing the particles resulting from the collision to pass through the shields untouched.

2) They also serve as barriers between the uncontrolled environment of the PHENIX Hall and the MVD's environment. This allows the MVD's environment to be controlled, which in turn allows the electronics inside the MVD to be kept at optimum operation levels as well as ensuring that the mechanical components are not subjected to an unnecessary amount of stress due to outside temperature and humidity variations.

Noting these objectives, a high strength to density ratio foam (Rohacell IG-71) was chosen to be the primary structural component of the enclosures in order to minimize absorption of the heavy ion collisions' particles as well as provide a tough outer covering. Rohacell also has excellent insulative properties which makes it a good material for isolating the temperature outside the MVD from the temperature inside. It is also a good electrical insulator, making it a nice barrier between the RF shields on the inside and outside of each enclosure.

The inner enclosure is referenced in Figure 1 as Item number 2. The flat surfaces are thin sheets of mylar sandwiched between aluminum foil. The cylindrical part is thermoformed Rohacell, which curves with a 45.5mm outer radius around the beam pipe. The outer enclosure is referenced in Figure 1 as Item number 3. It is also thermoformed Rohacell, but with a 290mm outer radius.

The RF shielding is constructed of aluminum. Aluminum was chosen because of it's long radiation length and it's relatively high strength to density ratio.

The material used to attach the RF shielding to the Rohacell is Dielctric Polymer's NT 988-2 Dry Transfer Adhesive. This is one of the few materials found that will effectively adhere aluminum to Rohacell as well as being the easiest to manipulate and the least toxic.

All of the relevant material properties of the enclosure are tabulated in Table 1 below.

Table 1: Materials Used to Construct Outer and Inner Enclosures

Structural Material	Rohacell IG-71 (3mm and 0.25" thick)
- density	75 kg/m^3 [1]
- elastic modulus	90.3 MPa [1]
- compressive strength	1.47 MPa [1]
- flexural strength	2.45 MPa [1]
- radiation length	545 cm [1]
- thermal conductivity (k)	0.03 W/mK [1]
- surface resistance	5500 GΩ [1]
Radiation Shielding Material	Aluminum foil (0.0005" thick)
- density	2.7 Mg/m^3 [3]
- elastic modulus	70 GPa [3]
- radiation length	8.9 cm [2]
Structure to Shielding Adhesive	NT 988-2 dry transfer adhesive (0.002" thick)
- density	1130 kg/m^3 [4]

[1] Rohm Tech, Inc.'s Rohacell catalog. Address: 195 Canal St. Malden, MA 02148 Phone: 1-800-666-7646 Fax: (617)322-0358 Contact: Donald J. Loundy
[2] Particle data book
[3] Crandall et al. *An Introduction to the Mechanics of Solids: Second Edition with SI Units*. McGraw-Hill, Inc. New York, 1978.
[4] Dielectric Polymers, Inc. Address: 218 Race St. Holyoke, MA 01040 Phone: (413)532-3288 Fax: (413)533-9316 Contact: George Bean (chemist)

The Forming Procedure

Rohacell is shipped from its distributor (Technology Marketing Inc.) in flat, sheet form. These sheets must be curved to match the shape of the MVD. In order to minimize cost while maintaining optimal strength, the method chosen to shape the Rohacell is called forming. This method is preferred over machining the Rohacell because it requires much less waste of material and thus much less waste of money. During the forming process, the sheet is brought up to the temperature at which the molecular bonds that give Rohacell its strength start to weaken. This is known as the forming temperature. Once the bonds have been weakened, the sheet can be molded into a different shape. When the desired shape has been obtained, the temperature is lowered. As the temperature is lowered, the molecular bonds reform and the Rohacell regains its original strength, but the new shape remains.

Tests were performed to determine the optimum forming procedure. For this application, the optimum procedure is the one that minimizes the thickness growth and springback that can occur during forming. Thickness growth refers to an increase in the thickness of the Rohacell during forming. Springback is the tendency of Rohacell to return to its original shape instead of the shape it is molded into. These can be problems if the Rohacell grows or springs back so much that it begins to interfere with the electronics on the endplates of the MVD or with the fitting of the two halves of the MVD clamshell together around the beam pipe. Any growth in length and/or width do not matter, because the formed Rohacell enclosure must be machined to the correct length and width in order to fit in the MVD. This process only removes a small amount of material (and thus limits waste) and is needed in order to ensure a good fit after forming.

The Inner RF Enclosure Tests

General Procedure

A general description of the procedure used in most of the inner enclosure forming tests follows:

1) Preheat the oven and fixture used to form the Rohacell to a specified temperature
2) Place the Rohacell inside the fixture in the oven for a specified time, letting the weight of the fixture mold the Rohacell into the desired shape as the molecular bonds weaken
3) Remove the Rohacell (still inside the fixture) from the oven and let cool for a specified time
4) Take the formed Rohacell out of the fixture and store at room temperature until needed for RF shield adhesion

Experimental Variables

In order to find the optimum procedure several characteristics of the process need to be controlled and varied. These characteristics of the forming process are:

1) The method in which the sheet is forced to change shape (M)
   - Two different methods were tested:
     a) Allowing the Rohacell to reach the forming temperature, placing it into the already warmed jig, then applying a quick, but smooth, external force to the jig to mold the sheet $\longrightarrow M_A$
     b) Immediately placing a room-temperature sheet into an already warm jig and oven, and then letting the weight of the jig do the molding of the sheet slowly and without any external pressure $\longrightarrow M_B$
2) The amount of time the Rohacell is left in the oven before being formed (t_{f1})
   - The Rohacell was only left in the oven before being formed when method "M_A" was used, and then was left in the oven only 60 seconds before forming it (t_{f1} = 60 for M_A; $t_{f1} = 0$ for M_B).
3) The temperature of the air in the oven before the Rohacell is formed (T_{A1})
   - The temperature of the air surrounding the sheet was held constant at 180ºC ($T_{A1}=T_{A2}=180$ºC). This temperature was determined by results of previous tests from the summer of 1996 done by Richard Conway, the results of tests performed

in the fall of 1996 by Eric Bosze, and the data sheets describing the forming properties of Rohacell IG supplied by Rohm Tech, Inc (See Appendix B).

4) The amount of time the Rohacell is left in the oven while being formed (t_{f2})

   - The amount of time the sheet was kept in the oven at the forming temperature was varied between 60sec < t_{f2} < 240sec.

5) The temperature of the air in the oven while the Rohacell is being formed (T_{A2})

   - See description under 3).

6) The temperature of the molding fixture while the Rohacell is being formed (T_{F1})

   - The temperature of the molding fixture while the Rohacell was being formed was varied from 105ºC < T_{F1} < 180ºC.

7) The amount of pressure put on the Rohacell while being formed (p_1)

   - The amount of pressure exerted on the Rohacell varied with the size of the specimens and the time elapsed during the forming process, but the only force applied was from the weight of the molding fixture, which was approximately 11lbs, yielding a pressure varying between 540Pa < p_1 < 5000Pa.

8) The amount of pressure put on the Rohacell after being formed (p_2)

   - After the Rohacell was formed, the pressure on the specimens only varied with their sizes, from 357Pa < p_2 < 540Pa.

9) The amount of time the Rohacell is left in the oven after being formed (t_{f3})

   - The Rohacell was not kept in the oven after being formed, so $t_{f3} = 0$.

10) The amount of time the Rohacell is allowed to cool down before the test is considered complete (t_{f4})

    - The time the Rohacell was allowed to cool down was varied between 5min < t_{f4} < 24hrs.

11) The rate at which the formed sheet is allowed to cool down (dT/dt)

    - The rate at which the formed sheet was allowed to cool was controlled by the amount of time the formed sheet was left inside the forming jig, t_{f4}, and the temperature of the fixture, T_{F1}.

12) The temperature of the fixture at which the test is considered complete, the pressure of the fixture is removed, and the Rohacell is taken out and put into storage (T_{F2})

    - The temperature of the Rohacell when it was taken out of the fixture was varied from 23ºC < T_{F2} < 68ºC.

Experimental Apparatus

The instruments used in the inner enclosure forming tests were:

1) A VWR 1655D forced-convection oven, with inside dimensions of approximately 31.5"x26"x60", with a Watlow 700 controller employing a thermocouple temperature sensor, variable rate temperature controller, timer, multiple stage settings controller, and a digital display.
2) An aluminum fixture capable of forming a sheet of Rohacell approximately 8"x30"x3mm. See schematic drawings in Appendix A for a full description. A type "J" thermocouple connected to a Hewlett Packard 3478A digital multimeter with a sampling rate of approximately 2 samples per second was used to monitor the temperature of the aluminum fixture.

Experimental Procedure

A detailed listing of the original procedure for the inner enclosure forming tests follows.

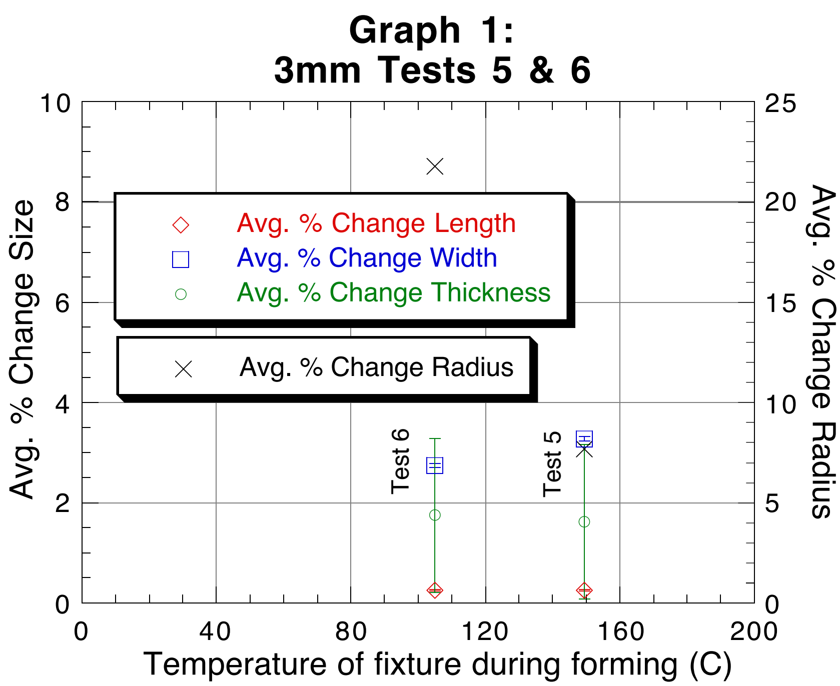
1) Preheat the VWR 1655D oven to 180°C. This takes about 25 minutes.
2) Using the data from the fixture warm-up time thermocouple tests (see Appendix C_1) let the jig sit for the specified amount of time to bring the fixture temperature up to a certain point.
3) Set the Watlow 700 controller to the specified temperature and time settings.
4) If procedure M_A is being used, then put the Rohacell into the oven and let it sit for the specified time. Otherwise skip this step and,
5) With heat resistant ZetexPlus gloves, align and place the Rohacell onto the bottom half of the fixture and then align and place the top half of the fixture onto the Rohacell.
6) Start the timing cycle on the Watlow 700. Let the Rohacell sit under the weight of the top half of the fixture for the specified time.
7) Take out the fixture and let the Rohacell cool inside it for the specified amount of time. This time can be converted into the rate of cooling and the final Rohacell temperature using the results of the fixture cool down time and fixture temperature measurements. The data taken and results of the data analysis can be found in Appendix C_2.
8) In some of the tests, the top half of the molding fixture was removed from on top of the Rohacell in order to raise the cooling rate (dT/dt). The time after the top half was removed and the temperature of the Rohacell at that time (T_{F2}) were noted.

Eight tests were performed to help determine the optimal forming procedure for the inner enclosure. During three of the tests the jig temperature was not measured, so only five tests had data that could be compared while being certain that only one variable was changing during the comparison.

The main portion of the experimental data has been excluded from the body of the report for conciseness, but Appendix D contains all data from the inner enclosure tests. Similarly, the uncertainties of the measurements were calculated using the propagation of error theory, and the calculations and estimations are detailed in Appendix E.

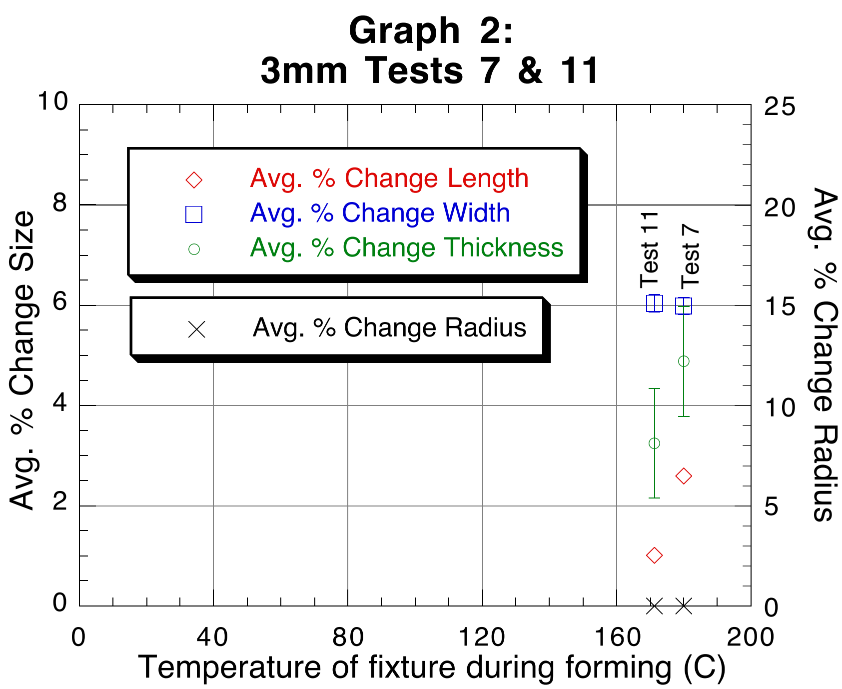
Tests Varying T_{F1}

Two graphs have been constructed using the temperature of the fixture when the Rohacell was being formed (T_{F1}) as the dependent variable. The independent variables are, 1) the percent change in length, width, and thickness ($\%\Delta\ t$) from before being formed to after (on the left vertical axis), and 2) the percent change in radius of the Rohacell from when it is being formed (effectively, this is the radius of the mold) to when it is completely cooled. The percent change in thickness, $\%\Delta\ t$, is used to determine the thickness growth, and the percent change in radius, $\%\Delta\ r$, is used to measure the amount of springback that occurs.



Observations of Graph 1

- For the parameters of Tests 5 and 6, the percent change in radius decreases as T_{F1} increases
- It also suggests that changes in size (length, width, and thickness) are independent of the initial fixture temperature
- However, the results are not firm because the parameters that were fixed in Graph 1 were not completely the same, but rather were within the same range of operation. Specifically, the main variation in the tests other than the difference in T_{F1} is that Test 5 was allowed to cool approximately twice the total time that Test 6 was (Test 5 dT/dt < Test 6 dT/dt).



Observations of Graph 2

- Graph 2 suggests that length growth increases significantly with an increase in the temperature of the fixture when the Rohacell is being formed, T_{F1}
- It also suggests that width, thickness, and radius changes are independent of T_{F1}.

Comparative Analysis and Discussion of Graphs 1 & 2

Comparing Graph 1 to Graph 2 provides useful information about other changes in the forming procedure. Between the graphs, there is a significant difference in the percent change in width, a possible significant difference in the percent change length and thickness, and a very distinct difference in the percent change of the radius.

Some possible reasons for these differences are:

1) The differences in the average cool down rates (dT/dt):
   - Test 5 = 2.0 degrees C / minute
   - Test 6 = 1.6 degrees C / minute
   - Test 7 > 0.11 degrees C / minute
   - Test 11 > 0.10 degrees C / minute
2) The differences in the Rohacell's time in the oven (t_{f2}):
   - Test 5 = 3 minutes
   - Test 6 = 3 minutes
   - Test 7 = 4 minutes
   - Test 11 = 3.5 minutes
3) The differences in the temperatures of the fixture while the Rohacell is forming (T_{F1}):
   - Test 5 = 150°C
   - Test 6 = 105°C
   - Test 7 = 180°C
   - Test 11 = 171°C
4) The difference in the final fixture temperatures (T_{F2}):
   - Test 5 = 54°C
   - Test 6 = 68°C
   - Test 7 = 24°C
   - Test 11 = 23°C

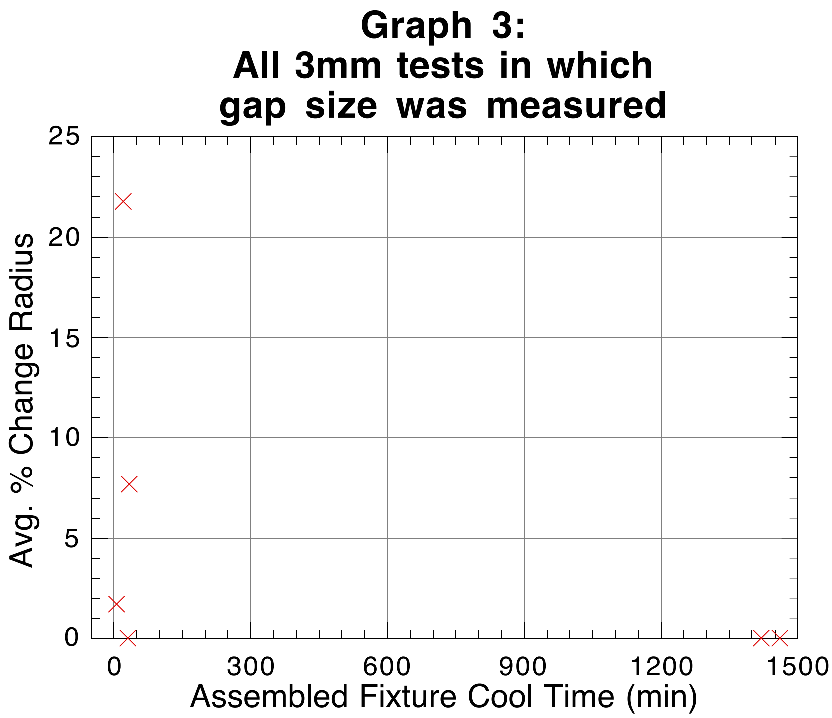
- The most reasonable cause for the differences between the graphs' $\%\Delta r$ is the cool down rates, because there is a much bigger difference in the graphs' average cool down rates than in the other parameters mentioned.

There is a sensible physical explanation as to why less springback occurs with a slower cool down rate. I propose that a major cause of springback could be residual stresses putting the expanding side of the Rohacell (the side farthest away from the center of curvature) in tension. Because the expanding side has a larger surface area than the contracting side, it can conduct heat away at a higher rate. As it conducts the heat away it cools down, and that cooling causes it to contract slightly. However, because the contracting side is cooling and contracting at a lower rate than the expanding side, tension between the surfaces builds up and pulls the edges of the expanding side out. This pulling out of the edges is the springback.

If the Rohacell is kept in the fixture in the assembled configuration, then both its sides cool at close to the same rate, which is a much smaller rate than if the Rohacell is taken out of the fixture. Because the cooling rate is close to the same, the stress and tension do not build up nearly as much, and therefore, there is less springback.

The Relationship between Cool Down Rate and $\%\Delta r$

Graph 3 includes **all** the tests of the inner enclosure forming procedure in which the size of the gaps between the Rohacell and the fixture, which has been converted into the percent change in radius, were measured. All of their procedures were not the same, and therefore many of the parameters were varied; therefore, this graph cannot be used to prove a relationship between the percent change of radius and cooling rate, but it does support the possibility deduced from Graphs 1 and 2 that a lower cooling rate will decrease the springback.



- In Graph 3 the average percent change of radius for the tests with short cool down times is much higher than the average of the tests with long cool down times.

Conclusions and Recommendations based on Inner Enclosure Tests

From these graphs it seems that one probable relationship is:

- the amount of springback can be reduced by lowering the cooling rate.

Other Forming Tests

Fourteen other tests were performed to help determine the optimal forming procedure for a different sheet thickness and radius of curvature than used in the inner enclosure tests. These tests used 0.25" thick Rohacell Industrial Grade 71, which is exactly the same material the outer enclosure will be made of. However, the length and width of the specimens are much smaller than the dimensions of the outer enclosure, and therefore the results of these tests cannot be guaranteed to provide a reliable forming procedure when scaled up to the outer enclosure's dimensions.

Ten of the twelve variables in the forming process were controlled and monitored. The temperature of the fixture was not monitored; therefore, the temperature of the fixture when the Rohacell was being formed, T_{F1}, and the final temperature of the fixture, T_{F2}, during the tests are not known, and the cooling rate can only be specified relative to the other specimens by the amount of time the specimens were allowed to cool inside the fixture, t_{f4}.

Experimental Apparatus

The instruments used to control and monitor the variables for tests done on the outer enclosure forming procedure were:

1) A VWR 1300U natural convection oven, with inside dimensions of approximately 12"x12"x12", employing a simple temperature controller that does not give feedback of what the oven temperature
2) A Rochester bimetal thermometer ranging from 0 to 300°C
3) A wall clock
4) A molding fixture made of aluminum and brass, capable of forming Rohacell with dimensions of approximately 3.25" x 2.75" ID x 0.25"
5) A composite structure pole of dimensions 16.75" x 1.25" OD, a lead brick of approximate weight 6.25 pounds and a lead cylinder of approximate weight 4.5 pounds used to control the amount of pressure used in forming the Rohacell.

Experimental Procedure

The procedure used in the outer enclosure tests is detailed below.

1) Preheat the oven to the specified temperature. Estimated preheating time is 45 minutes.
2) Insert the jig and allow it to warm up (the fixture temperature was not monitored).

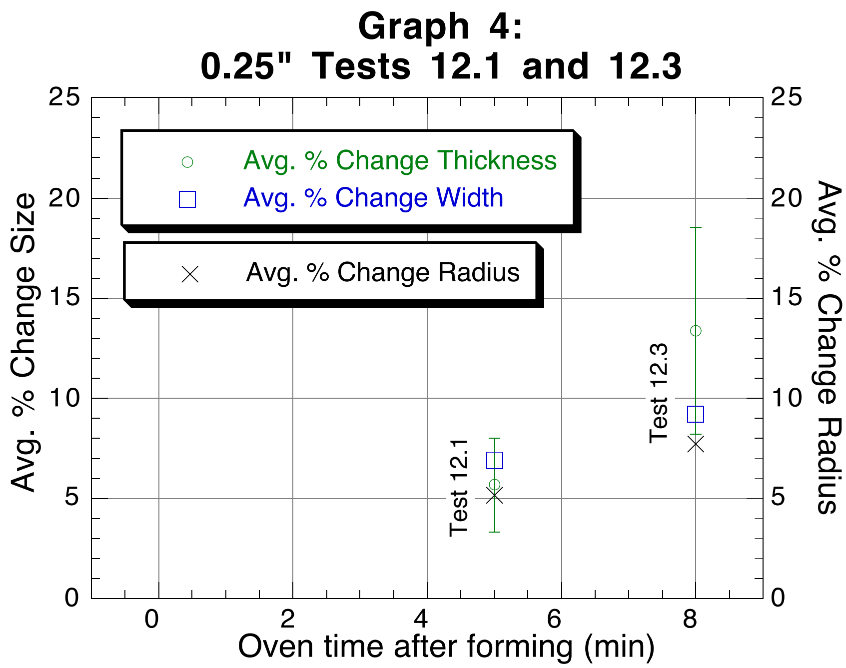
3) If specified, put the Rohacell into the oven and let it warm up
4) Put the Rohacell into the fixture and allow it to sit for the specified time
5) Put the specified weight onto the top half of the jig
6) Let the fixture and Rohacell sit in the assembled configuration for the specified amount of time.
7) Remove the weight and the take the fixture (with the Rohacell) out of the oven.
8) Let the Rohacell cool for the specified amount of time in room temperature air.

Because of changes in the forming procedure from test to test, all the data is not graphed together. Only graphs from some of the data are shown. However, all the data can be found in Appendix F.

Tests Varying t_{f3}

Graph 4 shows the relationship between Rohacell's time in the oven after being formed, t_{f3}, versus its percent growth, $\%\Delta t$, and percent change of radius, $\%\Delta r$. The following list details the parameters of the procedure used in both tests shown in the graph:

Average oven temperature (the average of T_{A1} and T_{A2}) = 185°C
Amount of time the Rohacell was in the oven before being formed (t_{f2}) = 5 minutes
Amount of time the Rohacell was allowed to cool down in the fixture (t_{f4}) = 0 minutes



Observations of Graph 4

- Graph 4 suggests that Rohacell's percent growth is higher the longer it is left in the oven after it has been formed.
- Also, the percent change in radius does not change significantly in the graph, and so Graph 4 suggests that percent change of radius is independent of the time it is allowed to stay in the oven after being formed (t_{f3}).

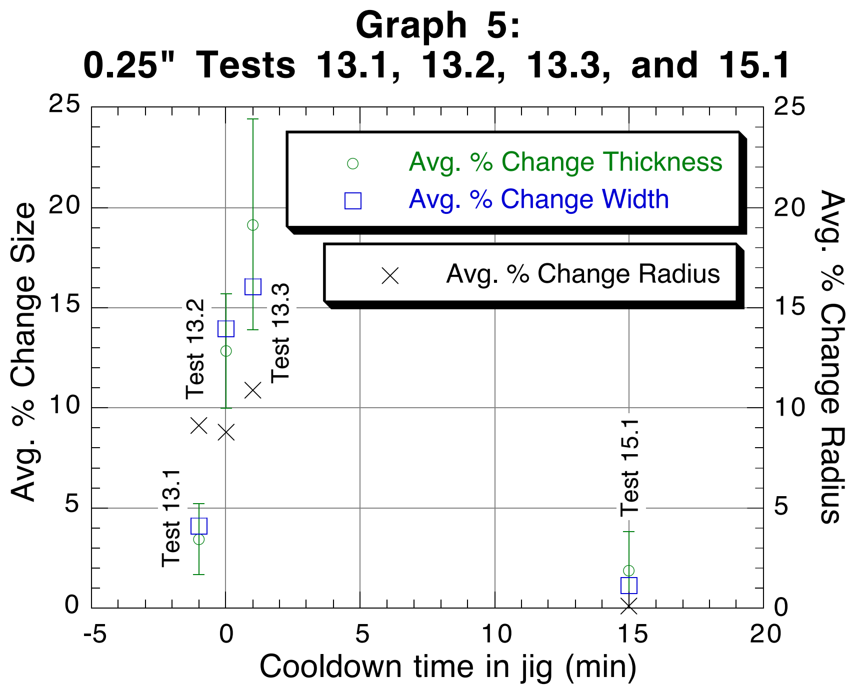
Tests Varying Cool Down Time, t_{f4}

Graph 5 compares a change in the amount of time the Rohacell is left in the fixture after it has been formed (t_{f4}) to its percent change of radius. The parameters of the procedures of these four tests were:

Average oven temperature (the average of T_{A1} and T_{A2}) = 165°C - 172.5°C

Amount of time the Rohacell was in the oven before being formed (t_{f2}) = 3 minutes

Amount of time the Rohacell was in the oven after being formed (t_{f3}) = 0 minutes



(Test 13.1 did not have a negative cool down time, and Test 13.3 did not have a cool down time of one minute. Rather, they both were allowed to cool down for zero minutes, but are spread apart to distinguish their separate values.)

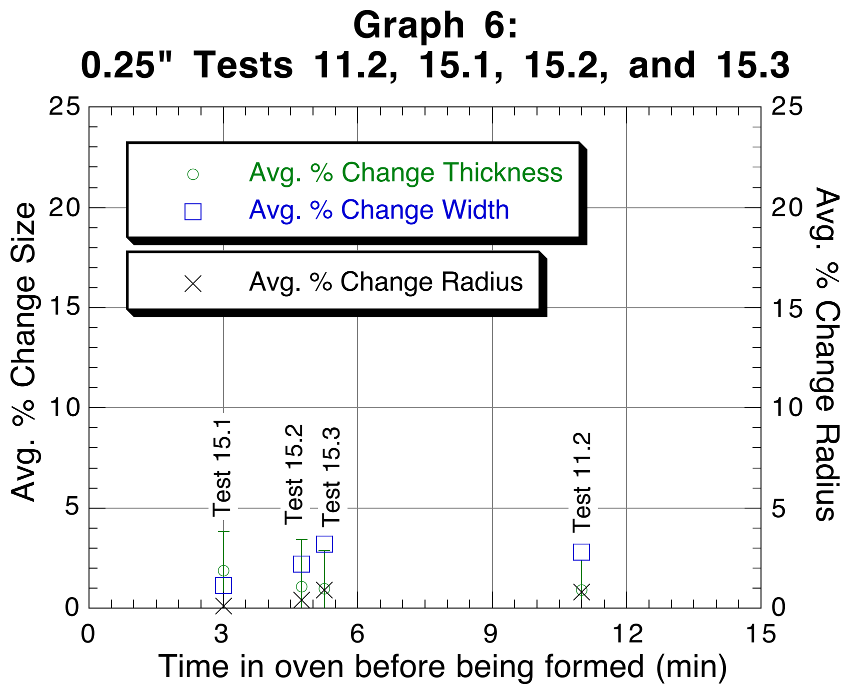
Observations of Graph 5

- Graph 5 suggests that allowing the Rohacell to cool down at a slower rate reduces the percent change of radius, and therefore also reduces the amount of springback.

Tests Varying Pre-Forming Time in Oven, t_{f1}

Graphs 6 and 7 show the relationships between the amount of time the Rohacell is left inside the oven before being formed, t_{f2}, and the percent change of size and radius. The parameters of the graphs are listed below:

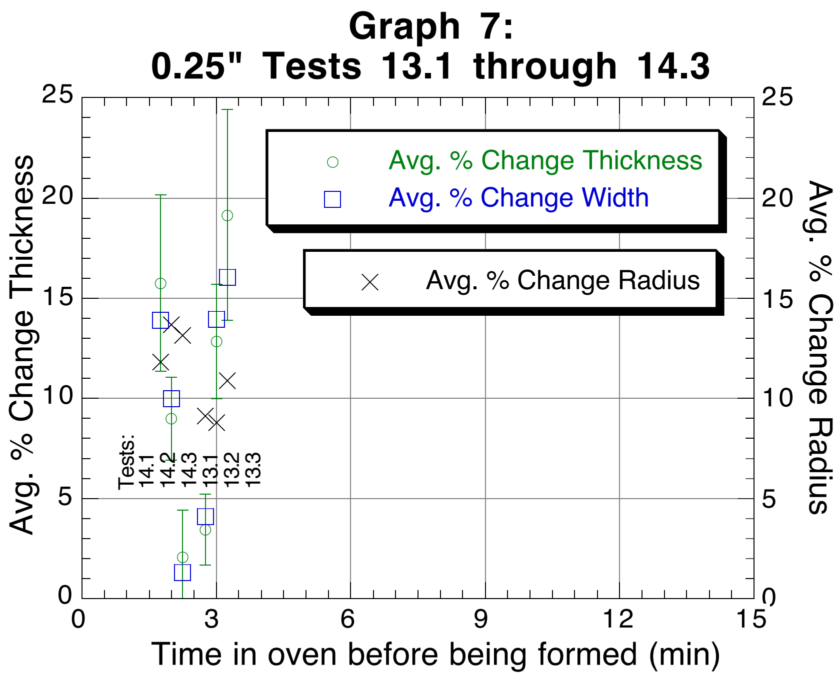
Average oven temperature (the average of T_{A1} and T_{A2}) =
165°C - 175°C for Graph 6
165°C - 173°C for Graph 7
Amount of time the Rohacell was in the oven after being formed (t_{f3}) =
3 minutes for Graph 6
2 - 3 minutes for Graph 7
Amount of time the Rohacell was allowed to cool down in the fixture (t_{f4}) =
15 minutes for Graph 6
0 minutes for Graph 7



Observations of Graph 6

The percent growth of size and radius are both low and fairly stable over the range of t_{f2} tested, and the size growth is also fairly low and stable over that range.

- This suggests that both the percent growth of size and radius are independent of t_{f2} over that range
- The low values suggest that the procedure parameters used for the tests in Graph 6 are near to the optimal values.



Observations of Graph 7

Although the six tests in Graph 7 have a stable percent change in radius, the size growth is very unstable.

- The range over which the time, t_{f2}, is varied is small, and the difference in the percent growth is large, suggesting that there could be another variable that was not controlled which affected the percent growth. This uncontrolled variable is probably the temperature of the fixture, but could be other uncontrolled variables as well.
- The percent change of radius is stable, but is not very low. This suggests that it is independent of t_{f2}, but the procedure used for the tests in Graph 7 is not the optimal one.

Comparative Analysis and Discussion of Graphs 6 and 7

The controlled differences between Graphs 6 and 7 are the cool down time, t_{f4}, and the amount of time the Rohacell was in the oven before it was formed, t_{f2}. The differences in the dependent variables (percent growth of size and radius) must be a result of the differences in the procedures used for Graphs 6 and 7. Therefore, the differences in percent growths must be due to t_{f4}, t_{f2}, an uncontrolled variable, or a combination thereof. I can suggest one hypothesis of the reason for the differences based on the comparison of Graphs 6 and 7.

It makes logical sense that the longer Rohacell is kept at a high temperature, the more it is going to grow in size, until the Rohacell reaches the temperature of the substance surrounding it. Rohacell is a closed-cell foam, meaning that Rohacell is made of a huge number of tiny air-tight bubbles. When the air inside the bubbles heats up, it puts pressure on the walls of the bubbles. As the temperature of the walls nears the forming temperature, the walls become more and more pliable. When the pressure is high enough and the bubble walls are pliable enough, the bubble walls start to expand, which causes macroscopic size growth. Up to the steady state point, the longer the Rohacell is at the elevated temperature, the more the Rohacell will grow.

However, Graphs 6 and 7 do not show that trend. In Graph 7, the average percent growth is larger than the average in Graph 6, but the values of t_{f1} are larger in Graph 6 than in Graph 7. Because that is the case, it seems reasonable that the difference in growth size is not due to the difference in values of t_{f1}.

It also makes logical sense that if pressure is held on the Rohacell piece as it is cooling down to below the temperature at which the molecular bonds of the Rohacell reform, that pressure will force the tiny bubbles to contract as the temperature of the air inside them decreases (and therefore the pressure as well). That contraction over thousands of bubbles can minimize the amount of size growth originally caused by the expansion of the same bubbles. If the pressure is not applied as the Rohacell cools, it makes sense that the size growth will not decrease as the air inside the bubbles cools down and their pressure on the bubble walls decrease.

Graphs 6 and 7 do seem to support that trend, because the pressure on the specimens as they were cooling in Graph 6 is much higher than those in Graph 7, and Graph 6 shows a much lower average percent growth of size. Accordingly, my hypothesis is that the difference in the size growth is due to the weight of the fixture on the Rohacell as it cools down to below the forming temperature.

As for the difference in percent change of radius, my hypothesis is that the rate of cooling of the Rohacell is a major contributing factor to the amount of springback. The slower the cooling rate, the less springback will occur. This hypothesis is supported by the comparison of Graphs 6 and 7, because the specimens in Graph 6 were allowed to cool inside the fixture, giving them a lower cooling rate. The logical reasoning behind this hypothesis is explained in the comparison of Graphs 1 and 2 on page 13, which tested 3 mm thick Rohacell instead of 0.25" thick Rohacell.

Conclusions drawn from Graphs 6 and 7

- Based on knowledge of the material makeup of Rohacell, it does not seem likely that the reason for the difference in percent growth of size is due to the difference in t_{f2}.
- Based on knowledge of the method used to form the Rohacell, it is likely that the reason for the difference in percent growth of size is due to the difference in the way the Rohacell was allowed to cool down. Specifically, the added pressure on the Rohacell forced it to contract as the specimens cooled.

- The rate that the Rohacell is cooled after forming is a major factor in determining the amount of springback that occurs. The lower the cooling rate, the less the amount of springback.

Tests of Consistency

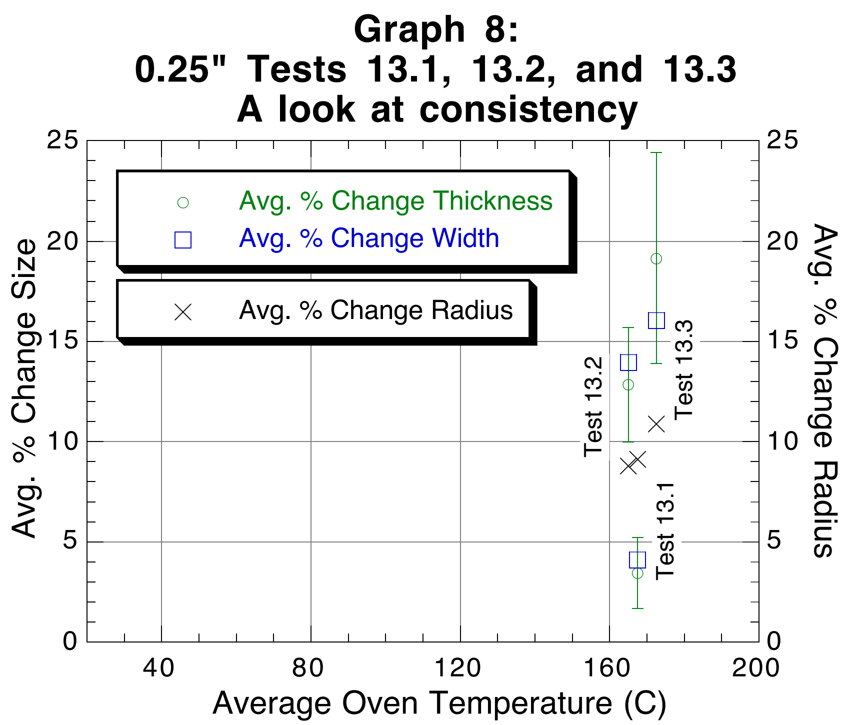
In order to get an idea of how reproducible the data in the graphs are, several graphs have been constructed which compare the measurements of specimens which have been formed in almost exactly the same ways.

Graphs 8, 9, and 10 are shown to give an idea of what the consistency of the tests results. All three graphs have the average oven temperature as the independent variable and the percent growth of size and radius as the dependent variables. The parameters of the tests are listed below.

Amount of time the Rohacell was in the oven before being formed (t_{f1}) =
3 minutes for Graph 8
2 minutes for Graph 9
5 minutes for Graph 10

Amount of time the Rohacell was in the oven after being formed (t_{f3}) =
0 minutes for Graph 8
0 minutes for Graph 9
0 minutes for Graph 10

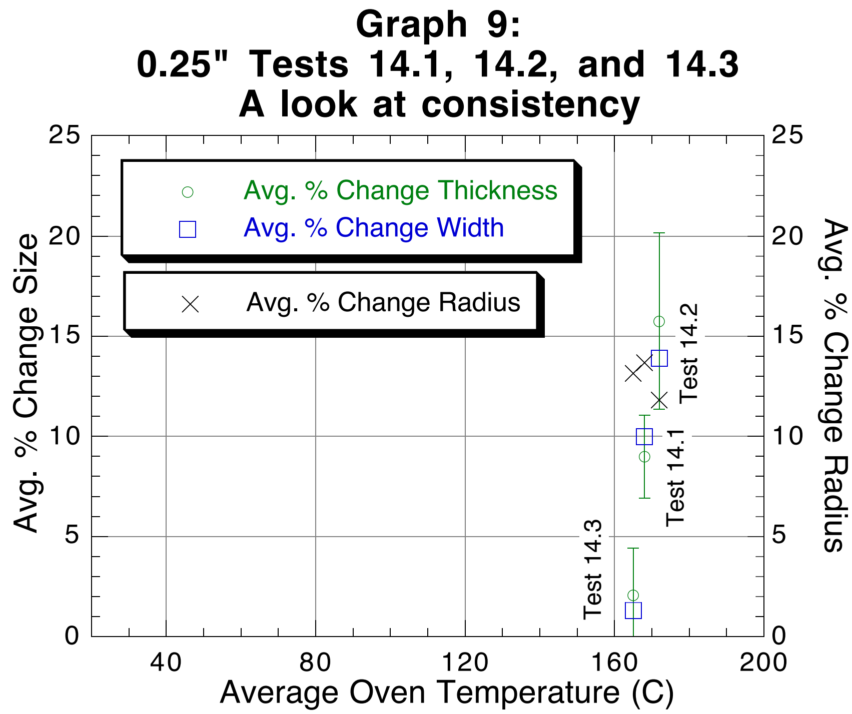
Amount of time the Rohacell was allowed to cool down in the fixture (t_{f4}) =
0 minutes for Graph 8
0 minutes for Graph 9
15 minutes for Graph 10



Observations of Graph 8

The tests in Graph 8 show a very stable but large percent change of radius, but the percent growth of size is very unstable.

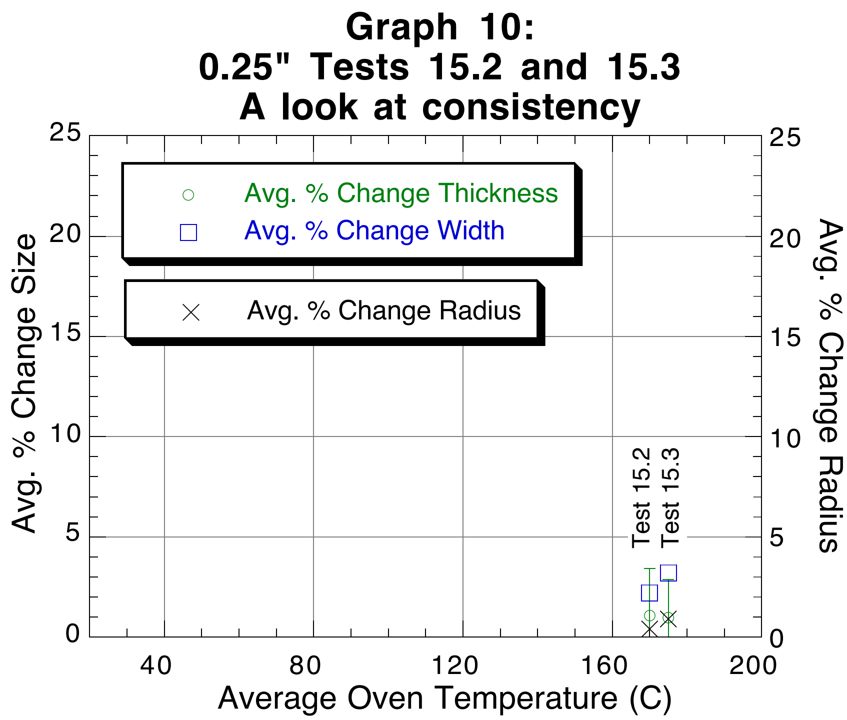
- Because the parameters of the tests are almost exactly the same, the only good explanation for the instability of the percent growth is a difference in one or more unmonitored variables such as the temperature of the forming fixture.



Observations of Graph 9

Just as in Graph 8, the percent change of radius is stable but large, and the percent growth of size is unstable. The same conclusions can be drawn as well, i.e.

- Because the parameters of the tests are almost exactly the same, the only good explanation for the instability of the percent growth of size is a difference in one or more uncontrolled variables.



Observations of Graph 10

Both the percent growth of size and radius are fairly stable, and both are also very low.

- These are the type of results that are expected from tests that have such similar parameters.

Comparative Analysis and Discussion of Graphs 8, 9, and 10

As can be seen in the list of parameters for each graph shown above, the Rohacell's time in the oven after being formed, t_{f3}, is consistently 0 minutes. Also, from examining the graphs, one can see that the range of average oven temperatures for all three graphs is small, that is, $165°C < \frac{T_{A1} + T_{A2}}{2} < 175°C$. Thirdly, the difference in the amount of time the specimens were kept in the oven before being formed, t_{f1}, was small (3 minutes). The main difference in the graphs was the amount of time the specimens were allowed to cool down inside the fixture after being formed, t_{f4}. This difference was 15 minutes.

Because t_{f4} is the only large difference between the graphs, the major differences in the percent growths of sizes and radii should either be attributed to the differences in t_{f4} or the differences in uncontrolled variables. The hypothesis that the difference in percent change of radius is due to the difference in t_{f4} has been supported by the results of the other graphs, so that hypothesis is more likely to be the correct explanation than any others.

Concerning the difference in percent growth of size, it seems that a longer t_{f4} produces less size growth. A logical explanation for this is given in the comparison of Graphs 6 and 7 on page 20, and once again this hypothesis is supported.

Conclusions drawn from Graphs 8, 9, and 10

- The more time the Rohacell is allowed to cool down in the fixture, the lower the cooling rate, and also the less the amount of springback.
- The more time the Rohacell is allowed to cool with the weight of the fixture on it, the less the percent size growth.

Putting It All Together: Conclusions and Recommendations

Key Conclusions from both the Inner Enclosure and Other Tests:

1) **The amount of springback can be reduced by lowering the cooling rate** (supported by graphs 1, 2, 3, 5; comparison of graphs 8,9, & 10; and comparison of graphs 6 & 7)

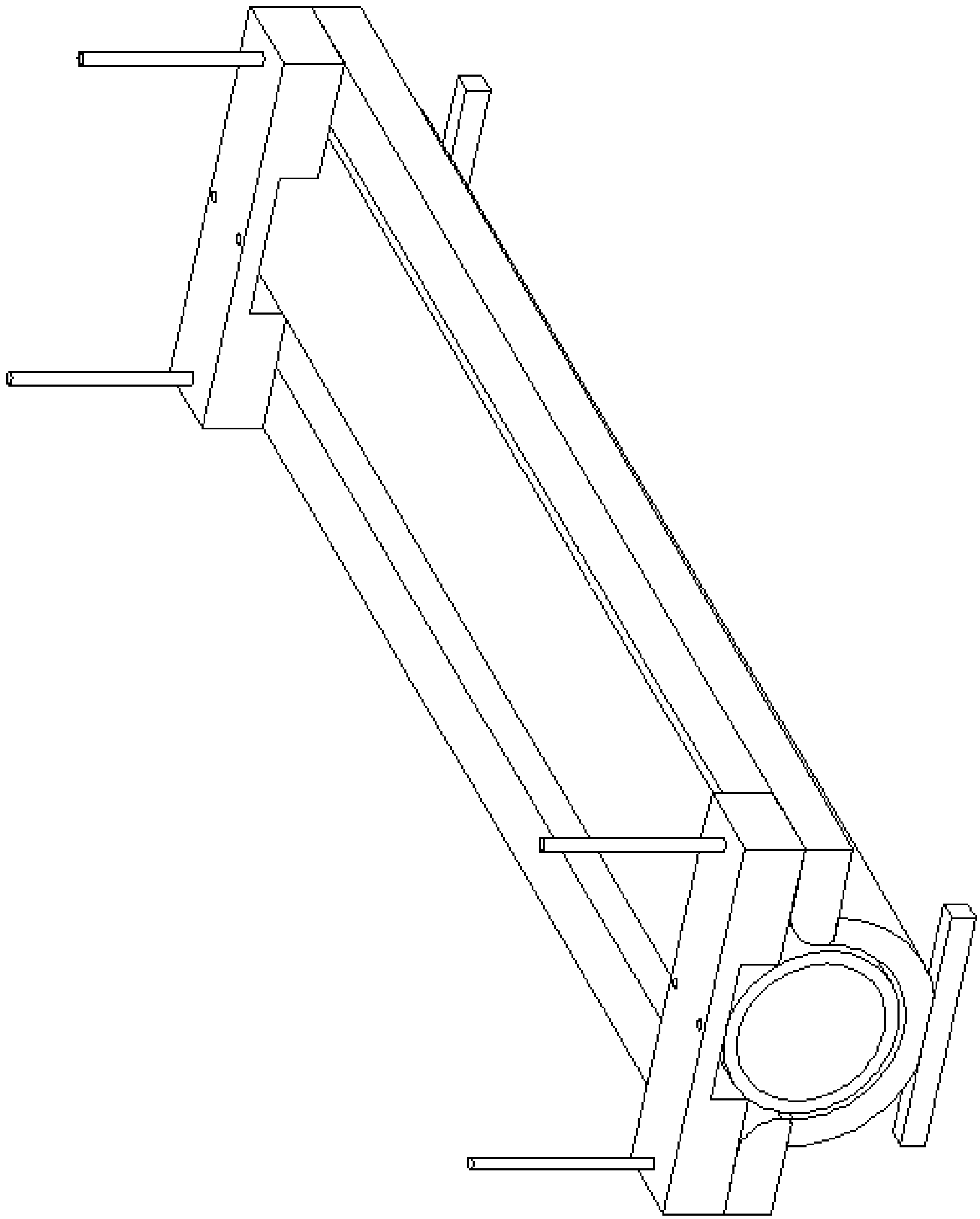
2) **The pressure of the fixture on the Rohacell during the cool down process helps to reduce the size growth** (supported by comparison of graphs 6 & 7 and by comparison of graphs 8, 9, & 10)

Recommendations

Because of the small number of data points in any individual graph, more tests need to be done, increasing the range of variation, to show that the conclusions drawn are reproducible and are in fact the correct conclusions. Specifically, more tests need to be performed at intermediate cool down rates and times to test the hypothesis that springback is a function of cool down rate, and the reason for the inconsistency in thickness growth in Graphs 5, 7, 8, and 9 should be determined.

APPENDIX A

An aluminum jig was designed and constructed for the inner enclosure forming process tests.



Forming

Moldings can be relatively simply produced from ROHACELL sheets. The smallest attainable bending radius is about twice the sheet thickness.

Heating the ROHACELL sheets

Before heating the ROHACELL sheets, they should be dried for 2 hrs. at 248 °F (120 °C), using a heating cabinet with air circulation. ROHACELL becomes thermoelastic and can therefore be formed at a temperature of 338 to 374 °F (170 – 190 °C). The required forming temperature depends on the degree of shaping, the pretreatment and the density.

The heating time for ROHACELL sheets in a heating chamber with air circulation that has been brought to forming temperature is about 1 min/0.04 in. (1 min/mm) sheet thickness. Care must always be taken so see that the hot air sweeps uniformly over both sides of the foam plastic sheets and that no heat is allowed to accumulate (Fig. 37). This method is particularly suitable for the manufacture of prototypes. Heating is much simpler and more dependable between heating plates, which you can easily make yourself (Fig. 38). This method can be recommended for series production.

Radiant heaters can be used to warm up thin sheets of ROHACELL up to 0.24 in. for line bending (Fig. 39). A vacuum forming machine may be used to mold these same sheets.

Caution: The forming temperature is close to the foaming temperature, so that it must be accurately controlled in order to prevent post-foaming. This is particularly important when warming up the ROHACELL sheet by means of radiant heaters.

Avoiding unduly fast cooling

Since the heat capacity of the rigid foam is low because of its small mass and the sheet surfaces cool quickly because of the multitude of cut cells which act as "cooling vanes", the blanks must be protected against cooling while they are moved from the heating cabinet or the heating plates to the forming device. Unduly fast cooling is avoided by covering the ROHACELL sheets on all sides with cotton cloth, thin aluminium foil, glass fabric or silicone rubber. The foam plastic is heated and formed together with this cover. The cover is intended to keep the ROHACELL sheet just long enough at the necessary forming temperature until forming is finished.

With simple moldings a cover on one side is often sufficient if the work is done fast. The cover must be applied to that side of the ROHACELL sheet which is subject to tensile stress during forming (Fig. 41).

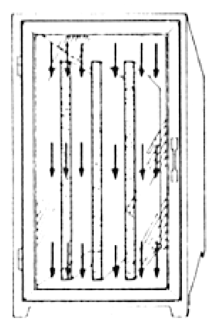
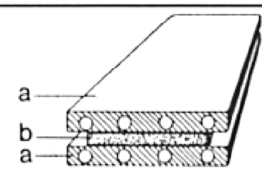
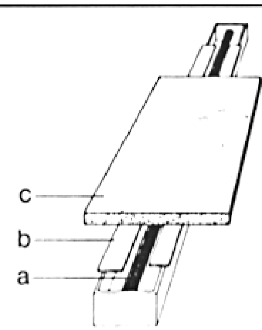


Fig. 37: Heating in a cabinet with air circulation



a) heated plate
b) ROHACELL sheet

Fig. 38: Heating between plates



a) radiant heater
b) cover strips
c) ROHACELL sheet

Fig. 39: Line bending of thin ROHACELL sheets

Fig. 40: ROHACELL sheet covered all around

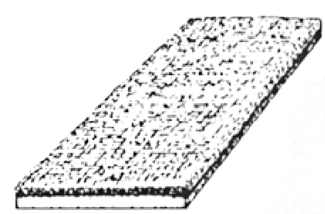


Fig. 41: ROHACELL sheet covered on one side only

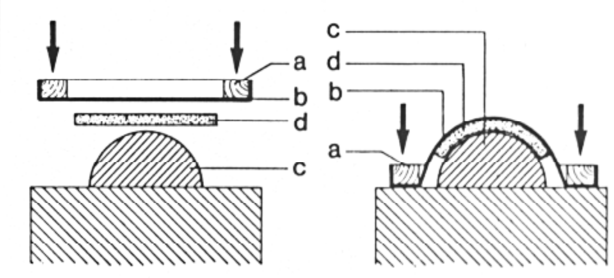
For series production, the heating plates and the forming tool can be put in such a position that, when the heated ROHACELL blank is quickly and automatically taken from the heating plates to the forming tool, there is often no need for any cover.

Design of the forming tools

Tools which are not heated can be used for simple parts when the degree of forming is small. Tool temperatures of 176 to 212 °F (80 – 100 °C) may be necessary when more complex parts have to be formed.

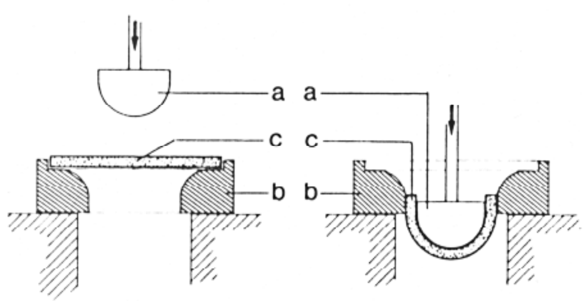
The foam plastic cools quickly because of its low heat capacity, and once the formed part has cooled down to c. 176 °F (80 °C) it may be removed from the tool. With simple parts, the molds are not subjected to a substantial amount of heat, so that hardwood molds are adequate. Polyester and epoxy resin molds are also used. The advantage of these non-metallic molds is that the ROHACELL surfaces do not cool down so quickly during forming because of the relatively poor heat conductivity. Metal molds should be thermostatically controlled.

In order to ensure that the ROHACELL sheet can be drawn into the mold without much resistance, the edges should have large radii. If the radii are too small, the edge is squeezed into the heated foam at the start of forming and impedes further sliding. Cracks at these points will then be unavoidable. Forming itself should be done uniformly and quickly. Abrupt forming must be avoided.



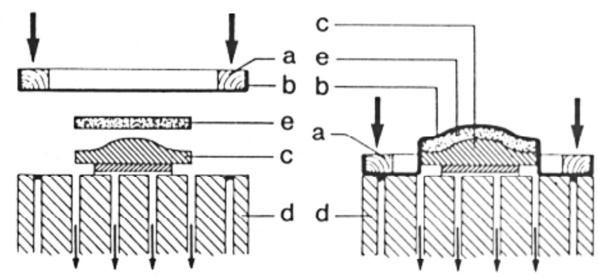
a) frame b) stretch rubber c) mold d) ROHACELL

Fig. 44: Forming ROHACELL with stretch rubber



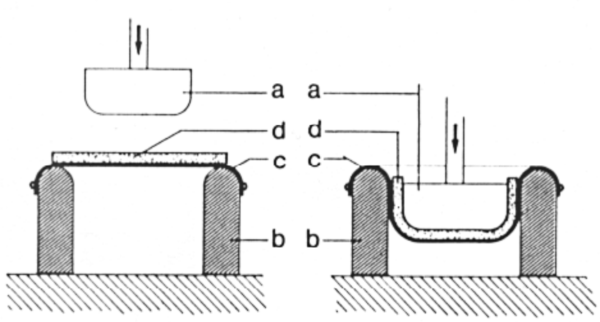
a) force plug b) annular mold c) ROHACELL

Fig. 42: Forming of a hemisphere from ROHACELL



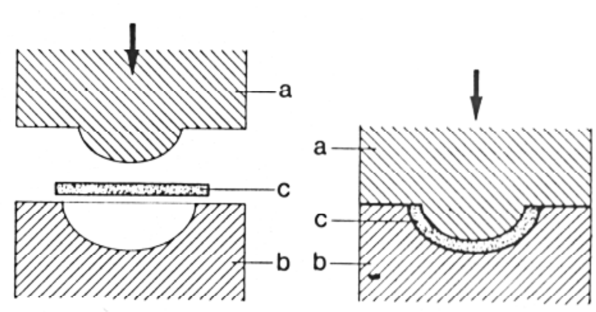
a) frame b) stretch rubber c) mold
d) vacuum table e) ROHACELL

Fig. 45: Forming ROHACELL with stretch rubber



a) force plug b) mold c) stretch rubber d) ROHACELL

Fig. 43: Forming ROHACELL with stretch rubber



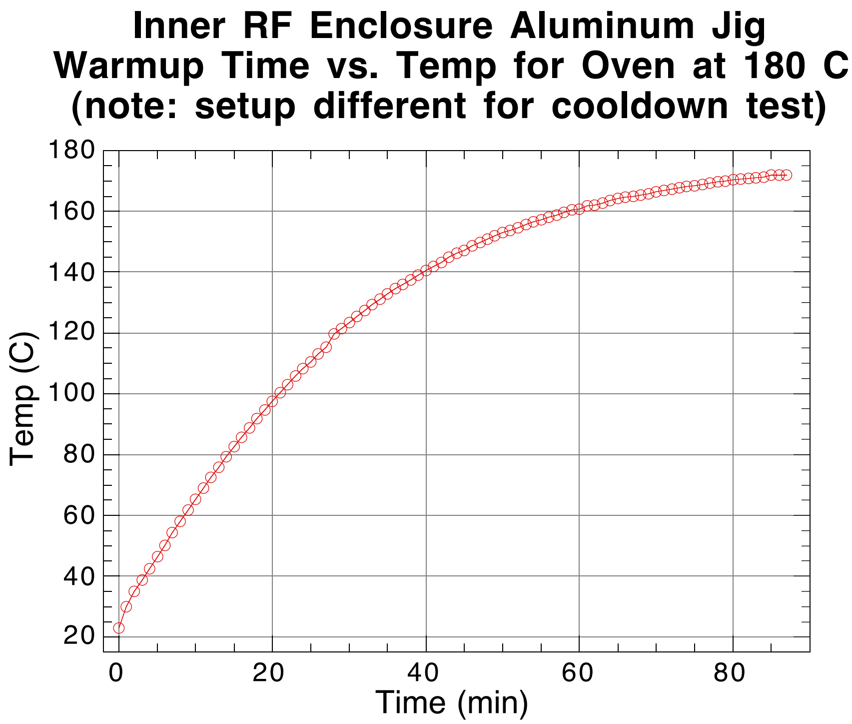
a) force plug b) mold c) ROHACELL

Fig. 46: Forming in the tool

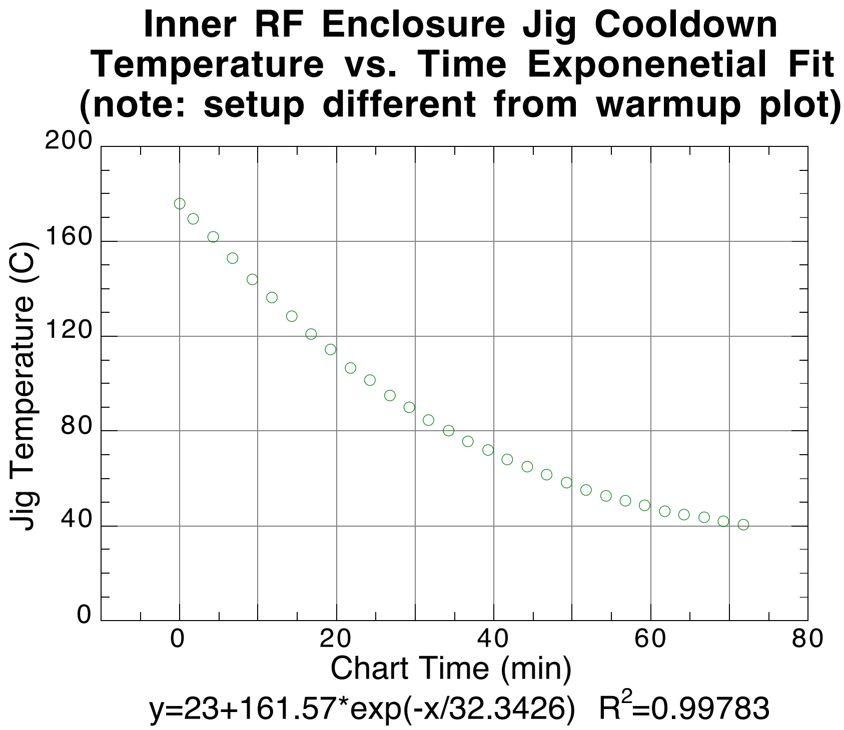
APPENDIX C

Using a type "J" thermocouple and a rapid sampling voltmeter, the rate at which the jig warms up and cools down was determined. The two halves of the jig are warmed with the jig unassembled, but during the cool down process the jig remains assembled with the formed sheet still inside. The formed sheet acts as an insulator between the top and bottom halves and greatly restricts the convection of heat off of the jig, thereby lowering the cooling rate significantly. These rates of warming up and cooling down can be seen below. They are crucial to monitoring and controlling the temperature of the sheets during the forming process, and therefore they are also crucial to being able to determine the optimal forming procedure.

APPENDIX C_1



APPENDIX C_2



Inner RF Enclosure Jig Cooldown
Temperature vs. Time Exponenetial Fit
(note: setup different from warmup plot)
Jig Temperature (C)
200
160
120
80
40
0
0
20
40
60
80
Chart Time (min)
y=23+161.57*exp(-x/32.3426) R2=0.99783

Appendix D: Inner Enclosure Test Data

Rohacell Tests with Inner Enclosure Aluminum Jig

									Al foil adhere
Test Number		1	2	3	4	5	6	7	11
Initial Temp:	Jig	?	120	?	?	149.5	104.9	180	171.2
	Oven	180	180	180	180	180	180	180	173
Final Temp:	Jig	?	124	?	?	151	109	180	174
	Oven	180	180	180	180	180	180	180	180
Avg. Temp:	Jig	?	122	?	?	150.25	106.95	180	172.6
	Oven	180	180	180	180	180	180	180	176.5
Forming Time		1	1.5	1.5	2.5	3	3	4	3.5
Forming Method		heat then for	continuous	continuous	continuous	continuous	continuous	continuous	continuous
Cool Time (whole jig)		15	5	15	30	33	20	1440	1440
Jig Temp after cool		?	100	?	?	73.9	70.6	24	23
Cool Time (1/2 jig)		30	10	5	10	15	5	0	0
Jig Temp after cool		?	60	?	?	53.5	67.8	24	23
Initial Dims:	Length 1	20.875	24.5625	24.625	24.5625	24.6875	24.5	30	29.875
	Length 2	20.875	24.5625	24.625	24.5625	24.6875	24.5	30.0312	29.875
	Length 3	20.875	24.5625	24.5625	24.625	24.6875	24.5	30.0625	29.9375
	Width 1	6.5	6.4375	6.125	6.0625	6	6.0625	8	7.25
	Width 2	6.5	6.4688	6.125	6.125	6.0625	6.125	8	7.25
	Width 3	6.5	6.4844	6.125	6.1875	5.1875	6.0625	8	7.25
	Thickness 1	0.115	0.105	0.113	0.114	0.113	0.114	0.112	0.117
	Thickness 2	0.115	0.101	0.113	0.115	0.113	0.114	0.113	0.116
	Thickness 3	0.115	0.102	0.113	0.114	0.112	0.113	0.114	0.116
	Thickness 4	0.115	0.114	0.114	0.113	0.114	0.113	0.113	0.111
	Thickness 5	0.115	0.115	0.114	0.113	0.114	0.114	0.112	0.112
	Thickness 6	0.115	0.114	0.113	0.113	0.113	0.114	0.113	0.11
Final Dims:	Length 1	21	24.5625	24.5625	24.625	24.75	24.5625	30.6875	30.1875
	Length 2	20.9375	24.5625	24.5625	24.625	24.75	24.5625	30.9375	30.1562
	Length 3	20.875	24.5	24.5625	24.6875	24.75	24.5625	30.8125	30.25
	Width 1	6.75	6.625	?	6.3125	6.1875	6.25	8.625	7.6875
	Width 2	6.6875	6.625	?	6.375	6.25	6.25	8.5625	7.8125
	Width 3	6.6875	6.625	?	6.3125	5.375	6.25	8.25	7.5625
	Thickness 1	0.124	0.106	0.114	0.114	0.114	0.114	0.117	0.119
	Thickness 2	0.13	0.104	0.121	0.118	0.119	0.12	0.127	0.119
	Thickness 3	0.124	0.103	0.115	0.115	0.115	0.114	0.116	0.12
	Thickness 4	0.127	0.119	0.113	0.117	0.113	0.113	0.116	0.113
	Thickness 5	0.134	0.122	0.115	0.121	0.116	0.118	0.117	0.116
	Thickness 6	0.135	0.122	0.115	0.118	0.113	0.115	0.117	0.117
Gap Size:	End 1	0.872	0.693	?	0	0.562	1.075	0	0
	End 2	0.391	0.685	?	0	1.478	1.7	0	0
Avg. Gap Size		0.6315	0.689	?	0	1.02	1.3875	0	0
Avg. % Change Length		0.30	-0.08	-0.17	0.25	0.25	0.26	2.60	1.01
Avg. % Change Width		3.21	2.50	#VALUE!	3.41	3.28	2.74	5.99	6.03
Avg. % Change Thickness		12.17	3.73	1.92	3.09	1.63	1.76	4.88	3.25
	u(length 1-1)	-4.819E-05	-4.071E-05	-4.0506E-05	-4.08161E-05	-4.06089E-05	-4.092E-05	-3.41E-05	-3.382E-0
	u(length 2-1)	-4.805E-05	-4.071E-05	-4.0506E-05	-4.08161E-05	-4.06089E-05	-4.092E-05	-3.43E-05	-3.379E-0
	u(length 3-1)	-4.79E-05	-4.061E-05	-4.0712E-05	-4.07122E-05	-4.06089E-05	-4.092E-05	-3.409E-05	-3.375E-0
	u(length 1-2)	4.7904E-05	4.0712E-05	4.06091E-05	4.07125E-05	4.05063E-05	4.0816E-05	3.3333E-05	3.3473E-0
	u(length 2-2)	4.7904E-05	4.0712E-05	4.06091E-05	4.07125E-05	4.05063E-05	4.0816E-05	3.3299E-05	3.3473E-0
	u(length 3-2)	4.7904E-05	4.0712E-05	4.07125E-05	4.06091E-05	4.05063E-05	4.0816E-05	3.3264E-05	3.3403E-0
Unc. % Change Length (95%)		0.0117517	0.0099683	0.00994721	0.009976722	0.009934551	0.0100107	0.0082633	0.008234
	u(width 1-1)	-0.0001598	-0.0001599	#VALUE!	-0.00017175	-0.000171875	-0.00017	-0.0001348	-0.000146
	u(width 2-1)	-0.0001583	-0.0001583	#VALUE!	-0.000169929	-0.00017005	-0.0001666	-0.0001338	-0.000148
	u(width 3-1)	-0.0001583	-0.0001576	#VALUE!	-0.000164881	-0.000199739	-0.00017	-0.0001289	-0.000143
	u(width 1-2)	0.00015385	0.00015534	0.000163265	0.000164948	0.000166667	0.00016495	0.000125	0.0001379
	u(width 2-2)	0.00015385	0.00015459	0.000163265	0.000163265	0.000164948	0.00016327	0.000125	0.0001379
	u(width 3-2)	0.00015385	0.00015422	0.000163265	0.000161616	0.000192771	0.00016495	0.000125	0.0001379
Unc. % Change Width (95%)		0.0382933	0.0383742	#VALUE!	0.040687009	0.043646308	0.040824	0.031552	0.03482
	u(thick 1-1)	-0.0046881	-0.0048073	-0.00446394	-0.004385965	-0.004463936	-0.004386	-0.0046636	-0.004346
	u(thick 2-1)	-0.0049149	-0.0050975	-0.00473804	-0.004461248	-0.004659723	-0.0046168	-0.004973	-0.004421
	u(thick 3-1)	-0.0046881	-0.00495	-0.00450309	-0.004424438	-0.004583865	-0.0044639	-0.0044629	-0.00445
	u(thick 4-1)	-0.0048015	-0.0045783	-0.00434749	-0.004581408	-0.004347492	-0.0044248	-0.0045423	-0.004585
	u(thick 5-1)	-0.0050662	-0.0046125	-0.00442444	-0.004738037	-0.004462912	-0.0045399	-0.0046636	-0.004623
	u(thick 6-1)	-0.005104	-0.0046938	-0.00450309	-0.004620565	-0.004424779	-0.0044244	-0.0045814	-0.004834
	u(thick 1-2)	0.00434783	0.0047619	0.004424779	0.004385965	0.004424779	0.00438596	0.00446429	0.004273
	u(thick 2-2)	0.00434783	0.0049505	0.004424779	0.004347826	0.004424779	0.00438596	0.00442478	0.0043103
	u(thick 3-2)	0.00434783	0.00490196	0.004424779	0.004385965	0.004464286	0.00442478	0.00438596	0.0043103
	u(thick 4-2)	0.00434783	0.00438596	0.004385965	0.004424779	0.004385965	0.00442478	0.00442478	0.004504
	u(thick 5-2)	0.00434783	0.00434783	0.004385965	0.004424779	0.004385965	0.00438596	0.00446429	0.0044642
	u(thick 6-2)	0.00434783	0.00438596	0.004424779	0.004424779	0.004424779	0.00438596	0.00442478	0.0045454
Unc. % Change Thick (95%)		1.60	1.63	1.54	1.55	1.54	1.54	1.57	1.55
Static Cooling Pressure (Pa)		79829.6161	79756.1594	#DIV/0!	79775.56628	79805.7574	79783.7098	79647.4133	79647.413

Appendix E: Uncertainty Calculations

Caliper Measurement Error Analysis

THICKNESS Error Analysis

Same spot meas.	Left/right of line	Up&down the line	
Formed	Formed	Formed	Flat(diff. piece)
0.284	0.284	0.298	0.258
0.283	0.286	0.287	0.258
0.283	0.283	0.292	0.257
0.284	0.284	0.289	0.257
0.283	0.285	0.292	0.258
0.283	0.283	0.288	0.258
0.282	0.285	0.313	0.258
0.283	0.283	0.297	0.257
0.283	0.282	0.29	0.257
0.282	0.283	0.286	0.257
0.282	0.283	0.283	0.258
0.282	0.285	0.294	0.258
0.282	0.281	0.314	0.258
0.284	0.283	0.292	0.257
0.282	0.283	0.288	0.258
Avg.	Avg.	Avg.	Avg.
0.2828	0.283533333	0.29353	0.2576
S.D.	S.D.	S.D.	S.D.
0.000774597	0.001302013	0.00903	0.000507093

Bias Unc. (flat-95%)
0.001597617

Bias Unc. (formed-95%)
0.00916

WIDTH Error Analysis

Same spot meas.	Left/right of line	Up&down the caliper jaws	
Formed	Formed	Formed	Flat(diff. piece)
2.284	2.282	2.282	1.639
2.283	2.284	2.281	1.64
2.283	2.283	2.28	1.641
2.283	2.282	2.28	1.639
2.282	2.28	2.271	1.638
2.281	2.283	2.279	1.633
2.283	2.282	2.28	1.637
2.282	2.283	2.28	1.637
2.282	2.281	2.28	1.637
2.282	2.281	2.279	1.638
2.282	2.282	2.279	1.638
2.283	2.282	2.278	1.633
2.281	2.282	2.278	1.635
2.281	2.282	2.279	1.635
2.28	2.282	2.268	1.635
Avg.	Avg.	Avg.	Avg.
2.282133333	2.282066667	2.27826667	1.637
S.D.	S.D.	S.D.	S.D.
0.001060099	0.00096115	0.00375056	0.00239045[illegible]

Bias Unc. (flat-95%)
0.00278602

Bias Unc. (formed-95%)
0.00401426

Appendix F: Outer Enclosure Test Data

Summer 1997 Tests. Procedure not the same as 1996 tests.

All temperatures in degrees CELCIUS

		INITIAL THICK	FINAL THICK	% THICK		AVG % THICK	STANDARD DE\	Bias Unc. (95%)	u(thick-95%)	INITIAL WIDTH	FINAL WIDTH	% WIDTH	AVG % WIDTH	STANDARD DE\	Bias Unc. (95%)	u(width-95%)	GAP	Cooling Press. (Pa)	Initial Temp	Forming Temp	AVG TEMP	Std. Dev. Tem	Time in oven before forming (min)	Time in oven after/during forming (min)	Cool down tim in jig (min)
Specimen 11.	1	0.255	0.247	-3.14%	X					1.999	2.032	1.65%							175	175	175	0	11	0	15
	2	0.256	0.256	0.00%						2.005	2.075	3.49%							"	"			"	"	let cool in
	3	0.256	0.259	1.17%		0.91%	0.82%	1.26%	1.50%	2.005	2.056	2.54%	2.81%	0.76%	0.11%	0.76%	0.086	17,913	"	"			"	"	ammebled jig,
	4	0.255	0.259	1.57%						2.008	2.077	3.44%							"	"			"	"	then let cool ir
	5	0.255	0.254	-0.39%	X					2.003	2.062	2.95%							"	"			"	"	half jig
Specimen 11.	1	0.257	0.25	-2.72%						1.995	2.014	0.95%							140	180	160	28.2842712	5	5	0
	2	0.257	0.253	-1.56%						1.995	2.006	0.55%							"	"			"	"	"
	3	0.257	0.25	-2.72%		-2.24%	0.58%	1.44%	1.56%	1.999	2.013	0.70%	1.04%	0.49%	0.11%	0.50%	0.075	18,300	"	"			"	"	"
	4	0.258	0.253	-1.94%						1.995	2.019	1.20%							"	"			"	"	"
	5	0.257	0.259	0.78%	X					1.996	2.032	1.80%							"	"			"	"	"
Specimen 12	1	0.258	0.269	4.26%	X					1.984	2.18	9.88%							185	185	185	0	5	5	0
	2	0.258	0.274	6.20%						1.986	2.079	4.68%							"	"			"	"	"
	3	0.258	0.267	3.49%		5.68%	1.98%	1.25%	2.34%	1.992	2.05	2.91%	6.89%	3.18%	0.11%	3.18%	0.271	17,368	"	"			"	"	"
	4	0.259	0.278	7.34%						1.995	2.131	6.82%							"	"			"	"	"
	5	0.258	0.28	8.53%	X					1.997	2.2	10.17%							"	"			"	"	"
Specimen 12.	1	0.257	0.285	10.89%	X					1.996	2.214	10.92%							160	185	172.5	17.6776695	5	5	0
	2	0.257	0.316	22.96%						1.996	2.271	13.78%							"	"			"	"	"
	3	0.258	0.308	19.38%		21.64%	1.96%	1.26%	2.33%	1.996	2.283	14.38%	13.89%	1.80%	0.11%	1.81%	0.375	17,368	"	"			"	"	"
	4	0.257	0.315	22.57%						1.997	2.311	15.72%							"	"			"	"	"
	5	0.258	0.283	9.69%	X					1.994	2.286	14.64%							"	"			"	"	"
Specimen 12.	1	0.255	0.288	12.94%	X					1.998	2.2	10.11%							185	185	185	0	5	8	0
	2	0.255	0.3	17.65%						1.998	2.182	9.21%							"	"			"	"	"
	3	0.254	0.274	7.87%		13.36%	5.00%	1.27%	5.16%	2.001	2.155	7.70%	9.20%	0.98%	0.11%	0.98%	0.33	17,368	"	"			"	"	"
	4	0.254	0.291	14.57%						1.999	2.178	8.95%							"	"			"	"	"
	5	0.254	0.279	9.84%	X					1.997	2.197	10.02%							"	"			"	"	"
Specimen 13.	1	0.257	0.264	2.72%						1.995	2.065	3.51%							155	180	167.5	17.6776695	3	0	0
	2	0.256	0.267	4.30%						1.997	2.084	4.36%							"	"			"	"	"
	3	0.256	0.266	3.91%		3.44%	0.70%	1.62%	1.77%	1.996	2.087	4.56%	4.10%	0.41%	0.11%	0.42%	0.356	17,762	"	"			"	"	"
	4	0.256	0.265	3.52%						1.996	2.079	4.16%							"	"			"	"	"
	5	0.256	0.263	2.73%						1.996	2.074	3.91%							"	"			"	"	"
Specimen 13.	1	0.257	0.281	9.34%						1.999	2.272	13.66%							160	170	165	7.07106781	3	0	0
	2	0.258	0.295	14.34%						2	2.314	15.70%							"	"			"	"	"
	3	0.257	0.287	11.67%		12.83%	2.35%	1.62%	2.86%	2	2.286	14.30%	13.93%	1.25%	0.11%	1.25%	0.35	17,368	"	"			"	"	"
	4	0.258	0.293	13.57%						2.002	2.277	13.74%							"	"			"	"	"
	5	0.256	0.295	15.23%						2	2.245	12.25%							"	"			"	"	"
Specimen 13.	1	0.256	0.291	13.67%	X					1.998	2.288	14.51%							170	175	172.5	3.53553391	3	0	0
	2	0.256	0.316	23.44%						1.998	2.351	17.67%							"	"			"	"	"
	3	0.256	0.302	17.97%		19.14%	5.04%	1.46%	5.25%	2.002	2.341	16.93%	16.03%	1.72%	0.12%	1.72%	0.385	17,368	"	"			"	"	"
	4	0.256	0.314	22.66%						1.997	2.34	17.18%							"	"			"	"	"
	5	0.256	0.288	12.50%						1.997	2.274	13.87%							"	"			"	"	"
Specimen 14.	1	0.256	0.289	12.89%						1.997	2.182	9.26%							165	175	170	7.07106781	2	0	0
	2	0.256	0.312	21.88%						2.001	2.301	14.99%							"	"			"	"	"
	3	0.256	0.291	13.67%		15.74%	4.15%	1.46%	4.40%	2.004	2.325	16.02%	13.89%	2.86%	0.11%	2.86%	0.399	17,368	"	"			"	"	"
	4	0.255	0.292	14.51%						2.006	2.329	16.10%							"	"			"	"	"
	5	0.256	0.283	10.55%	X					2.006	2.268	13.06%							"	"			"	"	"
Specimen 14.	1	0.256	0.263	2.73%	X					1.995	2.154	7.97%							170	170	170	0	2	0	0
	2	0.256	0.28	9.38%						1.995	2.21	10.78%							"	"			"	"	"
	3	0.256	0.283	10.55%		8.98%	1.46%	1.46%	2.06%	1.995	2.246	12.58%	9.98%	2.06%	0.11%	2.07%	0.424	17,368	"	"			"	"	"
	4	0.256	0.279	8.98%						1.995	2.211	10.83%							"	"			"	"	"
	5	0.256	0.274	7.03%						1.995	2.15	7.77%							"	"			"	"	"
Specimen 14	1	0.256	0.257	0.39%	X					1.995	2.01	0.75%							165	165	165	0	2	0	0
	2	0.256	0.26	1.56%						2	2.03	1.50%							"	"			"	"	"
	3	0.256	0.265	3.52%		2.05%	1.87%	1.45%	2.37%	1.996	2.046	2.51%	1.30%	0.81%	0.11%	0.81%	0.417	18,249	"	"			"	"	"
	4	0.256	0.265	3.52%						1.996	2.023	1.35%							"	"			"	"	"
	5	0.256	0.255	-0.39%						1.995	2.003	0.40%							"	"			"	"	"
Specimen 15.	1	0.255	0.255	0.00%						1.996	2.009	0.65%							160	170	165	7.07106781	3	0	15
	2	0.255	0.263	3.14%						1.999	2.027	1.40%							"	"			"	"	"
	3	0.255	0.26	1.96%		1.86%	1.33%	1.46%	1.98%	2.002	2.032	1.50%	1.12%	0.34%	0.11%	0.36%	0.015	18,245	"	"			"	"	"
	4	0.255	0.261	2.35%						2.007	2.028	1.05%							"	"			"	"	"
	5	0.255	0.256	0.39%	X					1.998	2.018	1.00%							"	"			"	"	"
Specimen 15.	1	0.257	0.262	1.95%	X					1.993	2.025	1.61%							170	170	170	0	5	0	15
	2	0.258	0.261	1.16%						1.994	2.04	2.31%							"	"			"	"	"
	3	0.258	0.263	1.94%		1.07%	1.86%	1.44%	2.36%	1.995	2.05	2.76%	2.19%	0.49%	0.11%	0.50%	0.05	18,113	"	"			"	"	"
	4	0.257	0.264	2.72%						1.993	2.043	2.51%							"	"			"	"	"
	5	0.257	0.253	-1.56%						1.995	2.03	1.75%							"	"			"	"	"
Specimen 15.	1	0.257	0.255	-0.78%						1.993	2.053	3.01%							170	180	175	7.07106781	5	0	15
	2	0.258	0.261	1.16%						1.997	2.064	3.36%							"	"			"	"	let cool in
	3	0.257	0.262	1.95%		0.97%	1.21%	1.45%	1.88%	1.995	2.065	3.51%	3.19%	0.28%	0.11%	0.30%	0.094	17,930	"	"			"	"	ammebled jig,
	4	0.257	0.261	1.56%						1.995	2.06	3.26%							"	"			"	"	then let cool ir
	5	0.256	0.262	2.34%	X					1.994	2.05	2.81%							"	"			"	"	half jig